JIMMA UNIVERSITY

SCHOOL OF POSTGRADUATE STUDIES

JIMMA INSTITUTE OF TECHNOLOGY

FACULTY OF CIVIL AND ENVIRONMENTAL ENGINEERING

CHAIR OF HYDROLOGY AND HYDRAULICS ENGINEERING

MASTERS OF SCIENCE PROGRAM IN HYDRAULICS ENGINEERING

Evaluation of Groundwater Potential and Sustainable Management in Upper Gilgel Gibe Watershed, Omo Gibe River Basin, Ethiopia

By: Wondmagegn Taye

A Thesis submitted to the School of Graduate Studies of Jimma University in Partial Fulfillment of the Requirements for the Degree of Masters of Science in Hydraulics Engineering.

November, 2018
Jimma, Ethiopia

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Main Advisor: Dr. Ing. Tamene Adugna

Co-Advisor: Dawd Temam (PhD candidate)

November, 2018
Jimma, Ethiopia

DECLARATION

I, Wondmagegn Taye, declare that the contents of this thesis is entirely my original work with the exception of quotations or references which have been attributed to their sources or authors. This thesis partially of fully has not been previously submitted to any other university for the reward of Degree of Masters of Science in Hydraulics Engineering.

Wondmagegn Taye ________________ ________________

Signature Date

APPROVAL

School of graduate studies

The undersigned certify that the thesis entitled: "**Evaluation of Groundwater Potential and Sustainable Management in Upper Gilgel Gibe Watershed, Omo Gibe River Basin, Ethiopia"** is the work of Wondmagegn Taye and we hereby recommend for the acceptance by school of Post Graduate Studies of Jimma University in partial fulfilment of the requirements for Degree of Master of Science in Hydraulics Engineering.

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As member of Board of Examiners of the MSc. Thesis Open Defense Examination, we certify that we have read, evaluated the thesis prepared by Wondmagegn Taye and examined the candidate. We recommended that the thesis could be accepted as fulfilling the thesis requirement for the Degree of Master of Science in Hydraulics Engineering.

________________________	__________________	________________
External Examiner	Signature	Date
____________________	____________________	_______________
Internal Examiner	Signature	Date
_______________________	___________________	________________
Chairperson	Signature	Date

DEDICATION

I dedicate this thesis manuscript to my family especially, to my Mother Felekech Alemu (Etete) and Abebe Alemu.

ABSTRACT

The demand for freshwater is increasing as the world's population continues to grow and expects higher standards of living. Groundwater plays a crucial role in Ethiopia in providing drinking water, increasing food and agricultural production, and facilitating industrial developments. Thus, a quantitative evaluation of the resource is a pre-requisite especially in developing countries like Ethiopia, where most people rely on it as a source of potable water and domestic uses. This study focused to quantify the groundwater resource potential and assess the sustainability of groundwater reserve at Upper Gilgel Gibe watershed using water balance method. The study was commenced through defining the boundary of the project area, review of previous works and collection of valuable primary and secondary data. The analysis and interpretations of data was supported by the application of different software like ArcGIS 10.4.1, Thornthwaite monthly water balance model, Soil Water characteristics of SPAW (Soil-Plant-Air-Water) computer model, Minitab 18, XL STAT 2018, Base Flow Index (BFI+ 3.0), pcp stat and Water Balance (WTRBLN) model. Estimation of areal depth of precipitation and Actual Evapotranspiration was carried out through the use of Isohyetal method and WTRBLN model and found as 1664.5 mm/year and 911.6 mm/year respectively. A total water volume of 875,829,800 m^3/year is estimated to recharge the aquifer system. The present annual groundwater abstraction is estimated as 10.15 MCM per year. The estimated specific yield, exploitable groundwater reserve and safe yield of the catchment are 5.9%, 520,557,000 m^3/year and 522,768,349 m^3/year respectively. The total groundwater abstraction is much less than the recharge and the safe yield of the aquifer. The renewable groundwater resources per capita, total groundwater abstraction/groundwater recharge, and total groundwater abstraction/exploitable groundwater resources are estimated as 3960.6 l/day/capita, 0.012 and 0.019 respectively. The groundwater sustainability indicators show that there is sufficient groundwater in the study area and the groundwater resources of the area considered as under developed.

(Key words: Abstraction, Groundwater potential, Over-exploitation, Recharge, Sustainable, Water balance)

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ACRONYMS AND ABREVEATIONS

°C	Degree Celsius
AET	Actual Evapo-transpiration
BCM	Billion Cubic Meter
BFI	Base Flow Index
BH	Borehole
CFCs	Chlorofluorocarbons
CSA	Central Statistics Agency
DEM	Digital elevation model
DR_O	Direct runoff
DWD	Deep Well with Distribution
EEPCO	Ethiopian Electric Power Corporation
FAO	Food and Agriculture Organization
GIS	Geographic Information System
GW	Ground Water
HDW	Hand Dug Well
HDWNP	Hand Dug Well with Normal Pump
ITCZ	Inter Tropical Convergence Zone
IWMI	International Water Management Institute
IWRM	Integrated Water Resource Management
$l/sec/Km^2$	Liter per second per kilometer square
m.a.sl	above mean sea level
MCMC	Markov Chain Monte Carlo
mm	Millimeter
Mm^3	Million cubic meter
MoWIE	Ministry of Water, Irrigation and Energy
MoWR	Ministry of Water Resource
NMSA	National Metrological Service Agency
OGRB	Omo Gibe River Basin
OLS	Ordinary Least Squares

PET	Potential evapotranspiration
RF	Rainfall
RH	Relative Humidity
RO	Runoff
S	Surplus
SPAW	Soil-Plant-Air-Water
ST	Soil-moisture Storage
STC	Soil-moisture storage Capacity
STW	Storage Withdrawal
SW	Shallow Well
WAPCOS	Water and Power Consultancy Services
WASH	Water Sanitation and Hygiene
WRI	Water Resource Institute
WRS2	Worldwide Reference System
WTRBLN	Water Balance

1. INTRODUCTION

1.1. Background

The demand for freshwater is increasing as the world's population continues to grow and expects higher standards of living. Water conservation, better systems' operation, higher end use, and water allocation efficiencies have not been able to offset the growing demand. Although water is abundant on earth, fresh water accounts only for about 2.5% of global water reserves. Out of this amount, approximately 30% is stored as groundwater and the same amount is on the surface as rivers and lakes; the remaining reserves are held in glaciers, ice caps, soil moisture, and atmospheric water vapor. In both arid and semiarid areas, groundwater may represent 80% or more of the total water resources (Karamouz *et al*., 2011). According to the report of Water Resource Institute, about 1.5 billion people depended on groundwater for their drinking water supply (WRI, 1998). World Meteorological Organization estimated that about 20% of global water withdrawals comes from groundwater (Shiklomanov, 1997).

Groundwater plays a vital role in Ethiopia in providing drinking water, increasing food and agricultural production, and facilitating industrial improvements. The rural areas which account more than 85% of the country's population are come across with shortage of potable water supply which can be solved by proper groundwater utilization (Tamiru, 2006). Ethiopia, being one of the most hydrologically blessed countries in East Africa, is believed to have a large groundwater potential. As stated by Moges (2012), studies show flawed results of 2.5 BCM by WAPCOS, to 185 BCM by Tamiru and Tenalem, (2001). Other study by Awulachew *et al.* (2007) indicates that, the groundwater potential of Ethiopia can be estimated as 2.6 - 6.5 BCM. Which can be taken as an indication of how much detailed study and survey is needed to estimate the countries resources with a better accuracy.

The rapid expansion of agricultural sector and the rising population growth heavily required groundwater. Consequently, many boreholes are drilled, and groundwater have been developed and exploited. This inevitably may lead to an excessive extraction and depletion of groundwater resource. Hence, it is crucial to regulate and maintain the groundwater reserve in the state of dynamic equilibrium over a period of time without disturbing the natural condition of the ecosystem (Adem, 2012). The public has a perception of groundwater as a reliable, clean, and nearly unlimited source of water supply. Even though there could be exceptions, it is a dependable source almost all over the world (Karamouz *et al.*, 2011).

Over-dependence on the groundwater resources for many purposes has led to its' over-exploitation, and this has led to much concern for groundwater characterization, potential assessment and management. Owing to increased demand and natural climate change, groundwater is often abstracted beyond its natural recharging capacity causing depletion of the resource (Badient *et al.*, 2002). The amount of water potentially to be extracted from an aquifer without causing depletion is mainly dependent on the groundwater recharge. Thus, a quantitative evaluation of the resource is a pre-requisite especially in developing countries like Ethiopia, where most people rely on it as a source of drinking water and domestic uses.

The water balance of the aquifer system is the key to the identification of the aquifer resources and the consequences of deviations in exploitation. The water balance is based on the principle of the continuity of flow (Kovalevsky *et al.*, 2004).

Upper Gilgel Gibe sub-basin is found on the upper reach of the Gibe basin, contributing flow to the larger Omo Gibe basin. The study area is generally characterized by high relief hills and mountains. The geology of the study area delivers serviceable groundwater resources potential and delivers upright diffusion of rainfall to recharge aquifers, which produce springs and feed perennial rivers. Generally, the study area is characterized by numerous intermittent rivers. The main source of water to the rivers is the rainfall from the Northern highlands. The downstream catchment of the study area is lowland, so there is maximum recharge from highlands in to this lowland catchment. The northern and the western portion of the study area are highly rainfall region, due to this reason the maximum recharge is in the lowland area. In the highlands portion of the study area there is a steep slope, so maximum runoff is present compared to the lowland area.

1.2. Statement of the Problem

Lack of proper estimation of groundwater potential is the main reason why groundwater exploitation and management have serious problems compared to surface water in the country. Thus, in order to ensure wise use of groundwater, a systematic evaluation of groundwater is required. Sustainable development, use and management of groundwater resources is a challenge under the current population growth, land degradation and climate change. Thus, economic development requires proper quantification of groundwater recharge (Gintamo, 2015).

Many shallow wells have been drilled and developed in localized area. In general, the people have been exploiting groundwater from these wells without understanding the groundwater potential and the consequence of over pumping. The problem of such increasing competitive demand of the water resources for domestic, agricultural & other purposes in the area due to the rapid population growth along with increasing living standard & intensified irrigation agriculture & other developmental activities indicate the need for efficient utilization through further investigation of the water resources potential, particularly the groundwater (Birhanu, 2015).

According to Villholth (2006), abstraction of groundwater has an associated impact on the water balance and hence on the availability of water resources on other parts of the water cycle. Thus, understanding of the aquifer system and assessment of the water balance components of the river basin is crucial for the sustainability of the resource.

Despite the above facts, no detailed studies have been carried out about the overall groundwater balance of the study area, particularly about the groundwater abstraction; and no detailed ecological considerations in relation to both the water and land resources development and management aspects are available that make possible the effective utilization of the resources with sound ecological balance to bring about integrated sustainable development in the region. Most of the previous researches are mainly focused on surface water, and little information is known about the groundwater potential of the area.

Despite the existence of numerous hydro-geological studies in the country, particular study on the Upper Gilgel Gibe watershed in relation to estimating the total groundwater resource (groundwater recharge, specific yield, exploitable groundwater reserve and safe yield) of the catchment, sustainability of groundwater reserve and proper strategies for groundwater sustainability however, is scanty.

1.3. Objectives

1.3.1. General Objective

This study has the general objective of quantifying the groundwater resource potential and assessing the sustainability of groundwater reserve with respect to appropriate groundwater sustainability indicators in the region.

1.3.2. Specific Objectives

Specifically, this study aims at achieving the following objectives:

1. To evaluate annual groundwater recharge, exploitable groundwater resource, total abstraction and safe yield of the watershed.
2. To assess the sustainability of groundwater reserve in the watershed with respect to appropriate groundwater sustainability indicators.
3. To suggest proper strategies that foster sustainable groundwater resource management in the area.

1.4. Research Questions

The research questions which addressed in this particular study are given below:

1. How much the total groundwater potential reserve in the watershed?
2. What is the current situation of groundwater reserve in the watershed with respect to sustainability?
3. What are proper strategies that foster sustainable groundwater resource management in the area?

1.5. Significance of the Study

This study is important in a sense that; it provides nearly the true nature of groundwater potential and sustainability in upper Gilgel Gibe watershed. The study tried to fill the knowledge gap by estimating the groundwater resources potential in the study area using water balance method. Moreover, the outcome of the study may also shed lights on effective groundwater regulating mechanisms and sustainable strategies which will be implemented by the communities. It also gives an important input to administrative managers, decision and policy makers, and researchers. The study can be used to ensure sustainability of the groundwater potential of the study area by implementing the suggested proper strategies.

According to Kumar (2012), the groundwater balance study of an area may serve; as a check on whether all flow components involved in the system have been quantitatively accounted for, and to know what components have the greatest behavior on the problem under study, to calculate unknown component of the groundwater balance equation while, all other components are quantitatively known with sufficient accuracy, and it can also be used for modeling of hydrological processes which is used to forecast changes within the groundwater system.

2. LITERATURE REVIEW

Different documents were reviewed for this work, which can help to know more about the groundwater potential, geology, hydrology, hydrogeology, the intermittent and the perennial rivers, surface topography, water sources and others. There are some studies in the study area; typically, most of the researches are conducted in governmental level and personal researchers. Even if there are some studies on the water potential of study area, most of the studies are on surface water and limited studies on groundwater. The study area is under-utilization due to the availability of sufficient ground and surface water potential for different water resources development projects (like water supply from groundwater resources, irrigation and hydropower) to eradicate different problems across the nations. On this paper, the literature review focuses on related groundwater characterization and potential assessment or research's conducted before by different scholars on the study area (generally on Omo Gibe river basin) about the character and potential assessment of the groundwater.

2.1. Groundwater Potential

The groundwater potential means the amount of water, which is stored in the subsurface of the groundwater reservoirs (Aquifers), recharged from rainfall, internal groundwater flow from one aquifer having a better hydraulic head to another aquifer having lower hydraulic head. According to MoWR report on (2014), the estimated annual groundwater recharge, mean annual surface runoff, and groundwater contribution to surface water fraction are 10 Billion m^3, 17.9 Billion m^3/year and 0.56 respectively. The study indicates that, Omo Gibe river basin is the biggest contributor compared to the river basins of Ethiopia. Ethiopia has enormous surface water and groundwater resources, although the distribution is uneven in regional or national level. Very little has been done in this field and development of the water resources, particularly in areas of groundwater resources. Groundwater utilization has been restricted to community water supply using shallow hand dug wells and unprotected springs.

The occurrence of the groundwater resources potential in the study area were done by different researchers at different times using different groundwater resources potential assessment approach. Different studies have been conducted to evaluate the groundwater potential of the study area aquifer. Among the most comprehensive studies conducted are studying the national water master plan, WAPCOS (1990), made an effort to quantify the total groundwater potential using various direct and indirect empirical approaches. The methods adopted to assess the groundwater potential in the previous studies are; Base flow separation approach, Subsurface drainage approach and Recharge area approach.

By using the above approaches, the groundwater resource potential in the study area was estimated by different governmental and non-governmental organizations. firstly, Base flow separation approach was used to separate stream flow of Omo Gibe main and tributary rivers which originates from stored groundwater and it is referred to as groundwater runoff or base flow. This approach is the indirect way to estimate the groundwater resources potential. To study the total groundwater resources potential in the study area, different researchers take this method as basic tool and estimated the groundwater potential. Report by Water and Power Consultancy Service (WAPCOS) shows that, using the stream flow data of twenty-one years, the total base flow volume of the study area is estimated as 2785 Mm^3.

Subsurface drainage approach was the second method that the previous study used to estimate the groundwater potential in the study area. The method used generated groundwater runoff contour map of Ethiopia and the groundwater runoff contour map is superimposed in to the study area, then the groundwater represents the replenish able recharge of the study area. According to the report, the groundwater runoff is obtained as 1.35 $l/sec/Km^2$ and considering the total area of the basin, annual recharge of the study area is estimated as 3,329 Mm^3.

Recharge area approach was the third method that the previous researchers used to estimate groundwater potential in the study area. Groundwater recharges in the study area come due to infiltration of precipitation, and seepage from streams and other water bodies. Major groundwater replenishment in the study area takes place through direct precipitation over the upland areas of the watershed. The seasonal fluctuations of water level in the study area depend on the rate of replenishment of the saturated zone. This rate is a function of precipitation, surface run-off, permeability of soil, drainage network, and antecedent moisture content of the soil and the slope of the land surface. This approach is also used to identify the discharge and recharge zones of the study area. According to the report, mean annual rainfall, extent of recharge area, percentage of rainfall recharging groundwater, and replenishable recharge is estimated as 1469 mm, 35,811, 8%, and 4,208 Mm^3 respectively.

All the above groundwater potential of the study area was estimated indirectly, and the previous study does not consider the groundwater sources like springs, hand dug wells, shallow and deep wells developed before for different purposes (generally, groundwater abstraction) in the study area.

Another study by Birhanu Haile (2015), characterize and assess the groundwater potential and the groundwater aquifer system in Omo Gibe river basin uses a three dimensional (3D) steady state Finite Element Method based groundwater modeling code (TAGSAC). This model needs the hydro geologic, recharge and boundary conditions as its input. According to this study, the groundwater potential of Omo Gibe river basin is about 4.38 billion m^3.

From the studies conducted on sub basin level, study by Shimelis *et al.* in (2014), on Bulbul sub basin, uses water mass balance method to estimate different water balance components. The study shows the following results: Precipitation (771,932,000 m^3), Recharge due to irrigation practices (70,388,501 m^3), runoff (275,074,089 m^3), Evapo-transpiration (363,329,000 m^3), water abstraction for domestic use (560,184 m^3), change in soil water content (25,289,436 m^3), and groundwater recharge (178,067,792 m^3).

2.2. Concepts of Groundwater Recharge

Groundwater recharge may be defined as the downward flow or amount of water reaching the water table, forming an addition to groundwater (Misstear, 2000). The amount of this recharge depends upon the rate and duration of rainfall, the surface conditions at the upper boundary, the soil moisture conditions, the water table depth and the geology (lithology and structure).

There are different sources of recharge to a groundwater system. These include precipitation or direct recharge, river recharge, inter-aquifer flows, irrigation losses and urban recharge. Maximum groundwater potential originates as recharge from the highland areas. The precipitation infiltrates into the groundwater aquifer zone. Some water enters the subsurface by seeping out of the bottom of surface waters, a situation more common in arid climates than in humid climates. Groundwater discharges from the saturated zone back to the ground surface in low-lying areas, usually at springs or the bottom of surface waters. Since groundwater always moves towards lower head, these exit points are always at a lower elevation than the water table where groundwater enters the system as recharge. Recharge is maximum in areas with wet climates and permeable soil or rock types. In permeable materials, the rate of recharge can be as much as half of the precipitation rate, with slight overland flow. On the other hand, in low permeability materials only a small fraction of the precipitation becomes recharge. With massive clay soils, the recharge rate can be less than 1% of the precipitation rate (Fitts, 2002).

Quantitative understanding of the process of groundwater recharge is very important to the sustainable management of groundwater resources in such a way that, the amount of recharge dictates the amount of water that can be extracted sustainably from the aquifers and recharge has great importance to assess the impact of climate changes on groundwater resources and aquifer vulnerability to contamination (Gebreyohannes, 2008).

2.3. Water Balance and Groundwater Potential Evaluation

2.3.1. Recharge

The amount of recharge depends upon the rate and duration of rainfall, the surface conditions at the upper boundary, the soil moisture conditions, the water table depth and the geology (lithology and structure). The groundwater recharge of an area varies in a wide range governed by the rainfall distribution, topography, land use and geology. The major recharge to the aquifer originates from precipitation and river channel losses. Main direct recharge is assumed to occur in all areas except where low permeable lacustrine soils exist (Tenalem *et.al.,* 2008).

Groundwater recharge can be affected by many parameters. These include: At the land surface - topography, precipitation (magnitude, intensity, duration, spatial distribution), runoff and ponding of water, cropping pattern, Actual Evapo-transpiration (AET), Irrigation - nature of irrigation scheduling, losses from canals and water courses, Rivers - rivers flowing into and leaving out of the study area, rivers gaining water from or loosing water to the aquifer, Soil zone - nature of soil, depth, hydraulic parameters, variability of the soil spatially and with depth, rooting depth of the soil, and cracking of soil on drying out or swelling due to wetting, Unsaturated zone between soil and aquifer - flow mechanism through unsaturated zones with different hydraulic conductivities and Aquifer - ability of aquifer to accept water, variation of aquifer condition with time (Misstear, 2000).

The amount of water that may be extracted from an aquifer without causing depletion is primarily dependent upon the groundwater recharge. Quantification of the natural groundwater recharge is a basic pre-requisite for efficient groundwater resource management. It is important in areas with large demands for groundwater supplies, where such resources are the key to economic development (Kumar, 2003).

2.3.2. Groundwater Recharge Estimation Methods

Recharge estimation methods can be classified based on the three hydrologic zones of studies namely surface water, unsaturated zone and saturated zone. Each of these zones provides a different set of data that can be used for estimation of the groundwater recharge. Within each of the hydrologic zones, the recharge techniques are further classified into physical techniques, tracers and numerical modeling. Recharge estimation methods based on surface water studies include physical methods (e.g., channel-water budget, seepage meters and base flow discharge); tracer methods (e.g., stable isotopes of oxygen and hydrogen); numerical modeling methods (e.g., deep percolation model, and water budget equation). Methods based on the unsaturated zone studies include physical methods (e.g., lysimeters, Darcy's law and zero flux plane); tracer techniques (e.g., Bromide, Hydrogen, visible dyes, and Chlorine), and numerical modeling methods (e.g., soil water storage routing, quasi-analytical approaches and numerical solutions to the Richards equation) and for saturated zone water table fluctuation and Darcy's law can be used as lamped water balance approach and tracers such as Hydrogen, Helium, Chlorofluorocarbon, Chlorine and Carbon are commonly used (Lerner *et al*., 1990).

Direct quantitative measurements of groundwater recharge flux, actually arriving at the water table and determined as volume per time (e.g. ft^3/day or m^3/day) are often cost prohibitive or not feasible. Installation, operation, and maintenance of lysimeters, which are the only devices capable of direct measurement of the recharge flux in vadose zone, are very expensive. Moreover, because of the inherent heterogeneity of soils, many lysimeters would be needed for any reliable estimate of recharge at a scale greater than the extent of one single lysimeter. In semiarid and arid regions with deep water tables, installation of lysimeters is not feasible (Kresic, 2009).

Groundwater recharge estimation must be treated as an iterative process that allows progressive collection of aquifer-response data and resource evaluation. In addition, more than one technique needs to be used to verify results. Indirect estimates of groundwater recharge have numerous limitations, particularly in arid environments. First and foremost, calculations are highly sensitive to changes in physical and empirical parameters. The water table fluctuation method experiences similar problems in semiarid settings due to the significant time lag between infiltration at the ground surface and a corresponding rise in the water table (Sophocleous, 2004). Another major problem with indirect physical methods is their reliance on idealized, theoretical equations, which do not accurately depict flow mechanisms in the vadose zone. It has been known for decades that infiltration occurs in the form of an uneven front even in seemingly homogeneous soils (Nimmo, 2007).

Generally, indirect physical methods are better suited in humid climates where water managers can have a better handle on the water balance. Heterogeneity and hydraulic sensitivity dominate semi-arid and arid environments, where the influence of preferential flow through macro pores further compromises accuracy of recharge estimates. When measured physical parameters fall in the dry range, recharge flux calculations are often in error by at least an order of magnitude (Sophocleous,2004).

2.3.2.1. Physical Methods

Physical methods based on direct measurements of hydrological parameters, usually used to estimate precipitation recharge because they are quick, inexpensive, or straightforward. However, these methods are often problematic in arid and semi-arid regions. Sophocleous (2004) as cited by Shimelis (2014), gave several reasons for this that low recharge fluxes largely depend on the vadose zone physical parameters and it is almost impossible to detect such small changes in physical parameters. Therefore, long time series are needed to assess mean annual recharge rate and spatial variability caused by changes in local topography, soil type, and vegetation requires a large number of measurement sites to assess the spatially averaged recharge rate. Nevertheless, with prudent appreciation of their limitations, physical methods can be a helpful tool for evaluating precipitation recharge (Scanlon *et al*., 2002 and Sophocleous, 2004).

2.3.2.2. Lysimeters

The most common procedure for direct physical measurement of recharge flux (net infiltration) involves the construction of lysimeters. Lysimeters are vessels filled with soil that are placed below land surface and collect the percolating water. The construction and design of lysimeters vary significantly depending on their purpose. Worldwide, the primary use of lysimeters was traditionally in agricultural studies, although more recently their use is increasing in general groundwater studies for water supply and contaminant fate and transport. Data collected from lysimeters is often used to calibrate empirical equations or numeric models for determining other water balance elements such as Evapotranspiration. The clear advantage of lysimeters is that they enable direct measurement of the quantity of water descending past the root zone over a time period of interest. Net infiltration flux is easily calculated from these measurements, eliminating much uncertainty in surficial processes such as Evapotranspiration and runoff. Lysimeters also capture infiltration moving rapidly through preferential flow pathways like macro pores and fractures. The main disadvantages of Lysimeters are their expensive construction costs and difficult maintenance requirements. Additionally, Lysimeters constructed with disturbed soils may have higher moisture contents, possibly skewing measurement results and overestimating recharge (Kresic, 2009).

2.3.2.3. Water Table Fluctuations

The water table fluctuation method for estimating groundwater recharge is based on the premise that rises in groundwater levels in unconfined aquifers are due to recharge water arriving at the water table and going immediately into storage. The recharge rate is calculated as follows (Scanlon *et al*., 2002):

$$R = S_y \Delta h \tag{2.1}$$

where R = recharge, Sy = specific yield (dimensionless) and Δh = water table rise.

Rise in water table after rainfall events is the most accurate indicator of actual aquifer recharge. It can also be used to estimate the recharge rate. The water table fluctuation method is also more useful, as immediate changes in water table elevation are visible after recharge events (Sophocleous, 2004). Because of its simplicity and general availability of water level measurements in most groundwater projects, the water table fluctuation method may be the most widely used method for estimating recharge rates in humid regions. The main uncertainty in applying this approach is the value of specific yield, which, in many cases, would have to be assumed. An important factor to consider when applying water table fluctuation method is the frequency of water level measurement. Delin and Falteisek (2007), point out that measurements made less frequently than about once per week may result in as much as a 48 percent underestimation of recharge based on an hourly measurement frequency.

2.3.2.4. Environmental Tracers

Environmental tracers have been irreplaceable in groundwater sustainability studies, as they provide answers about contemporary and historic recharge rates at time scales varying from days to thousands of years. They are useful in finding answers about possible mixing of groundwater of different age and origin within a groundwater system, or sources of groundwater recharge. They are also used to assess impacts and effectiveness of artificial recharge. In the unsaturated zone, environmental tracers mirror soil moisture movement, providing a sound means for estimating present-day recharge. Tracer methods are a good alternative to physical estimation in arid environments with low recharge fluxes, as tracer concentration measurements are much more precise than those of soil hydraulic properties (Kresic, 2009).

Environmental tracers commonly used to estimate the age of young groundwater (less than 50 to 70 years old) are the Chlorofluorocarbons (CFCs) and the ratio of Tritium and Helium-3 (3H/3He). Because of various uncertainties and assumptions that are associated with sampling, analysis, and interpretation of the environmental tracer data, groundwater ages estimated using CFCs and 3H-3He methods are regarded as apparent ages and must be carefully reviewed to ensure that they are geochemically consistent and hydrologically realistic (Rowe *et al.*, 1999). Isotopes typically used for the determination of older groundwater ages are Carbon-14, Oxygen-18 and Deuterium, and Chlorine-36, with many other isotopes are increasingly studied for their applicability (Geyh, 2000).

2.3.2.5. Chloride Mass Balance Method

The groundwater chloride mass-balance method is frequently used for estimating groundwater recharge, specially related to the fact that it is an inexpensive method, does not require sophisticated instrumentation and is independent of whether recharge is focused or diffuse. The method yields recharge estimates that are integrated in the space and in time, and was originally applied in the late sixties to estimate recharge rates in the coastal plain of Israel (Eriksson and Khunakasem 1969, cited by Scanlon 2002). The use of the chloride mass balance approach in groundwater requires the knowledge of three environmental variables, which are: the mean annual rainfall for the study region, the average annual total chloride fallout, and the average groundwater chloride concentrations in the study area.

According to the chloride mass-balance method, the mean annual recharge flux (R) is calculated as stated by the basic equation (Allison and Hughes,1978):

$$R = \frac{P(C_p + C_d)}{C_{gw}} \tag{2.2}$$

Where, P is the long-term mean annual precipitation, C_P is the weighted mean concentration of chloride in rainfall, C_d is the amount of chloride in the dry deposition and C_{gw} is the average chloride concentration in groundwater within the recharge area.

The method assumes that chloride ion behaves as a conservative, non-adsorbed environmental tracer under steady-state conditions, and the validity of its application is restricted by several assumptions and some of them are: the only origin of groundwater chloride is either from rainfall or from dry deposition, and it does not occur any recycling of chloride within the aquifer, rainfall and atmospheric input of chloride (wet and dry fallout) is considered to be constant with time overlong period, rainfall is evaporated and/or recharged to groundwater without any significant surface runoff, and no groundwater evaporation occurs up-gradient from the groundwater sampling points (Huang and Pang, 2011).

2.3.2.6. Darcy's Law

Darcy's law is used to calculate recharge (R) in the unsaturated zone by measuring or estimates of the vertical total head gradient and the unsaturated hydraulic conductivity at the ambient soil-water content. The method has been applied in many studies under arid and semiarid conditions (Sammis *et al*. 1982, Stephens and Knowlton, 1986) and also under humid conditions (Ahuja and El-Swaify, 1979; Steenhuis *et al*., 1985; Kengni, 1994; Normand *et al*., 1997). The rate of recharge is given by the equation:

$$R = -K(\theta)\left(\frac{dh}{dz} + 1\right) \tag{2.3}$$

Where, $K(\theta)$ is the hydraulic conductivity at the ambient water content θ, h is the matrix pressure head, and z is elevation.

2.3.2.7. Numerical Modeling Methods

A model is used to simulate the behavior of groundwater. The reliability of modeled recharge estimates highly dependent upon the accuracy of the model input parameters. Such models require information on groundwater levels, the permeability of the soil or rock and water flux measurements. Most authors agree that the estimation of recharge is best carried out as an iterative process since data is always limited and circumstances vary both in space and time. Lerner *et al*. (1990), specified that, before a quantitative evaluation of recharge is made, a conceptual hydro-geological model has to be built. The accuracy of the recharge estimate depends largely on the correlation of the conceptual model to the actual physical model. The use of modeling techniques has the advantage that it can be used for the purpose of forecasting recharge. Forecasting groundwater recharge has become important because of the impact of envisaged climate change and increased demand for groundwater resources in the future (Kirchner *et al*., 1991). Recharge techniques that have great potential to forecast recharge are those that have established relationships between rainfall, abstraction and water levels (Beekman and Xu, 2003).

2.3.2.8. Water Balance Method

The basic hydrological principles states that a balance must exist between the quantity of water supplied to the basin (inputs) and the amount leaving the basin (outputs) and the change in groundwater storage. The estimation of groundwater balance of a region requires quantification of all individual inflows to or outflows from a groundwater system and change in groundwater storage over a given time period. The basic concept of water balance is: the difference between input to the system and outflow from the system is equal to change in storage of the system over a period of time. The general methodology of computing groundwater balance consists of: identification of significant components, evaluating and quantifying individual components, and presentation in the form of water balance equation (Kumar, 2012). As much as possible, all elements of the groundwater balance equation should be computed using independent methods.

According to Kumar (2012), Water balance techniques have been extensively used to make quantitative estimates of water resources and the impact of man’s activities on the hydrological cycle. The study of water balance needs the systematic presentation of data on the water supply and its use within a given study area for a specific period. The water balance of an area is defined by the hydrologic equation, which is fundamentally a statement of the law of conservation of mass as applied to the hydrological cycle. With the help of water balance approach, it is possible to evaluate quantitatively individual contribution of sources of water in the system, over different time periods. A basin wise approach can give the best results where the groundwater basin can be characterized by prominent drainages. A thorough study of the topography, geology and aquifer conditions should be taken up. The limit of the groundwater basin is controlled by topography, disposition, structure and permeability of rocks and the configuration of the water table. Once the study area is identified, wide-ranging studies can be undertaken to estimate for selected period of time, the input and output of water, and change in storage to draw up water balance of the basin.

The water balance method is widely used because it can be applied nearly anywhere precipitation data are available. A major disadvantage of the method is that recharge is estimated as the residual term in an equation where the other budget terms usually are estimated with significant error, which can result in large errors in the recharge estimate (Nimmo *et al.* 2003, cited by Risser *et al.,* 2005).

2.4. General Groundwater Management Issues

2.4.1. Groundwater Development

Groundwater development begins with a few pumping wells and initially the groundwater management practice, in many cases, is geared to facilitate usage and development. As development progresses with more and more drilled wells distributed over the basin, issues such as overexploitation, equitable sharing of water and degradation of water quality become apparent in many basins. Thus, the emphasis of groundwater management practice has to be changed so that the available resource is utilized in an efficient, sustainable and equitable manner contributing to the economic and social wellbeing of the broader community. According to Gupta and Onta (1997), the following are key principles those reflect different aspects of concern in the evolution of sustainability in groundwater development.

Long term conservation of groundwater resources: Groundwater development must be sustainable on a long term basis which implies that the rate of extraction should be equal to or less than the rate of recharge. When the rate of extraction is higher than the rate of recharge, a continual lowering of water level is expected and this will steadily increase the pumping cost and then, at a certain level, it would no longer be economical to pump for many uses.

Protection of groundwater quality from significant degradation: The quantitative and qualitative aspect of resource availability for sustainable use is a basic concern for the evolution of resource management. The quality of groundwater in aquifers can be affected by natural and human activities. The potential contaminants must be controlled so that they cannot react with the groundwater system. Once contamination of a local groundwater supply has occurred, action must be taken to find and eliminate the sources, contain the contaminants in the area already affected and restore the water quality of the aquifer.

Consideration of environmental impacts of groundwater development: Hence, many problems like flooding, loss of property and human lives, severe deterioration of infrastructure facilities, groundwater pollution and health hazards have been attributed to the effects of excessive groundwater withdrawal and land subsidence, environmental impacts of groundwater development should be considered.

2.4.2. Groundwater Management

Groundwater is an important element of the environment; it is a part of the hydrologic cycle, and an understanding of its role in this cycle is necessary if integrated analyses ought to be promoted. The water resources including groundwater and surface water should be managed considering the issue of sustainability, that means groundwater use typically should be based on the current and future functions of groundwater as well as its expected values/costs. It can be addressed if one focus on the availability of resources for key services and their economical values. The consequence of losing access to such services that should be borne by the stakeholders should be equitably assessed (Karamouz *et al*., 2011).

The development of groundwater often provides an affordable and rapid way to alleviate poverty and ensure food security in the underdeveloped and developing countries (Mozumdar, 2012). Furthermore, by conjunctive use of groundwater and surface water, thorough integrated water resource management (IWRM) strategies can serve to foster efficient use and sustainability and enhance the longevity of water supply by improving the allocation and end user efficiencies (Owen *et al*., 2010).

Groundwater can be regarded as a renewable natural resource, if there exists to a balance between the recharge and abstraction from the basin. If pumping exceeds the total amount of recharge, groundwater depletion may occur and the aquifers are no longer sustainable. Generally, groundwater is a flow resource, a scarce one and also prone to negative externalities (over pumping and pollution) (Sheet, 2003). Hence, proper groundwater management is vital for the implementation of sustainable water resource development and conservation.

Groundwater management can be defined in brief as the planned and coordinated management of groundwater basin with a goal of long-term sustainability of the resource. The management of a groundwater basin implies a program of development and utilization of subsurface water for some stated purpose, usually of a social or economic nature. In general, the desired goal is to obtain the maximum quantity of water to meet predetermined quality requirements with the least cost (Owen *et al*., 2010).

Groundwater management is broadly concerned with the evaluation of the environmental, hydrologic, and economic impacts and trade-offs associated with the development and allocation of groundwater supply and quality to competing water uses' demands. The planning and management of groundwater problems is done based on a system's representation of the underlying physical, chemical, and hydraulic transport processes occurring within the groundwater basin (Villholth, 2006).

Understanding the quantity and quality of groundwater resources along with identifying the existing groundwater constraints are the fundamental issues for proper groundwater management over a given basin. Without considering such concerns, the effects of past development and prediction of the influences of future development cannot be adequately determined. Identification of major constraints related to groundwater resource is the main driving force for the commencement of groundwater management actions. It is highly important in designing and implementing appropriate future management tools and strategies. Degradation both in quantity and quality of groundwater are the main constraints that can be distinguished by the lowering of groundwater levels, subsidence, seawater intrusion and water quality degradation (Owen *et al*., 2010).

According to Hescock (2006) as cited by Tizro *et al*. (2007), the assessment and development of groundwater resource can be conceived by the application of water balance method that equates demand for water against abstraction requirement needs. A water balance represents the total amount of surface and groundwater entering and leaving a given basin over a specific period of time. It is used to evaluate whether the quantity of groundwater is abstracted at safe condition or not. The estimation of groundwater balance is essential in order to assess the safe yield of the aquifer systems and therefore to establish their rational exploitation and sustainable management (Voudouris, 2006).

Planning for sustainable development of water resources may include water conservation, waste and leakage prevention, improved efficiency of water systems, improved water quality, water withdrawal and usage within the limits of the system, water pollution within the carrying capacity of the streams, and water discharge from groundwater within the safe yield of the system. In groundwater management the concept of safe yield has been used to indicate the limits of pumpage from an aquifer. Safe yield is the rate at which groundwater can be withdrawn from an aquifer without producing an undesirable adverse effect (Dottridge and Jaber, 1999). The rate depends on the hydraulic parameters of the aquifer and the location of boreholes. Safe yield should be less than the average annual recharge in order to compensate for minor groundwater losses. The traditional definition of the safe yield assumes the pumpage rate is equal to the total recharge, but Feng-Xiang (2001) as cited by Voudouris (2006) assumed that the safe yield is 50% of the total natural recharge of groundwater.

The quality of groundwater had been given little attention in groundwater management issues in the past. However, it is now recognized just as important as its quantity. The quality of water is used to determine whether the water is satisfactory for the proposed use or not. Once groundwater has become polluted, it usually requires a very long, complex, and expensive task to restore the water quality in to its original condition. For these reasons, identification and assessment of threats to groundwater quality, and monitoring and prevention of groundwater pollution are considered as one component of groundwater management issue. Groundwater quality management can be implemented to avoid groundwater pollution through assessing pollution hazards and risks, delineating groundwater vulnerability zones and controlling effluent discharges (Luka and Weiss, 2008).

To make the notion of groundwater as a sustainable resource requires the responsible use, management and governance of groundwater. In particular, actions need to be taken by water users who sustain their well-being through groundwater abstraction; decision makers, both elected and none elected; civil society groups and associations; and scientists who must advocate for the use of sound science and Engineering in support of better management (Karamouz *et al*., 2011).

Instances of poorly managed groundwater development and the inadvertent impact of land-use practices have produced adverse effects on water quality, impairment of aquatic ecosystems, lowered groundwater levels and, consequently, land. Subsidence and the drying of wetlands. As it is less costly and more effective to protect groundwater resources from degradation than to restore them, improved water management will diminish such problems and save money (Kresic and Stevanovic, 2009).

3. METHODS AND MATERIALS

3.1. Study Area Description

3.1.1. Location

Upper Gilgel Gibe sub-catchment is found on the upper reach of the Omo Gibe basin, contributing flow to the larger Omo Gibe basin. The study area is situated on the upstream of the Gibe Dam in the South-Western part of Ethiopia, in Oromia regional state at some 260 km from Addis Ababa and the outlet point of the watershed is about 70 km North-East of Jimma. Geographically, Upper Gilgel Gibe lies between $7^{o}20'4.9''$ and $7^{o}59'16''$ North Latitudes and $36^{o}31'49''$ and $37^{o}13'40''$ East Longitudes with the catchment area of 2941 km^2 and with a perimeter of 319 km. The co-ordinate of the selected outlet point is $7^{o}46'4.8''$ N and $37^{o}12'11''$ E. The Western of the watershed is the range of hills and mountains that separate the Upper Gilgel-Gibe sub-basin from Abay Basin. To the North and North-West the watershed is bounded by the Tunjo sub-basin. To the East, the watershed is bounded by Lower Gilgel Gibe catchment with small area in the South-East bordering with the Gibe sub-basin with in Omo Gibe river basin. The whole of the Southern side borders the Gojeb sub-basin. The figure below shows the River basins in Ethiopia, Omo Gibe sub-catchments, Gilgel Gibe watershed and the Upper Gilgel Gibe watershed used for this study.

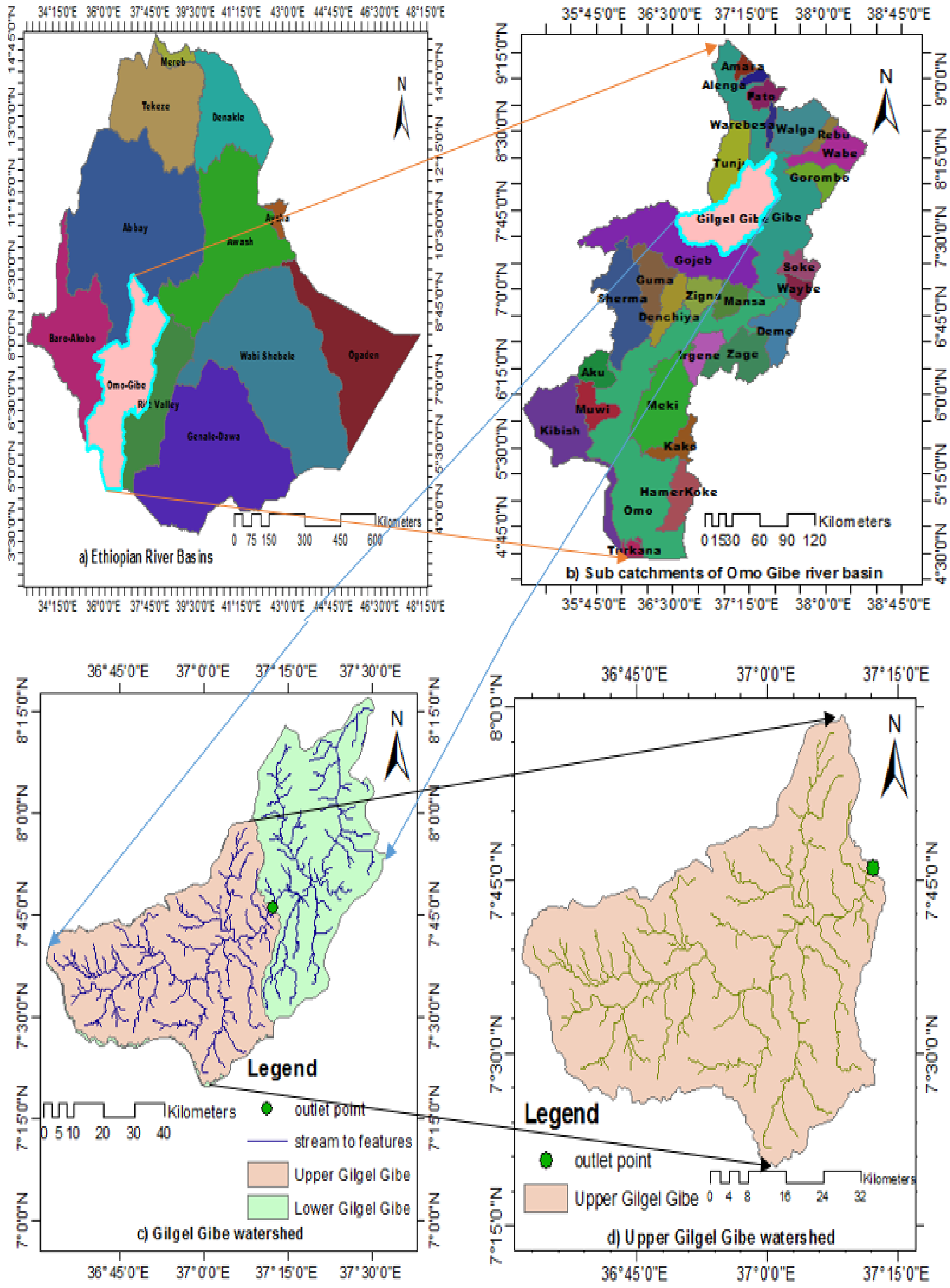


Figure 3.1: Location map of the study area

3.2. Overall Method Framework

The overall framework of the study methods starting from data collection and analysis up to suggestion of proper groundwater management strategies is shown in the figure below.

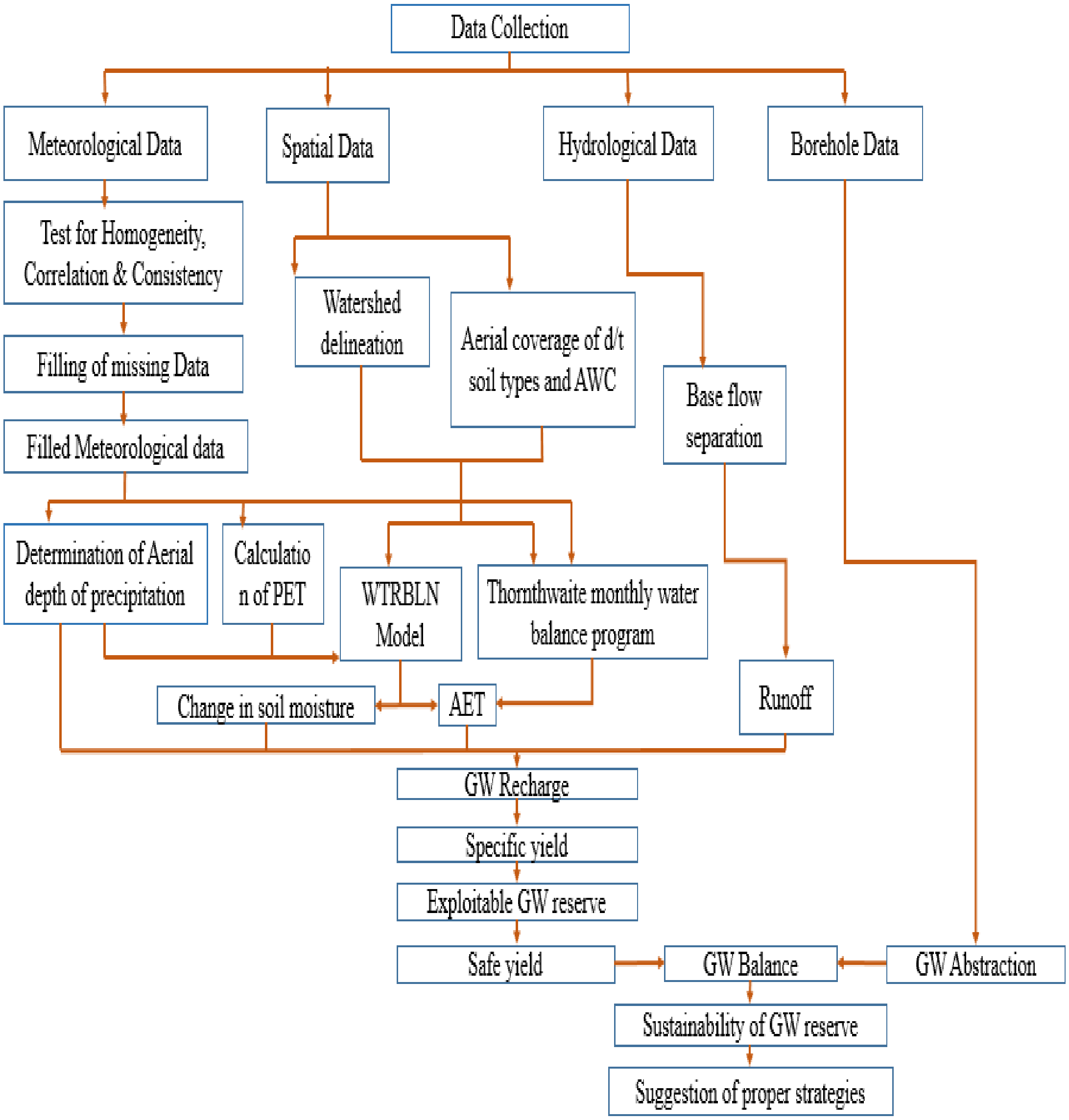


Figure 3.2: Work flow chart

3.3. Data Collection and Analysis

Evaluation of groundwater resources potential mainly requires Meteorological data, Hydrological data, Spatial data and Borehole data over a given time period.

3.3.1. Meteorological Data

Rainfall data is the most important data for evaluation of groundwater potential. Taking into account the length of record, continuity of data, concurrent period of observation and the distribution of stations in the sub-catchment, five meteorological stations were selected for the study. Meteorological data collected includes: rainfall, temperature (minimum and maximum), relative humidity, wind speed and sunshine hours of thirty-three years (1985-2017). The meteorological stations in and around the study area used to collect data for this study and the collected data are listed in table below.

Table 3.1: Meteorological stations in and around the study area and collected data

Name of meteorological station	Latitude (Degree North)	Longitude (Degree East)	Elevation (m)	Collected data				
				Rain fall	Tempe rature	Relative humidity	Wind speed	Sunshin e hours
Jimma	7.67	36.82	1718	✓	✓	✓	✓	✓
Dedo	7.52	36.87	2210	✓	✓	✓		
Assendabo*	7.75	37.22	1764	✓	✓	✓		
Shebe*	7.50	36.52	1813	✓	✓	✓		
Near Omo-Nada	7.65	37.18	1887	✓	✓	✓	✓	✓

*nearby stations

(source: National Meteorological Service Agency, NMSA of Ethiopia).

Prior to use meteorological data (precipitation, maximum and minimum temperature, sunshine hour, wind speed and relative humidity) were checked for homogeneity of stations and consistency of data. The most important time series data necessary for this study was rainfall data.

3.3.1.1. Homogeneity of Stations

In order to fill the missed rainfall data, and to select representative meteorological stations, checking homogeneity of group stations is essential. Data quality control was done to establish the homogeneity of the meteorological data before using them. The homogeneity of the selected gauging stations monthly rainfall records has been carried out by non dimensionalizing precipitation using equation below (Bogale, 2011):

$$P_i = \frac{\overline{P_i}}{\overline{P}} * 100 \tag{3.1}$$

Where,

P_i = Non dimensional value of precipitation for the month i

$\overline{P_i}$ = Over years averaged monthly precipitation for the station i

$\overline{P}$ = The over years average yearly precipitation of the station

and plotted to compare the stations included in the computation of area rainfall with each other as shown in figure below.

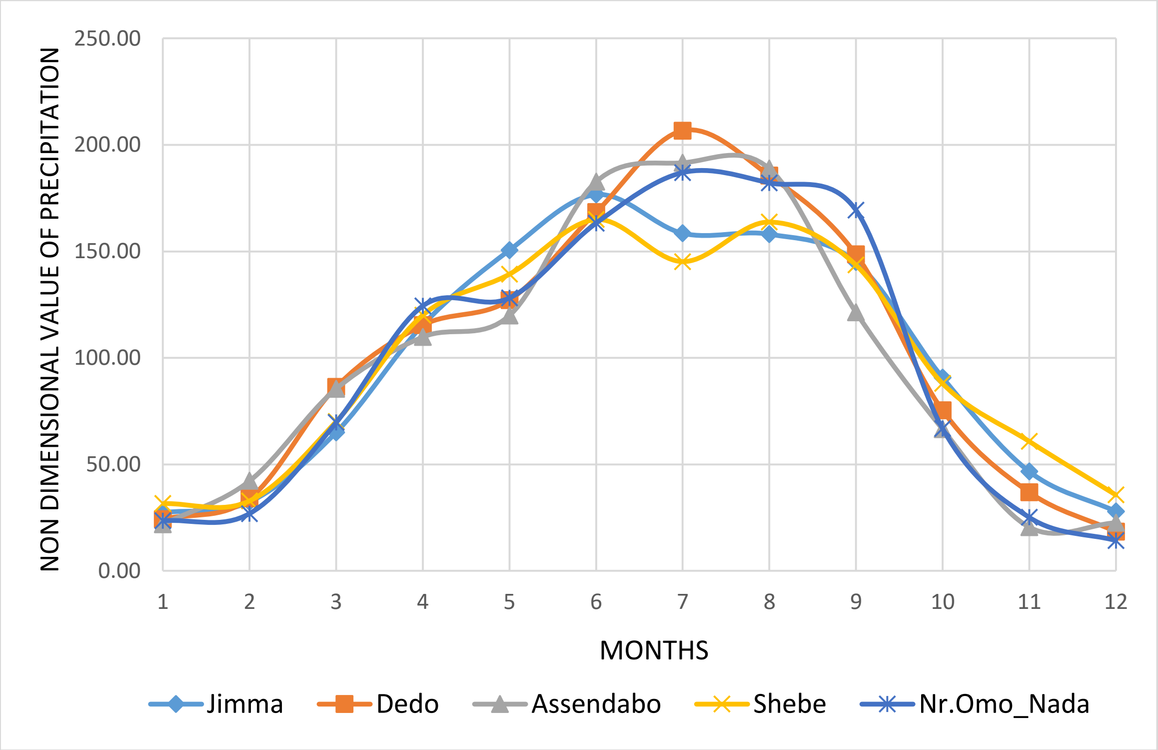


Figure 3.3: Homogeneity test for rainfall stations

3.3.1.2. Correlation Test

Correlation test used to compute different kinds of correlation coefficients, between two or more variables, and to determine if the correlations are significant or not. Pearson correlation coefficient corresponds to the classical linear correlation coefficient. This coefficient is suitable for continuous data and its value ranges from -

1 to 1, and measures the degree of linear correlation between two variables. Coefficients of determination or the squared Pearson correlation coefficient gives an idea of how much of the variability of a variable is explained by the other variable. Values of correlation coefficients are given in (Table 3.2) below and (see Appendix 1) for scatter plots for correlation between variables.

Table 3.2: Values of correlation coefficients

Correlation matrix (Pearson)					
Variables	Near Omo-Nada	Shebe	Assendabo	Jimma	Dedo
Near Omo-Nada	1	0.791	0.798	0.805	0.780
Shebe	0.791	1	0.838	0.867	0.822
Assendabo	0.798	0.838	1	0.862	0.839
Jimma	0.805	0.867	0.862	1	0.863
Dedo	0.780	0.822	0.839	0.863	1
All values are different from 0 with a significance level alpha = 0.05					
P-values (Pearson)					
Variables	Near Omo-Nada	Shebe	Assendabo	Jimma	Dedo
Near Omo-Nada	0	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Shebe	< 0.0001	0	< 0.0001	< 0.0001	< 0.0001
Assendabo	< 0.0001	< 0.0001	0	< 0.0001	< 0.0001
Jimma	< 0.0001	< 0.0001	< 0.0001	0	< 0.0001
Dedo	< 0.0001	< 0.0001	< 0.0001	< 0.0001	0
Coefficients of determination (Pearson)					
Variables	Near Omo-Nada	Shebe	Assendabo	Jimma	Dedo
Near Omo-Nada	1	0.626	0.637	0.648	0.609
Shebe	0.626	1	0.703	0.751	0.676
Assendabo	0.637	0.703	1	0.743	0.704
Jimma	0.648	0.751	0.743	1	0.746
Dedo	0.609	0.676	0.704	0.746	1

3.3.1.3. Consistency of Rainfall Data

If the conditions relevant to the recording of a rain gauge station have undergone a significant change during the period of record, inconsistency would arise in the rainfall data of that station. This inconsistency would be felt from the time the significant variation took place. The checking for inconsistency of a record can be done by using Double mass curve technique (Subramanya, 1998). The accumulated totals of the gauge in question are compared with the corresponding totals for a representative group of nearby gauge. If a decided change in the regime of the curve is observed, it should be corrected. However, for all stations the double mass curves were found more or less straight line showing all the selected stations in this study were consistent, there is no need of further correction. A sample (Figure 3.4) below shows Double mass curve for Jimma station and (see Appendix 2) for Double mass curve of the rest of meteorological stations.

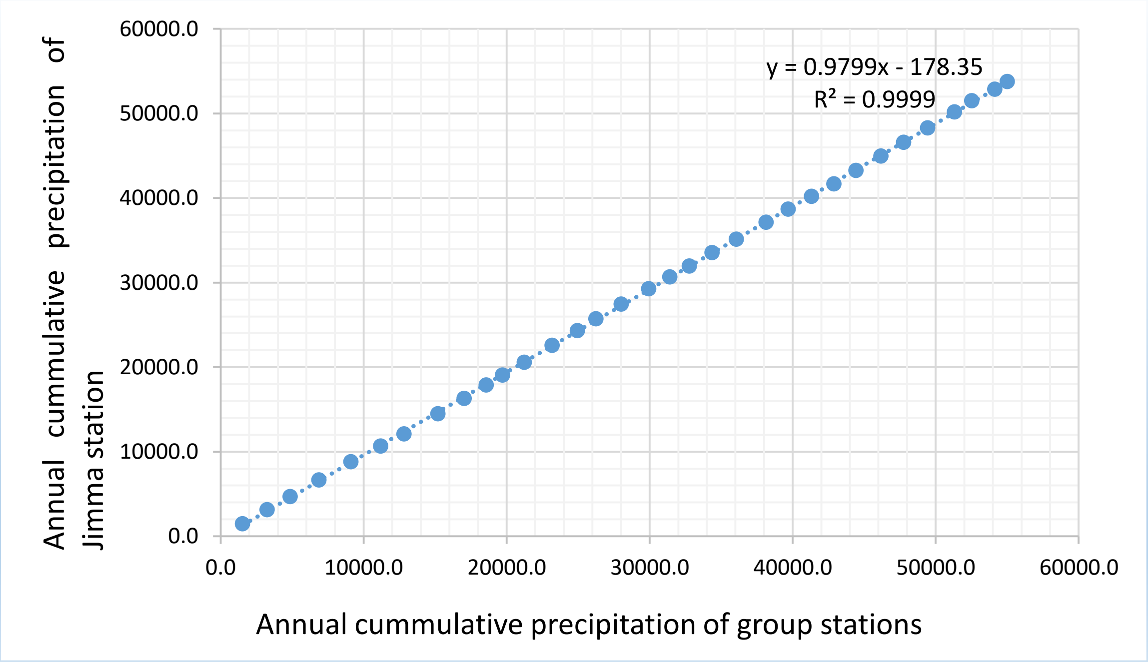


Figure 3.4: Double mass curve for Jimma station

3.3.1.4. Filling of Missing Data

Missing data for precipitation were estimated using linear regression method of XL STAT 2018 by considering correlation coefficients between variables. The principle of linear regression is to model a quantitative dependent variable Y through a linear combination of p quantitative explanatory variables, X_1, X_2, …, Xp (Jobson, 1999). The missing precipitation data for stations were estimated by considering values of correlation coefficients (Table 3.2). The figure below shows the sample regression plot between stations Jimma and Dedo with a correlation matrix (Pearson) or R^2 of 0.823 which is a higher value related to others.

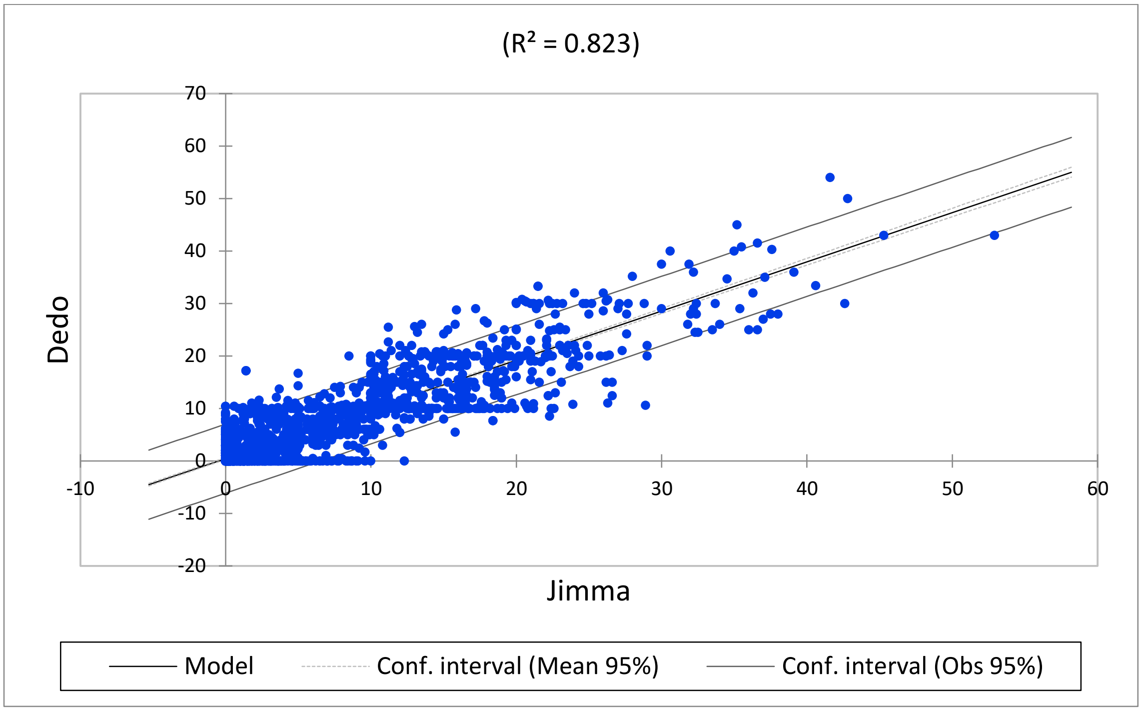


Figure 3.5: Correlation between station Jimma and station Dedo

Missing data for daily minimum and maximum temperature, relative humidity, wind speed and sunshine hour were filled using Multiple Imputation algorithm based on the Markov Chain Monte Carlo (MCMC) approach also called fully conditional specification (Van Buuren, 2007). Initial values of the missing values are obtained sampled from a normal distribution with mean and standard error equal to the mean and standard error obtained on available data and for each variable of the dataset with missing values, an imputation method based on sampling and Ordinary Least Squares (OLS) regression is applied. The used model is a regression model with the studied variable as dependent variable and all the other variables as independent variables. Disturbance using data sampled from different distributions are also used. New imputed values are obtained using this model.

3.3.1.5. Rainfall

A total of 33 years (1985 up to 2017) daily rainfall data from stations listed above were used to see the patterns of rainfall distribution in the catchment. (Figure 3.6) below shows the time series plot of rainfall data for different stations.

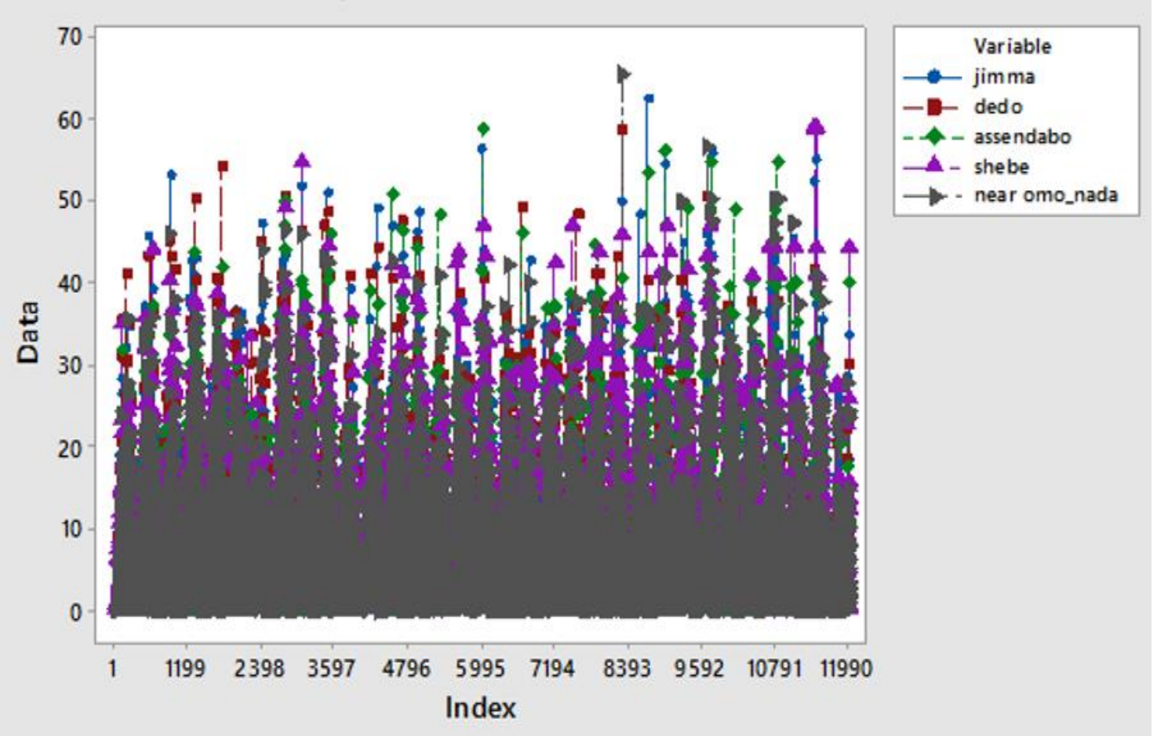


Figure 3.6: Time series plot of rainfall data for different stations

The study area, has rainfall for about seven months, from March to September with in a range of 1200-2000 mm per annum. The small rains are from October to March and the main from April to September with a marked increase in July and August. The Northern part (including Serbo and Kersa) and North-Eastern part of the study area has a rainfall within a range of 1200-1600 mm per annum. Whereas, the Southern part (around Dedo) and the Western (around Seka Chekorsa) and Central part including Jimma has a rainfall within a range of 1500-2000 mm per annum. The study area has a more even distribution of rainfall over March to September without any peak in July and august, around Jimma.

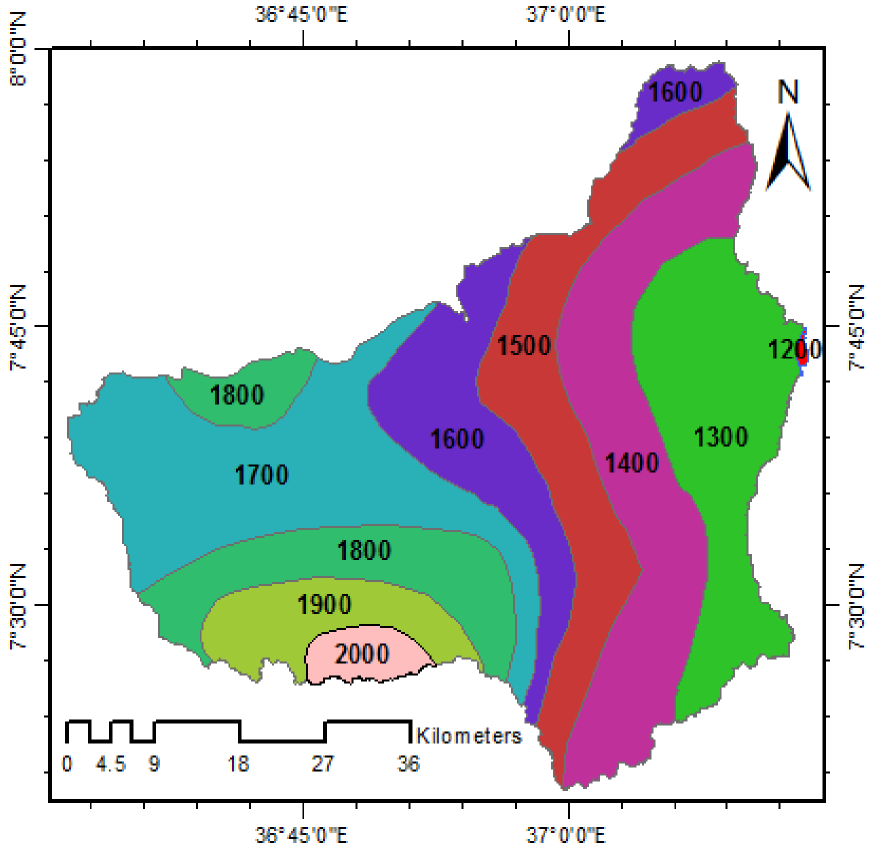


Figure 3.7: Isohyetal map of mean annual rainfall distribution over the study area

There is a significant seasonal variation of rainfall in the catchment. This has been identified from the monthly rainfall coefficient. Rainfall coefficient is the ratio between mean monthly rainfall and one twelfth of the mean annual rainfall. A month is designated as "rainy" when the monthly rainfall coefficient is equal and more than 0.6. Any value below 0.6 indicates dry (Daniel, 1977).

$$RC = {}^{P_m}\!\big/_{(P_y/12)} \tag{3.2}$$

Where,

RC = Rainfall coefficient

P_m = Mean monthly rainfall depth

P_y = Mean annual rainfall depth

Table 3.3: Mean monthly rainfall and Monthly rainfall coefficient

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Pm	30.5	36.9	90.63	164.81	207.71	246.5	271.75	264.8	181.36	97.1	43.87	28.57
RC	0.22	0.27	0.65	1.19	1.5	1.78	1.96	1.91	1.31	0.7	0.32	0.21

The calculated rainfall coefficient values indicate that the main rainy months last from March to October while the dry months last from November to February. According to Daniel Gamachu (1977), the rainfall regime of the catchment has been classified as Type-I with one rainy season. The long term monthly mean rainfall varies between 28.5 mm and 271.7 mm.

3.3.1.6. Temperature

The mean monthly temperature has been computed as the arithmetic average from long term meteorological stations. Air temperature in the study area shows small variation throughout the year. The long term monthly mean varies between 19.38°C and 16.91°C while the annual average temperature is 18.08°C.

3.3.1.7. Relative Humidity, Wind Speed and Sunshine Hours

Relative humidity expresses the ratio between the amount of water that the ambient air actually holds and the amount it could hold at the same temperature. It is dimensionless and is commonly given as a percentage. The highest relative humidity occurs when the rainfall is the highest. The study area is characterized by relatively high values of relative humidity. The long term mean monthly relative humidity varies between 83.9% and 54.6% with an annual average of 69.4%. The seasonal variation in Relative humidity follows a similar pattern to the rainfall.

The general wind condition of the catchment can be grouped as light air wind throughout the year. The average monthly wind speed for a period of thirty-three years varies between 0.80 m/sec and 0.99 m/sec with an average value of 0.90 m/sec. As the major factor affecting the average daily hours of sunshine on the study area is the cloud factor, with relatively little effect due to the seasonal movement of the earth. The average monthly sunshine hour for a period of thirty-three years fluctuates between 3.84 hrs./day and 7.67 hrs./day with a mean value of 6.27 hrs./day.

Table 3.4: Long-term monthly average weather parameters of the study area

	Mean monthly meteorological elements				
Months	RF (mm)	Temp (^oC)	RH (%)	Wind speed (m/s)	Sunshine hours (hrs./day)
Jan	30.50	18.43	56.7	0.93	7.14
Feb	36.90	19.02	54.6	0.97	7.22
Mar	90.63	19.38	60.5	0.99	6.91
Apr	164.81	18.99	69.0	0.96	6.34
May	207.71	18.65	74.9	0.94	6.51
Jun	246.50	17.81	80.7	0.83	5.59
Jul	271.75	16.91	83.9	0.80	3.84
Aug	264.80	17.20	82.7	0.80	4.21
Sep	181.36	17.60	79.6	0.83	5.52
Oct	97.10	17.62	69.8	0.92	6.85
Nov	43.87	17.73	62.0	0.92	7.51
Dec	28.57	17.67	58.3	0.92	7.67
Average	138.71	18.08	69.39	0.90	6.28

3.3.2. Hydrological Data

The study area groundwater resources potential is affected by variation of perennial river stages. According to Adem (2012), water flows from the river into the aquifer and the groundwater potential and the groundwater table rises when there is an increase in river stage with respect to the altitude of the groundwater resources potential storage and groundwater table.

Generally, the study area is characterized by numerous intermittent rivers. The main source of water to the rivers is the rainfall from the Northern highlands. Gilgel Gibe River is the main perennial river in the study area and Seka River is the tributary to this River. Daily river flow data or stream flow of Gilgel Gibe River used for this study was collected from Ministry of Water, Irrigation and Energy office (MoWIE). Gilgel Gibe river of the study area has a gauging station at Assendabo at a location of

7.45°N Latitude and 37.11°E Longitude with a drainage area of 2966 km^2. A total of twenty-four years (1990-2013) daily river flow data of Gilgel Gibe river recorded near Assendabo was used as hydrological data.

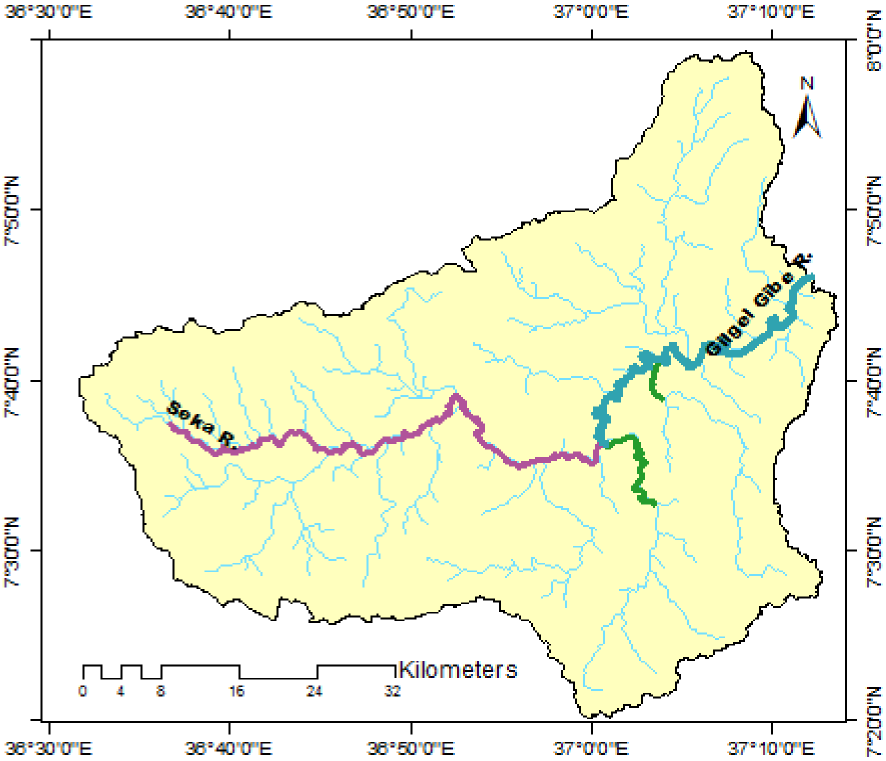


Figure 3.8: Rivers of the study area

3.3.3. Spatial Data

3.3.3.1. Digital Elevation Model (DEM)

DEMs are point elevation data stored in digital computer files which can freely downloaded from internet. These data consist of x, y grid locations and point elevation or z values. It is a commonly used digital elevation source and an important for watershed characterization. They are provided in a variety of ways for a different map resolutions or scales. Many agencies provide DEM data with 90 m, 30 m and 10 m resolutions. But for this specific study, resolution or pixel size of 30m by 30m from ftp://ftp.glcf.umd.edu/glcf/Landsat/WRS2/ server was used. The point elevation data was used to yield essential derivative products such as slope, flow accumulation and flow direction in process of watershed delineation.

3.3.3.2. Topography and Slope

The study area divides sharply and almost exactly into lowlands in the central part and highlands in the other ends. The highland areas have elevations as high as 3312 m.a.sl while the lowland areas fall in the altitudes up to 1677 m.a.sl. Steep slopes with dissected hills characterize the highlands while the lowlands are characterized by relatively gentle and undulating slopes.

The study area is generally characterized by high relief hills and mountains with an elevation of about 1677 m up to 3312 m above mean sea level and slope of 0 up to 67 degrees. The topography of the catchment is heterogeneous with upper plateaus that are cut by deep V-shape valleys in the flanks and flat terraces around the Gilgel Gibe river in the center of the catchment. The study area has mountainous to hilly terrain cut by the deeply incised gorges of the Gilgel Gibe river. The South-Eastern part of the watershed is characterized by high mountains (2900 m up to 3300 m) with steep slopes and rolling upland Plateaus. Most slopes are in between 0 and 10 degrees and the altitude range is 1677 m - 2004 m above mean sea level.

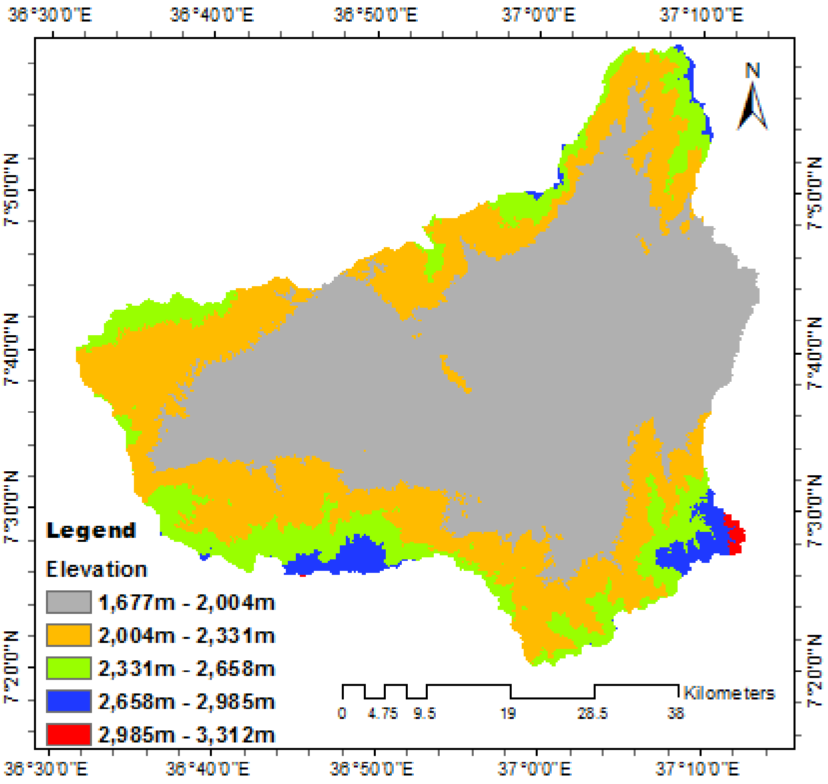


Figure 3.9: Elevation of the study area

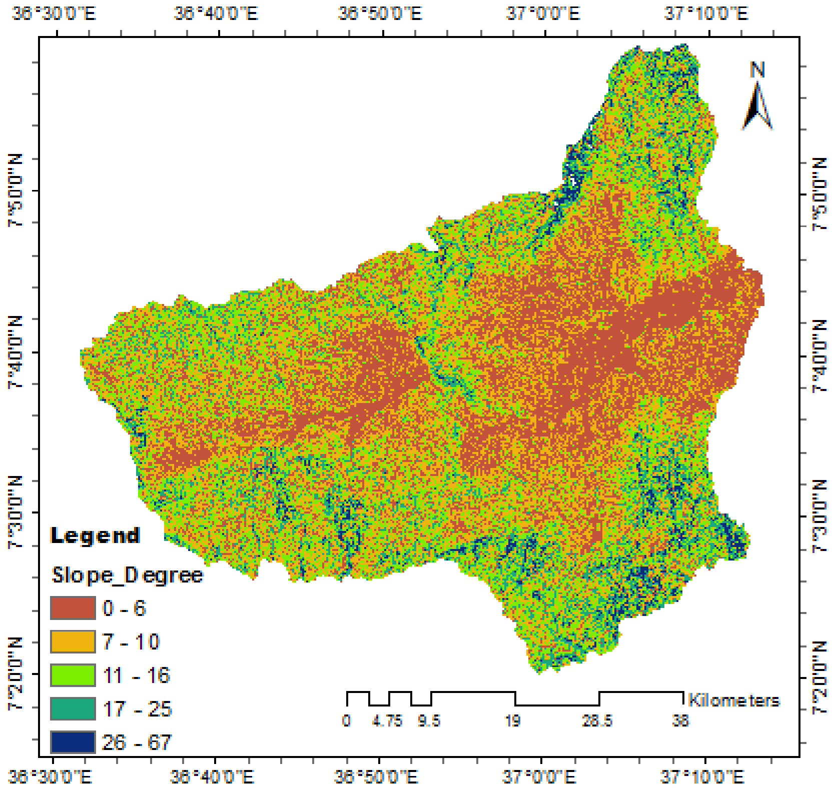


Figure 3.10: Slope of the study area

3.3.3.3. Soil

The soils in the study area are for the most part permeable and well drained. In the upper and middle parts of the catchment this is true of valley slopes near the catchment divide while the valley bottoms have significant areas of less permeable soils with impeded drainage. In the lower part, the sedimentary floodplain is mostly characterized by poor drainage. For this study, soil data or soil map of the study area was collected from the Ministry of Water, Irrigation and Energy office (MoWIE) and also FAO soil classification map was used in combination.

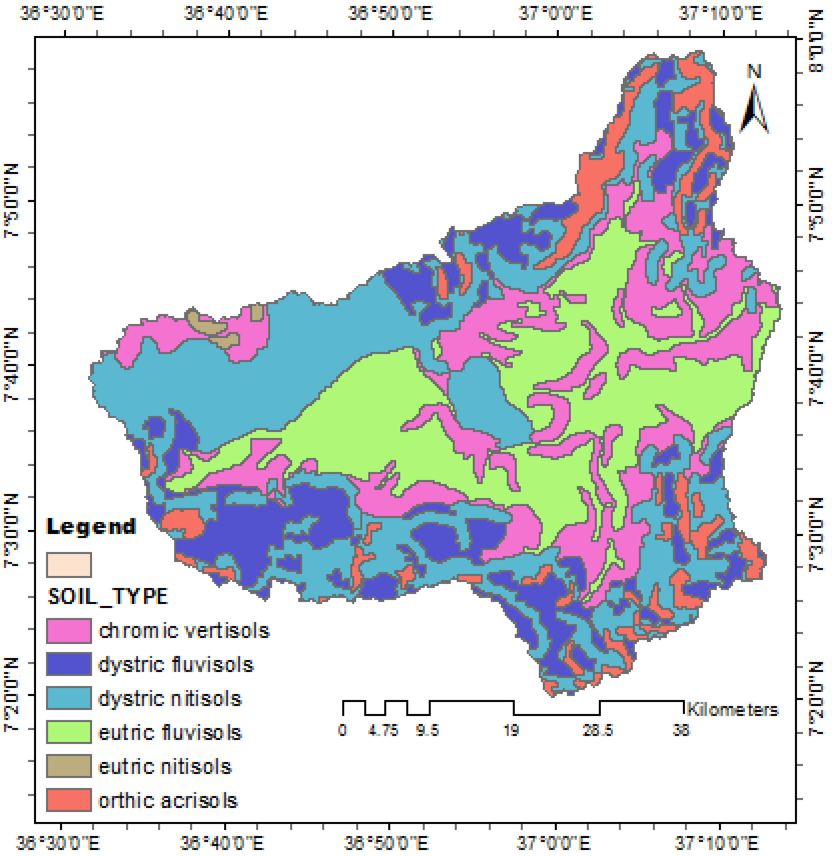


Figure 3.11: Soil map of the study area

3.3.3.4. Land Use Land Cover

The study area is under extensive cultivation with ever increasing pressure on land as a result of expansion of area under Agriculture. Forest areas are confined to areas of very steep and inaccessible by farmer, and often has an understory of coffee. Land use land cover was required to determine Evapotranspiration loss from the area and the data was also collected from Ministry of Water, Irrigation and Energy office (MoWIE).

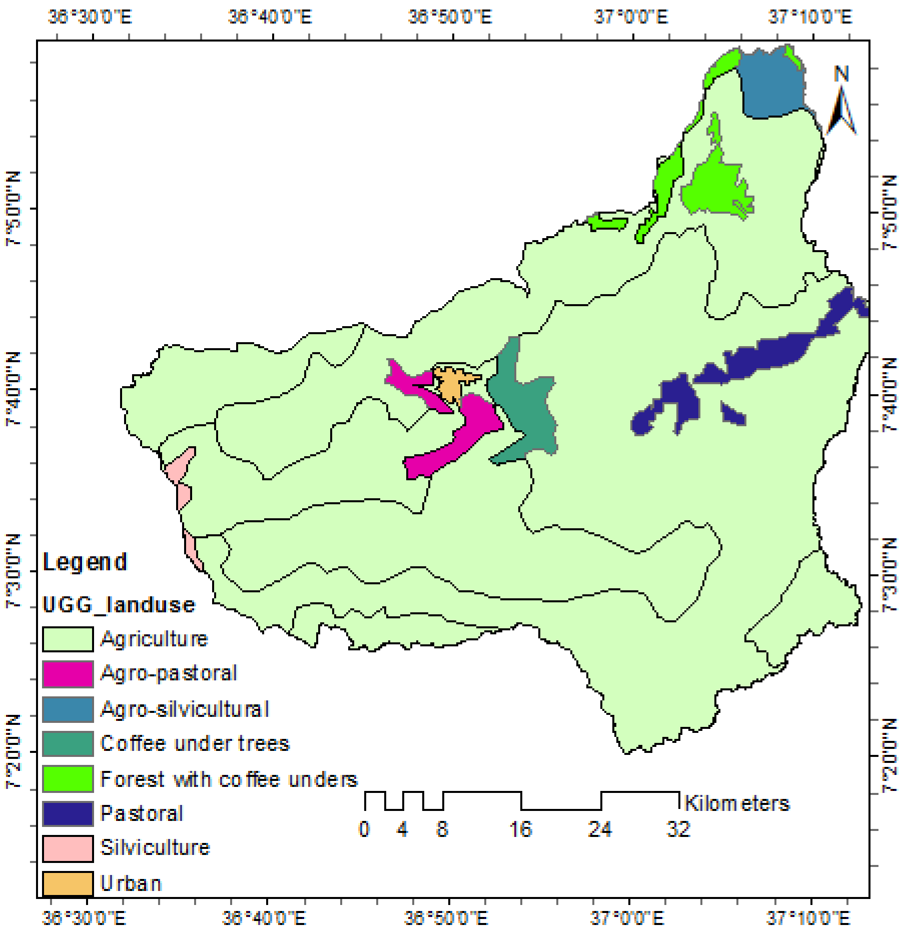


Figure 3.12: Land use land cover map of the study area

3.3.3.5. Geology and Hydrogeology of the Study Area

The characterization and assessment of the groundwater resources potential studies require a detail studies about the geology and hydrogeology of the study area. The occurrence of groundwater is mainly influenced by the geology, geomorphology, tectonics and the climatic conditions and others which are present in the study area. The geology of the study area delivers serviceable groundwater resources potential and delivers upright diffusion of rainfall to recharge aquifers, which produce springs and feed perennial rivers. The difficulty of obtaining productive aquifers is peculiar feature of Ethiopia, which is characterized by wide heterogeneity of geology, topography, and environmental condition (Alemayehu, 2006).

The base of the region consists of intensively folded and faulted Precambrian rocks, and is overlain by Mesozoic marine strata and Tertiary basalt traps. The Precambrian rocks, the oldest rocks in Ethiopia with ages of over 600 million years, contain a wide variety of sedimentary, volcanic and intrusive rocks which have been metamorphosed to varying degrees. They are overlain by more recent Mesozoic rocks mainly sandstone and limestone, except where the younger cover rocks have been eroded away exposing them in many parts of the country. The Mesozoic rocks in turn are overlain by Tertiary volcanic rocks. The volcanic rocks include rhyolites, trachytes, tuffs, ignimbrites, conglomerates and basalt that are the major part (Mohr 1971, cited by Shimelis, 2014).

The geology of the study area is dominated by basaltic lava flows, rhyolites, trachytes and ash flows of the trap series. Basic and sub-silicic volcanic rocks, frequently inter-layered with reddish paleosols of tertiary age characterize the area. Bedrock is characterized by rhyolites, as large dome and sheets, intercepts of andesite and trachyte, columnar basalt lava with layers of tuff and lacustrine elements. These types of rocks are grouped in different formations as: recent volcanics-rhyolites as large domes and sheets, with intercepts of andesite and trachyte; volcanic plugs of trachyte are also founded; Wollega basalts-columnar basalts interbedded with acidic tuffs and loose fluvio-lacustrine sediments; Jimma volcanic-rhyolites alternated with tuff and basalts (Oligocene-Miocene); Omo Basalts-tuffs and red paleosols (Negash 1987; Woodroofe 1996; EEPCO 2004, cited by Shimelis, 2014). Geology of the study area comprises rocks which range in age from Precambrian to Quaternary, more dominantly Pliocene age volcanic. The Jimma volcanic are a thick succession of basalts and sialic rocks which have two units: Jimma basalts and Jimma rhyolites which show a conformable relationship but they lie unconformable over the Precambrian basement.

The hydrogeology of the study area is the main constrained factor to characterize and to estimate the groundwater resources potential. The geology of the study area is quite complex, it is difficult to characterize and estimate the groundwater resources potential, which is stored in the basin. The complexity of geology of the study area has a direct impact on its hydrogeological characteristics (Karimi *et.al*., 2014). There are complex relationships between groundwater recharge, flow, storage and discharge and the surface water system. The frequent occurrence of groundwater as discreet bodies, which may not be readily identified, makes evaluation of the available groundwater resource extremely difficult (Jordi *et.al*., 2014).

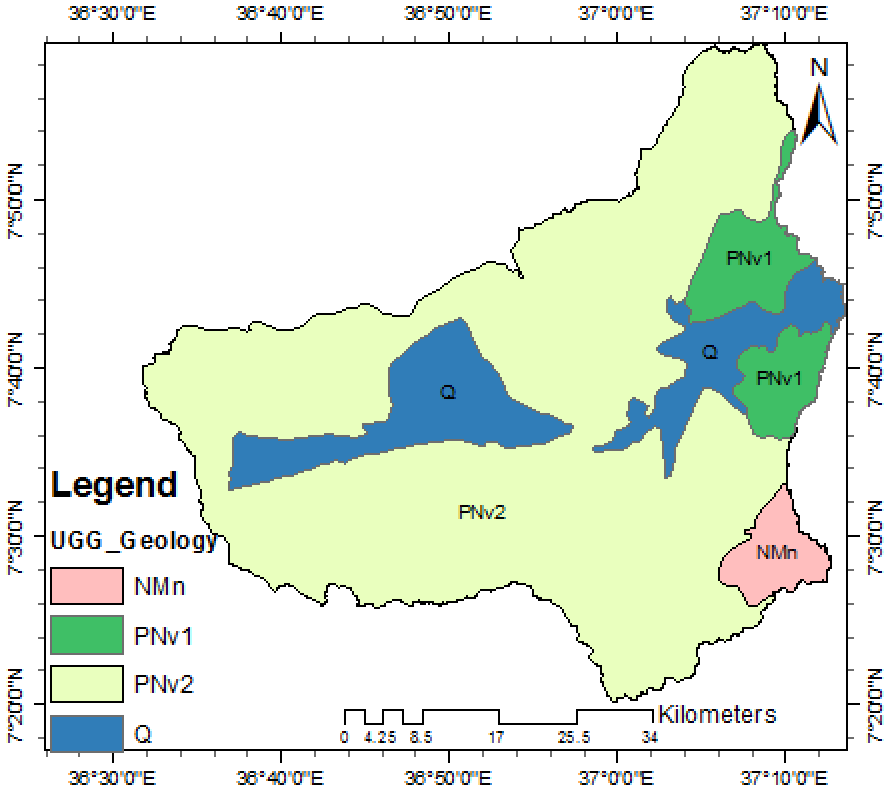


Figure 3.13: Geology of the study area

3.3.4. Borehole Data

The borehole data are the constraint input parameters for groundwater resource evaluation; therefore, collecting these data is a base line survey for this study. This data including the location (X and Y coordinates of boreholes and wells), the water table depth (static and dynamic water levels of the existing wells and boreholes) and the actual discharge of wells. Well inventory data used for this study were collected from different sources like; Jimma zone water, mineral and energy office, well completion reports of Jimma University and Jimma Airport, from previous study around the study area conducted by Dereje Belay (2015) and Jimma zone Water, Sanitation and Hygiene (WASH) report.

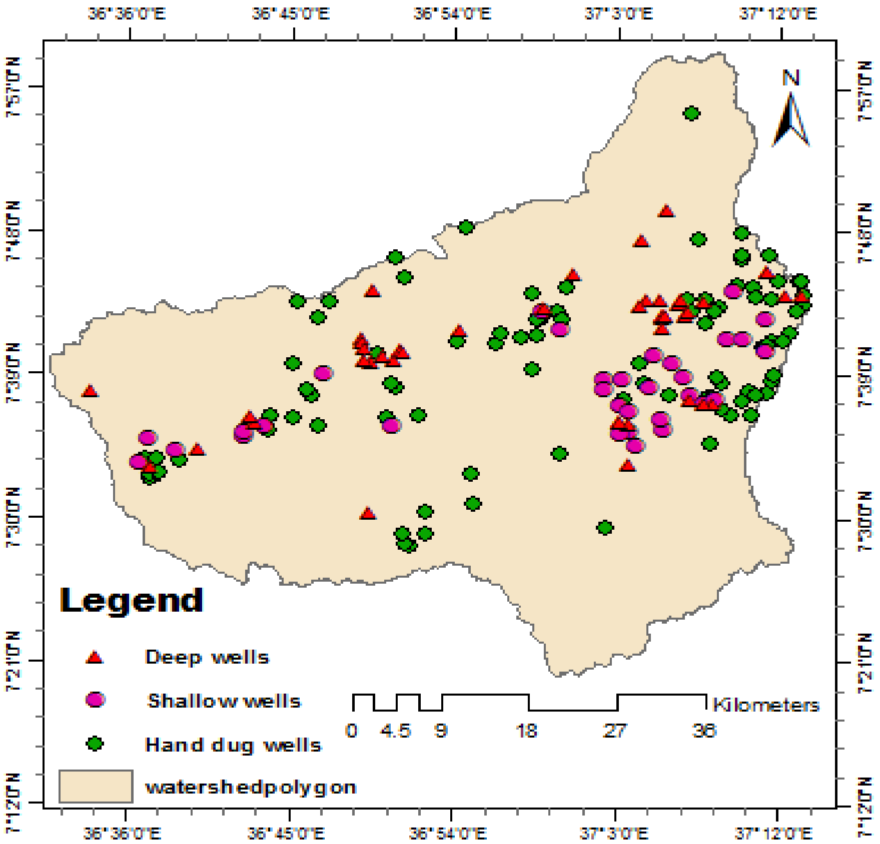


Figure 3.14: Location and types of wells collected

3.4. Material Used

To evaluate the groundwater potential of the study area, water balance approach was used. Thornthwaite Monthly Water Balance Program and WTRBLN Model were used to estimate different water balance components mainly actual Evapotranspiration (AET). Estimation of Available Capacity of root zone (AWC) and separation of base flow was carried out by using Soil-Water characteristics of Soil-Plant-Air-Water (SPAW) computer model and the Base Flow Index (BFI+ 3.0) software respectively.

3.4.1. Soil Water Balance Method

The basic hydrological principles states that a balance must exist between the quantity of water supplied to the basin (inputs) and the amount leaving the basin (outputs) and the change in groundwater storage. Water balance is the balance between the income of water from precipitation and snow melt and the out flow of water by Evapotranspiration, groundwater recharge, and stream flow (Thornthwaite, 1957). The general form of water balance equation for any natural area such as a river basin or water body indicates the relative values of inflow, outflow and change in water storage for the area or water body under consideration which can be given by:

$$\text{Inflow} - \text{Outflow} = \text{Change in storage } (\Delta S) \tag{3.3}$$

The inflow part of the water balance equation for the study area includes the precipitation (P) as rainfall. The out flow component of the equation comprises the Actual Evapotranspiration (AET) from surface and cropland and groundwater abstraction or withdrawal. Withdrawal indicates water use for irrigation and drinking and industry from all water sources.

The budget can be computed for a reservoir, soil profile, and aquifer drainage basin over a specific period of time. Soil water balance model was developed by Thornthwaite and later revised by Thornthwaite and Mather. It estimates the balance between the inflow and outflow of water in the soil. The soil water balance can be represented by:

$$G_r = P - AET + \Delta S_m - R_o \tag{3.4}$$

Where,

G_r = Groundwater recharge

P = Precipitation

AET = Actual Evapo-transpiration

ΔS_m = Change in soil moisture

R_o = Runoff

The advantage of the water balance method is that recharge can usually be estimated from easily available data (rainfall, runoff, water levels) and rapid to apply (Shimelis *et al.*, 2014).

Water balance is a quantitative evaluation of the total water gained or lost from a given hydrological system during a specific period of time (Tamiru and Tenalem, 2001). It considers all surface and groundwater that are entering, leaving or stored within the system. The study of water balance of a given basin forms a basis for the hydrological confirmation of projects for the rational use, control and redistribution of water resources in time and space. It is also used to make a quantitative evaluation of water resources and their change under the influence of man's activities. Knowledge of the water balance assists the prediction of the consequences of artificial changes in the regime of the given basin. Thus, for sustainable groundwater management, the water balance should be established for a given unit system over a given period of time.

3.4.2. Thornthwaite Monthly Water Balance Program

Monthly water-balance model driven by a Graphical User Interface or Thornthwaite Monthly Water Balance Program have been used as a means to examine the various components of the hydrologic cycle (for example, precipitation, evapotranspiration, and runoff). Inputs to the model consists of mean monthly temperature (T, in degrees Celsius), monthly total precipitation (P, in millimeters), and the latitude (in decimal degrees) of the location of interest. The latitude of the location is used for the determination of day length, which is needed for the computation of potential evapotranspiration (PET). Computations of monthly water-balance components of the hydrologic cycle can be done for a specified location. The Graphical User Interface allows the user to easily modify water-balance parameters and provide convenient estimates of water-balance components. The water-balance model examines the allocation of water among various components of the hydrologic system using a monthly accounting procedure based on the methodology originally presented by Thornthwaite. The model is also referred to as the Thornthwaite model (McCabe and Markstrom, 2007).

3.4.2.1. Precipitation

The first computation of the model is the estimation of the amount of monthly precipitation (P) that is rain (Prain) or snow (Psnow), in millimeters. When mean monthly temperature (T) is lower than a specified threshold (Tsnow), all precipitation is considered to be snow. If temperature is greater than an additional threshold (Train), all precipitation is considered to be rain. Between the range defined by

Tsnow and Train, the amount of precipitation that is snow decreases linearly from 100 percent to 0 percent of total precipitation. This relation is expressed by the following formula (McCabe and Markstrom, 2007):

$$P_{snow} = P\left[\frac{T_{snow} - T}{T_{rain} - T_{snow}}\right] \tag{3.5}$$

Prain then is computed as:

$$P_{rain} = P - P_{snow} \tag{3.6}$$

3.4.2.2. Direct Runoff

Direct runoff (DR_O) is runoff, in millimeters, from impervious surfaces or runoff resulting from infiltration which is excess of overflow. The fraction (*drofrac*) of Prain that becomes DR_O is specified; depending on previous water-balance analyses, 5 percent is a typical value to use and a runoff factor value of 0.5 is commonly used and the expression for DR_O is given below (Wolock and McCabe, 1999).

$$DR_O = P_{rain} * drofrac \tag{3.7}$$

Direct runoff (DR_O) is subtracted from Prain to compute the amount of remaining precipitation (Premain):

$$P_{remain} = P_{rain} - DR_O \tag{3.8}$$

3.4.2.3. Evapotranspiration and Soil-Moisture Storage

Actual evapotranspiration (AET) can be derived from potential evapotranspiration (PET), Ptotal, soil-moisture storage (ST), and soil-moisture storage withdrawal (STW). Monthly PET is estimated from mean monthly temperature (T). PET represents the climatic demand for water relative to the available energy. In this water balance, PET is calculated by using the Hamon equation:

$$PET_{Hamon} = 13.97 * d * D^2 * W_t \tag{3.9}$$

Where, PET_{Hamon} is PET in millimeters per month, d is the number of days in a month, D is the mean monthly hours of daylight in units of 12 hrs., and Wt is a saturated water vapor density term, in grams per cubic meter, calculated by:

$$W_t = \frac{4.95e^{0.062T}}{100} \tag{3.10}$$

Where, T is the mean monthly temperature in degrees Celsius.

When Ptotal for a month is less than PET, then AET is equal to Ptotal plus the amount of soil moisture that can be withdrawn from storage in the soil. Soil-moisture storage withdrawal linearly decreases with decreasing ST such that as the soil becomes drier, water becomes more difficult to remove from the soil and less is available for AET. STW is computed as follows (McCabe and Markstrom, 2007):

$$STW = ST_{i-1} - \left[abs(P_{total} - PET)\left(\frac{ST_{i-1}}{STC}\right)\right] \tag{3.11}$$

Where, ST_{i-1} is the soil-moisture storage for the previous month and STC is the soil-moisture storage capacity.

If the sum of Ptotal and STW is less than PET, then a water deficit is calculated as PET–AET. If Ptotal exceeds PET, then AET is equal to PET and the water in excess of PET replenishes ST. When ST is greater than STC, the excess water becomes surplus (S) and is eventually available for runoff.

3.4.2.4. Runoff Generation

Runoff (RO) is generated from the surplus, S, at a specified rate (r-factor). An r-factor value of 0.5 is commonly used (Wolock and McCabe, 1999). The r-factor parameter determines the fraction of surplus that becomes runoff in a month. The remaining surplus is carried over to the following month to compute total S for that month. Direct runoff (DRO), in millimeters, is added directly to the runoff generated from surplus (RO) to compute total monthly runoff (ROtotal), in millimeters.

3.4.2.5. Input Parameters

The model has seven input parameters: (runoff factor, direct runoff factor, soil-moisture storage capacity, latitude of location, rain temperature threshold, snow temperature threshold, and maximum snow-melt rate of the snow storage) that are modified through the graphical user interface. The range and default values for these parameters are set by the model.

3.4.3. WTRBLN Model

WTRBLN is a computer program that calculates water balance based on the long term average monthly precipitation, PET, soil and vegetation characteristics (combined in the water capacity of the root-zone), and surface runoff, according to the method proposed by Thornthwaite and Mather (Donker, 1987). Water balance, calculated for a single soil profile or for an entire catchment, refers to the balance between income of water by precipitation and outflow of water by evapotranspiration, groundwater recharge, and streamflow. Among several possible methods of calculation, the one introduced by Thornthwaite and Mather (1957), generally has been accepted. The method is fairly simple and has the advantage that only the mentioned flow characteristics of the meteorology, soil, and vegetation must be known. It, therefore, is applicable in those parts of the world that are monitored poorly and can indicate seasonal trends in rainfall, evapotranspiration, soil moisture, irrigation need, and runoff.

3.4.3.1. Direct Runoff

Direct surface runoff refers the portion precipitation that flows over the ground surface (overland flow). It is strongly influenced by the climate, geology, topography, soil and vegetation of the area (Misstear, 2000). The quantity (volume) of surface runoff is commonly assumed as a proportion (percentage) of the rainfall depth. The mean monthly direct surface runoff, DR_O can be obtained from runoff coefficient, K and rainfall depth by the following formula (Wolock and McCabe, 1999).

$$DR_O = K * Rainfall\ depth(mm) \tag{3.12}$$

The runoff coefficient (K) represents the percentage of rainfall that becomes runoff. The runoff coefficient has been determined based on the land use and land coverage of the area. The value of K has been calculated as an area-weighted composite of the different land uses in the catchment. Accordingly, the K of the catchment is estimated to be 0.05 (Wolock and McCabe, 1999). Direct runoff can be entered as average monthly figures which will be subtracted from the monthly rainfall figures. Direct runoff bypasses the calculations for the water balance and is treated immediately as runoff.

3.4.3.2. The Successive Approximation Method

Program WTRBLN calculates the soil moisture status for each month with Evapotranspiration exceeding precipitation by equation (3.15). The use of this equation assumes, however, that at least for the last month (m) of the period with precipitation in excess of potential evapotranspiration, the root zone of the soil is at field capacity. A difficulty arises if the climate is so dry that the water capacity of the root zone is never filled. In this situation the successive approximation method must be used to calculate the water balance. This procedure creates an accumulated potential water loss for month m. The increase in accumulated potential water loss for month m takes place in single steps (Donker, 1987).

This stepwise increase in accumulated potential water loss, together with the corresponding decrease in soil moisture, is transmitted through the dry months following month m and can be "wrapped around" from December to January, because of the circular structure of the calculations. There now are two ways in which the soil moisture of month m can be calculated: (1) Add soil moisture of the last month of the dry period to the sum of the subsequently monthly positive Peff - PET (the difference between the effective precipitation and potential evapotranspiration), values, depending on the use of the program). (2) Apply equation (3.15) using the introduced accumulated potential water loss of month m. The successive approximation is stopped when the results of these two methods match.

3.4.3.3. The Method Calculation Procedures

The model assumes that a certain fixed percent of rainfall leaves the area as direct runoff (DRo). This percent is used to obtain the direct runoff coefficient (K) where the remaining coefficient of rainfall is called the effective rainfall (P_{eff}) (Rwebugisa, 2008).

$$DR_O = KP_i \tag{3.13}$$

Where, DR_O = direct runoff, K = fixed percent of rainfall leaves the area as direct runoff, and P_i = the amount of rainfall received in a particular month.

$$P_{eff} = P - DR_O \tag{3.14}$$

Soil moisture can be calculated by the formula:

$$SM = W.\exp\left(-\frac{A_{cc}PWL}{W}\right) \tag{3.15}$$

Where, SM = soil moisture (mm), A_{cc}PWL = accumulated potential water loss (mm), and W = water capacity (mm).

Change in soil moisture (ΔSM):

$$\Delta SM = SM_{current\ month} - SM_{previous\ month} \tag{3.16}$$

Calculation of AET considers the following situations:

$$If, P_{eff} - PET > 0, AET = PET,$$

$$Otherwise, AET = \left(P_{eff} - \Delta SM\right) \tag{3.17}$$

Soil Moisture Deficit (SMD) is calculated by:

$$SMD = PET - AET \tag{3.18}$$

Moisture Surplus (S):

$$S = P_{eff} - (\Delta SM + AET) \tag{3.19}$$

Total water available for runoff (TARO):

$$TARO_i = S_i \, , i = first\ month$$

$$TARO_{i+1} = S_{i+1} + DET_i \dots TARO_j = S_j + DET_{j-1} \, , j = last\ month \tag{3.20}$$

Runoff (RO) and Detention (DET) can be calculated as:

$$RO_i = \%\ of\ runoff * TARO_i \tag{3.21}$$

$$DET_i = TARO_i - RO_i \tag{3.22}$$

Finally, runoff including direct runoff (ROTL) is calculated as:

$$ROTL = DR_O + RO \tag{3.23}$$

3.4.3.4. Inputs for the Program

The important input parameters for the model are 12 long-term average monthly precipitation values, 12 long-term average monthly direct runoff values, 12 long-term average monthly reference potential Evapotranspiration values, average monthly runoff expressed in percentage of water available for runoff and a value of 50% is recommended, and available water capacity of root zone in mm. Values for precipitation, direct runoff, and potential evapotranspiration are in mm and in integer form. The month to start is January.

The values of the available water capacity of the root zone are estimated on the basis of the soil texture of the different soil types of the catchment. Considering the different soil types of the catchment with their respective soil textures, the average available water capacity of the root zone has been estimated for each soil type.

3.4.4. Soil Water Characteristics

Hydrologic analyses consist the evaluation of soil water infiltration, conductivity, storage, and plant-water relationships. Defining the hydrologic soil water effects requires estimating soil water characteristics for water potential and hydraulic conductivity using soil variables such as texture, organic matter, and structure. Field or laboratory measurements are difficult, costly, and sometimes impractical for many hydrologic analyses. Statistical correlations between soil texture, soil water potential, and hydraulic conductivity can provide estimations adequately accurate for many analyses and decisions. For many purposes, overall estimates based on more readily available information such as soil texture are sufficient. Soil-water potential and hydraulic conductivity differ broadly and non-linearly with water content for different soil textures. Moreover, these relationships are comparatively difficult and expensive to measure or are not feasible for short-term or remote investigations. Experience has shown that soil texture predominately determines the water-holding characteristics of most agricultural soils and serve as the primary input for estimating soil-water characteristic relationships (Saxton, 2006).

In order to get more realistic value of available water capacity for different soil types, Soil water characteristics of SPAW (Soil-Plant-Air-Water) computer model were used in combination with CROPWAT 8.0. Soil water characteristics is a graphical and interactive method of relating soil texture to soil water holding characteristics is included with the SPAW model. It can also be obtained as a “stand-alone” program from web site: http://www.bsyse.wsu.edu/saxton/soilwater.

3.4.5. Base Flow Index (BFI+ 3.0)

The Base Flow Index (BFI+ 3.0) helps for analysis and separation of baseflow for total catchment discharge. Numerous hydrograph separation techniques have been applied for identification of the different flow components of the total flow. The components are thought to represent different flow paths in the catchment, each characterized by different flow has usually been separated into flow that originates from overland (direct), unsaturated (thorough-flow) and saturated (groundwater) flow. Methods for continuous separation generally separate the flow into one quick and one delayed component. The delayed flow component is thought to represent the proportion of flow that originates from groundwater and other delayed sources, defined as the baseflow, Qb (Hall 1968, cited by Gregor 2010).

According to Gregor (2010), time-series of baseflow have been seen as useful as a measure of the dynamic behavior of groundwater in a catchment, whereas the baseflow proportion of the total flow has as an index of the catchment's capability to store and release water during dry weather. A high index of baseflow would indicate that the catchment has more stable flow regime and is thus able to sustain river flow during extensive dry periods. Base flow indices have implemented satisfactorily as a catchment description in many low flow studies because even a rough estimate of storage properties greatly increases the performance of the estimation model (Tallaksen and van Lannen 2004, cited by Gregor 2010).

The Base Flow Index (BFI) was first developed during a low flow study in the United Kingdom (Institute of Hydrology 1980, cited by Gregor 2010). The index provides the ratio of baseflow to total flow calculated from a hydrograph smoothing and separation procedure using daily discharges. The BFI is thus considered as a measure of the river's runoff that derives from stored sources and as a general catchment descriptor it has found many areas of application, comprising low flow estimation and groundwater recharge assessment. Values of the index range from greater than 0.9 for permeable catchment with a very stable flow regime to 0.15 - 0.2 for an impermeable catchment with a flashy flow regime (Tallaksen and van Lannen 2004, cited by Gregor 2010).

3.4.6. Calculation of Specific Yield, Exploitable Groundwater Reserve and Safe Yield

3.4.6.1. Specific Yield

According to Kruseman and Ridder (1994), Hydrologists divide the water in groundwater storage into the part that will drain under the influence of gravity (called specific yield) and the part that is reserved as a film on rock surfaces and in very small openings (called specific retention). Specific yield states how much water is available for abstraction, and specific retention states how much water retained in the rock after it is drained by gravity.

Generally, specific yield can be defined as the volume of water that an unconfined aquifer releases from storage per unit surface area of aquifer per unit decline of the water table. The values of the specific yield vary from 0.01 to 0.30 and are much higher than the storativity of confined aquifers. It can be estimated using the formula (Kruseman and Ridder, 1994):

$$G_r = (S_y * A * Dl_w) + Q_b + Ls_o \tag{3.24}$$

Where,

G_r = Recharge

Sy = Specific yield

A = effective area for groundwater recharge

Dl_w = average water level rise in wet period

Q_b = groundwater abstraction during the recharge period that is equal to the volume of water used for domestic use in rainy season

Ls_o = Lateral subsurface out flow

3.4.6.2. Exploitable Groundwater Reserve

The exploitable groundwater reserve is the volume of groundwater that can be abstracted annually from a given aquifer under prevailing economic, technological and institutional constraints and environmental conditions. It represents the long-term average annual recharge under condition of maximum groundwater use (Voudouris, 2006). Estimation of exploitable groundwater reserve (Q_{ed}) requires defining the effective area for groundwater recharge (A), specific yield (S_y), and average water level decline in dry period (D_L). It can be calculated using the formula:

$$Q_{ed} = A * S_y * D_L \tag{3.25}$$

3.4.6.3. Safe Yield

In groundwater management, safe yield is defined as the rate at which groundwater can be withdrawn annually without producing an undesirable adverse effect (Dottridge and Jaber, 1999). In other words, the safe yield is the limit to the quantity of water which can be regulatory withdrawn without depletion of aquifer storage reserve. The traditional definition of the safe yield assumes the pumpage rate is equal to the total annual recharge of the basin. Safe yield is estimated from Naik and Awasthi (2003), as cited by Tizro *et al*. (2007), by the following formula:

$$\text{Safe yield} = Q_{ed} + Q_b + Q_{ri} + Q_{si} \tag{3.26}$$

Where,

Q_{ed} = Exploitable groundwater reserve

Q_b = groundwater abstraction during the recharge period that is equal to the volume of water used for domestic use in rainy season

Q_{ri} = Recharge due to irrigation returns

Q_{si} = Sewage infiltration

3.4.6.4. Abstraction

The total amount of withdrawal throughout the catchment consists of different water uses. Pumping from both hand dug wells and boreholes is the major way by which groundwater is abstracted from the system.

3.5. Sustainability of Groundwater Resources

Sustainable groundwater resources development indicates use of groundwater as a source of water supply, on a long term basis, in an effective and equitable way sustaining its quality and environmental diversity (Gupta and Onta, 1997). Sustainable groundwater resources development and environmentally sound protection is an integrated and at the same time holistic process. Its successful solution is closely related to water planning, policy and management and can be influenced by social and economic constraints. The main objective of this process is to safeguard quantity, quality, safety and sustainability of groundwater as a strategic source for life (for drinking and other sanitary purposes) and economic development (for agriculture and industry), and a significant component of the ecosystem.

3.5.1. Groundwater Resource Sustainability Indicators

Indicators can serve for a variety of policy goals. They help in the improvement of water resource management policy through better assessment of the water resource situation in a given hydrological and hydrogeological system. This can be achieved by identifying critical problems and their causes, which provide a basis for comparison with similar spatial units elsewhere (Groundwater indicators working groups, 2007). This also leads to improved monitoring and reporting of progress against set targets as well as improved evaluation of water policy strategy and actions which provide better mobilization of resources.

The main functions of indicators are to simplify, quantify, organize and communicate data for comparison of different regions of hydrogeological units. Indicators can provide information on the system under consideration in an understandable manner. They evaluate the effect of performed policy actions and plans; and also they can support to develop new actions. Thus, indicators act as an important communication means for policy-makers and managers. The most common use of indicators is explanation of the state of the resource. Consistent measurement of indicators provides time series (showing trends) that may provide information on the working of the system or its response to management activities. An indicator value can be compared to a reference condition, and used as a tool for assessment which eventually used for forecasting the future condition of the resource. Sustainable development in combination with the protection and management of water resources act as guiding principles for indicator development and formulation. Integrated Water Resources Management (IWRM) can be considered as the vehicle that makes the general concept of sustainability operational.

Groundwater indicators, based on monitoring and assessment programs, support sustainable management of groundwater resources, provide summary information about the present state and trends in groundwater systems, help to analyzed the extent of natural processes and human impacts on groundwater system in space and time and facilitate communication and public participation in resource planning and policy and indicators generation.

3.5.2. Selected Groundwater Sustainability Indicators

In the selected list of indicators each indicator describes a specific aspect of groundwater systems and/or processes and include the use of groundwater. The selected groundwater indicators are based on measurable and observable data. They provide information about groundwater quantity and focused on social, economic, and environmental aspects of groundwater resources policy and management. Considering the current availability of data, three groundwater indicators have been selected to evaluate groundwater sustainability of the study area at a catchment level. These are Renewable groundwater resources per capita, total groundwater abstraction/groundwater recharge, and total groundwater abstraction/exploitable groundwater resource. The table below shows the selected groundwater sustainability indicators and scenarios with descriptions given by Groundwater indicators working groups, (2007).

Table 3.5: Selected groundwater sustainability indicators with their scenarios

Sustainability indicators	Scenarios	Descriptions
$\frac{\text{Renewable groundwater resource}}{\text{Number of inhabitants}}$	> 1500 l/day/capita	Low negative impact on groundwater
	500-1500 l/day/capita	Moderate negative impact on groundwater
	< 500 l/day/capita	High negative impact on groundwater
$\frac{\text{Total groundwater abstraction}}{\text{Groundwater recharge}}$	< 0.9	Under developed groundwater resources
	= 1.0	Developed groundwater resources
	> 1.0	Over exploited groundwater resources
$\frac{\text{Total groundwater abstraction}}{\text{Exploitable groundwater resource}}$	< 0.9	Under developed groundwater resources
	= 1.0	Developed groundwater resources
	> 1.0	Over exploited groundwater resources

4. RESULTS AND DISCUSSIONS

4.1. Recharge

Quantification of the natural groundwater recharge is a basic pre-requisite for efficient groundwater resource management. Though there are several techniques to estimate the natural groundwater recharge, the soil water balance approach was used in this work. Therefore, in order to calculate the groundwater recharge of the study area, the water balance components in the equation (3.4) must be calculated first.

4.1.1. Determination of Aerial Depth of Precipitation

A precipitation event recorded by rain gauge is a point observation at specific location and may not be used as a representative value for the entire catchment under consideration. Hence, the recorded point precipitation has to be averaged over the catchment. Different methodological approaches exist for the estimation of aerial depth of precipitation over a given basin. The most frequently applied methods are simple Arithmetic mean, Thiessen polygon and Isohyetal methods. The criteria for selecting the best method include the densification of meteorological networks, the characteristics of the relief within the catchment and the size of the watershed.

4.1.1.1. The Arithmetic Mean Method

Arithmetic mean method is the simplest one for evaluation of mean uniform distribution of rainfall of a basin. The rainfall stations used in the calculation are those located in the catchment and nearby gauges considered representative of the area & relatively marked with no diversity in topography to get reliable measure of aerial rainfall. Thirty-three years (1985-2017) rainfall data obtained from the National Meteorology Service Agency was used for the analysis. The aerial depth of precipitation can be calculated using arithmetic mean as follows (Raghunath, 2006):

$$P = \left({}^{\sum P_i}/_{N} \right) \tag{4.1}$$

Where,

P = Annual Aerial depth of precipitation

P_i = Mean annual precipitation measured at i^th station

N = Number of gauging station

Table 4.1: Mean monthly aerial depth of precipitation by Arithmetic mean method

	Gauging stations				
Months	Jimma	Dedo	Assendabo	Shebe	Near Omo-Nada
Jan	29.2	27.5	22.5	30.3	41.4
Feb	35.3	38.0	29.4	33.5	45.6
Mar	85.4	94.6	78.9	85.2	102.4
Apr	166.7	162.2	141.2	156.3	185.4
May	211.9	207.2	175.6	202.9	225.7
Jun	254.8	248.3	226.9	230.9	253.6
Jul	269.8	288.4	250.1	246.2	284.3
Aug	265.3	273.6	239.2	243.4	283.2
Sep	183.4	179.9	148.2	168.9	213.2
Oct	97.0	92.8	78.2	97.4	112.9
Nov	44.3	42.5	30.5	46.9	51.9
Dec	26.4	23.8	19.3	28.8	42.4
Annual	1669.3	1678.8	1439.9	1570.6	1841.9
Annual aerial depth of precipitation					1640.1 mm/year

4.1.1.2. Thiessen Polygon Method

This method helps to calculate the weighted average precipitation of each station by the following formula (Raghunath, 2006):

$$P = \frac{\sum(P_i * A_i)}{100} \tag{4.2}$$

Where,

P = Annual Aerial depth of precipitation

P_i = Mean annual precipitation measured at ith station

A_i = Weighted area of ith station expressed as percentage

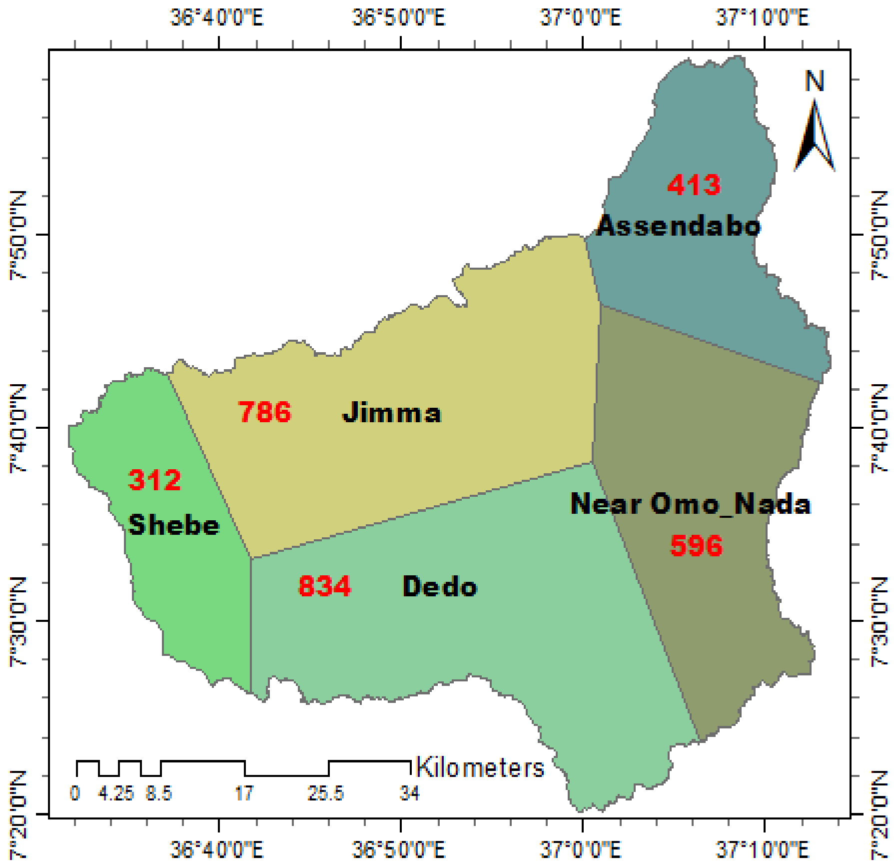


Figure 4.1: Thiessen polygon of the study area

Table 4.2: Mean monthly aerial depth of precipitation by Thiessen polygon method

1	2	3	4	5
Stations	Annual rainfall (mm)	Enclosed area (Km^2)	Weighted area (%)	Annual weighted rainfall (mm) [(Col. 2*Col. 4)/100]
Jimma	1669.28	786	26.7	446.1
Dedo	1678.81	834	28.4	476.1
Assendabo	1439.86	413	14.0	202.2
Shebe	1570.57	312	10.6	166.6
Near Omo-Nada	1841.85	596	20.3	373.3
Total		2941	100	1664.3
Annual aerial depth of precipitation				1664.3 mm/year

4.1.1.3. Isohyetal Method

This method takes in to account the influence of physiographic parameters which includes elevation, slope, and distance from the coast and exposure to rain bearing winds (Shaw, 1988). Since the study area has non-uniform land and varies in topography, the method is more preferred. Accordingly, Isohyetal method has been used for estimation of the aerial depth of precipitation of the catchment. Moreover, Isohyetal method is the most accurate approach for determining the average rainfall over an area (William, 2007). It is employed by drawing contours of equal aerial depth of precipitation.

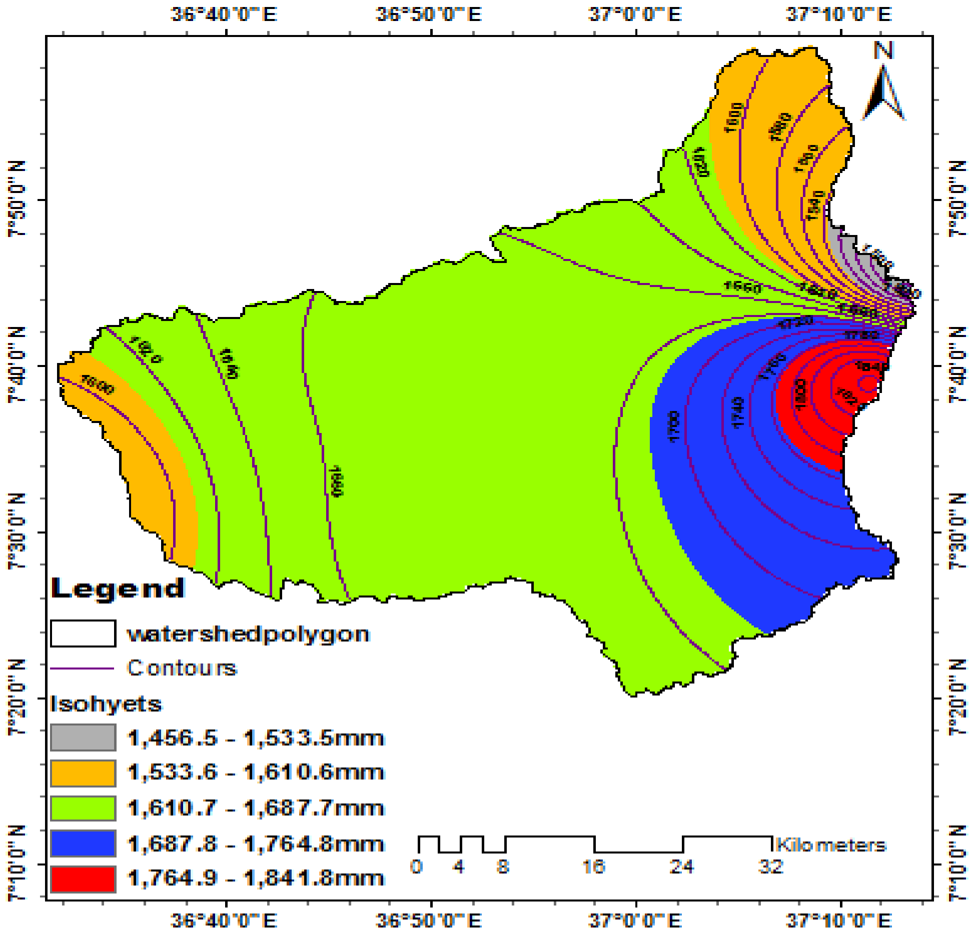


Figure 4.2: Isohyetal map of the study area

The general formula which has been used for estimation of the average aerial depth of rainfall by Isohyetal method is given by (Raghunath, 2006):

$$P_{av} = \frac{\sum(P_{1-2} * A_{1-2})}{\sum A_{1-2}} \tag{4.3}$$

Where,

P_{av} = Annual average Aerial depth of precipitation

P_{1-2} = Mean Isohyetal value

A_{1-2} = Area between the two successive isohyets

Table 4.3: Mean monthly aerial depth of precipitation by Isohyetal method

1	2	3	4	5
No.	Isohyets interval	Mean Isohyetal value, P_{1-2} (mm)	Area between Isohyets, A_{1-2} (km^2)	Col. 3 * Col. 4
1	1460-1480	1470	4.41	6479.5
2	1480-1500	1490	5.67	8453.5
3	1500-1520	1510	7.79	11763.0
4	1520-1540	1530	14.73	22531.2
5	1540-1560	1550	33.29	51597.8
6	1560-1580	1570	60.56	95078.1
7	1580-1600	1590	90.92	144558.6
8	1600-1620	1610	206.30	332137.0
9	1620-1640	1630	222.33	362394.6
10	1640-1660	1650	349.81	577190.4
11	1660-1680	1670	1231.83	2057152.1
12	1680-1700	1690	313.83	530367.9
13	1700-1720	1710	152.26	260371.2
14	1720-1740	1730	92.11	159358.8
15	1740-1760	1750	53.23	93146.3
16	1760-1780	1770	36.02	63758.3
17	1780-1800	1790	26.25	46988.9
18	1800-1820	1810	20.40	36928.8
19	1820-1840	1830	18.37	33610.1
Annual aerial depth of precipitation				1664.5mm/year

The calculated values of annual aerial depth of precipitation by Thiessen polygon method (1664.3mm/year) and by Isohyetal method (1664.5mm/year) are almost similar. Therefore, mean annual rainfall of the catchment is taken as 1664.5mm/year because this method considers also topographic or elevation effects.

4.1.2. Evapotranspiration

Evapotranspiration is difficult to measure directly from an appreciable area under natural condition and it is necessary to calculate evaporation and evapotranspiration using different conventional method and available hydro meteorological data. Its value varies according to the type of vegetation and the availability of water in the soil.

4.1.2.1. Potential Evapotranspiration

A value of the actual evapotranspiration (AET) over a catchment is more often obtained by first calculating the PET. Several methods have been developed to estimate the PET. In this work, Thornthwaite and Modified Penman methods were used to compute PET.

A) Thornthwaite method

Thornthwaite method relates PET to temperature with an adjustment being made for the number of daylight hour and gives figures for the consumptive use of short closed vegetation with adequate water supply. An estimate of the potential evapotranspiration (PET_m) calculated on a monthly basis is given by (Shaw, 1994):

$$PET_m = 16N_m\left[\frac{10\bar{T}_m}{I}\right]^a \qquad (4.4)$$

Where,

PET_m = Monthly Potential Evapotranspiration

N_m = Monthly adjustment factor related to hours of daylight

$\bar{T}_m$ = Monthly mean temperature, °C

I = Heat index for the year

Heat index for the year (I) is given by the formula:

$$I = \sum I_m = \sum \left[\frac{\bar{T}_m}{5}\right]^{1.5} \tag{4.5}$$

And,

$$a = 6.7 * 10^{-7} I^3 - 7.7 * 10^{-5} I^2 + 1.8 * 10^{-2} I + 0.49 \tag{4.6}$$

Table 4.4: PET of the study area according to Thornthwaite method

	Months											
Parameters	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
$\bar{T}_m$ (°C)	18.4	19.0	19.4	19.0	18.6	17.8	16.9	17.2	17.6	17.62	17.7	17.67
N_m	0.98	0.99	1.00	1.02	1.03	1.04	1.03	1.03	1.01	0.99	0.96	0.98
i_m	7.08	7.42	7.63	7.40	7.21	6.72	6.22	6.38	6.61	6.61	6.67	6.64
I												82.57
a												1.83
PET_m	67.8	73.0	76.2	74.6	73.4	68.0	61.4	62.8	64.4	63.5	62.0	62.73
Annual PET (mm/year)												809.89

B) Modified Penman method

Potential evapotranspiration can be calculated with various method based on the available meteorological data. Penman had produced a formula to describe the conditions under which evaporation plus transpiration takes place from a vegetated surface. The formula was later modified by MAFF (1967) as cited by Shaw (1994) and given by:

$$PET = \frac{(\Delta/\gamma)H_T + E_{at}}{(\Delta/\gamma) + 1} \tag{4.7}$$

Where, PET is Potential Evapotranspiration, Δ represents the slope of the curve of saturated vapor pressure plotted against temperature, γ is the hygrometric constant (0.27 mm of mercury/°F) = (0.5 mmHg/°K), H_T is the available heat often calculated from incoming (R_I) and outgoing (R_o) radiation determined from sunshine records, temperature and humidity, using:

$$H_T = R_I(1 - r) - R_o \tag{4.8}$$

Where, r is the reflective coefficient for incident radiations or the albedo which depends on the nature of the surface. For this study it is taken as 0.23 assuming majority of land cover of the study area as short grass surface.

R_I is a function of R_a, the solar radiation (fixed by latitude and season) modulated by a function of the ratio, n/N, of measured to maximum possible sunshine duration. Using r = 0.23:

$$R_I(1-r) = 0.77 R_a f_a(n/N) \tag{4.9}$$

For the study area within latitudes south of 54/2°N, (MAFF1967, cited by Shaw, 1994) gives the following formula:

$$f_a(n/N) = 0.16 + 0.62\,(n/N) \tag{4.10}$$

Where,

n = Annual average Aerial depth of precipitation

N = Maximum possible sunshine duration

The empirical equation for the outgoing radiation (R_o) takes the form:

$$R_o = \sigma T_a^4 (0.47 - 0.075\sqrt{e_d})(0.17 + 0.83\, n/N) \tag{4.11}$$

Where,

σ = The Stephan Boltzmann constant, = $5.67*10^{-8}$ Wm^{-2}/K^4

σT_a^4 = Theoretical black body radiation at T_a

T_a = Mean air temperature for a month, °C

e_d = Vapor pressure of the air (saturated vapor pressure at dew point)

The term E_{at} (parameter including wind velocity and saturation deficit) can be given as:

$$E_{at} = 0.35(1 + U_2/100)(e_a - e_d) \tag{4.12}$$

Where,

U_2 = Mean wind speed at 2 m above the surface

e_a = Saturated vapor pressure at air temperature Ta

$e_a - e_d$ = The saturation deficit

Based on the above basic formula given for PET, the calculated annual PET of the study area according to Modified Penman method is 1019.89 mm/year.

Table 4.5: PET of the study area according to Modified Penman method

	Months											
Parameters	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
T (^{o}C)	18.43	19.02	19.38	18.99	18.65	17.81	16.91	17.20	17.60	17.62	17.73	17.67
T (^{o}F)	65.17	66.24	66.88	66.17	65.58	64.06	62.44	62.96	63.69	63.71	63.91	63.80
e_a (mm/day)	15.9	16.4	16.9	16.4	16.1	15.3	14.4	14.7	15.1	15.1	15.2	15.1
RH (%)	56.7	54.6	60.5	69.0	74.9	80.7	83.9	82.7	79.6	69.8	62.0	58.3
e_d (mm/day)	9.01	8.95	10.23	11.32	12.06	12.35	12.09	12.16	12.03	10.54	9.42	8.81
U_2 (m/s)	0.93	0.97	0.99	0.96	0.94	0.83	0.80	0.80	0.83	0.92	0.92	0.92
n (hrs./day)	7.14	7.22	6.91	6.34	6.51	5.59	3.84	4.21	5.52	6.85	7.51	7.67
N (hrs./day)	11.7	11.9	12.0	12.2	12.4	12.5	12.4	12.3	12.1	11.9	11.5	11.7
n/N	0.61	0.61	0.58	0.52	0.53	0.45	0.31	0.34	0.46	0.58	0.65	0.66
f_a(n/N)	0.54	0.54	0.52	0.48	0.49	0.44	0.35	0.37	0.44	0.52	0.56	0.57
R_a (mm/day)	13.25	14.16	14.90	15.08	14.73	14.45	14.57	14.83	14.82	14.40	13.47	12.95
R_I(1-r) (mm/day)	5.49	5.85	5.93	5.60	5.51	4.86	3.95	4.25	5.05	5.73	5.86	5.65
αT_a^4 (mm/day)	14.52	14.62	14.69	14.62	14.55	14.40	12.24	14.30	14.37	14.37	14.39	14.38
R_o (mm/day)	2.40	2.42	2.19	1.91	1.85	1.61	1.09	1.35	1.66	2.11	2.46	2.54
H_T	3.09	3.43	3.74	3.69	3.66	3.26	2.86	2.90	3.40	3.62	3.40	3.11
Δ/γ	2.04	2.12	2.15	2.12	2.07	1.97	1.88	1.91	1.95	1.95	1.97	1.96
E_{at}	2.43	2.63	2.36	1.80	1.43	1.04	0.82	0.89	1.08	1.61	2.04	2.22
PET (mm/day)	2.87	3.17	3.30	3.08	2.93	2.51	2.15	2.21	2.61	2.94	2.94	2.81
PET (mm/month)	89.01	89.78	102.38	92.42	90.94	75.31	66.58	68.47	78.44	91.15	88.32	87.08
PET (mm/year)	1019.89											

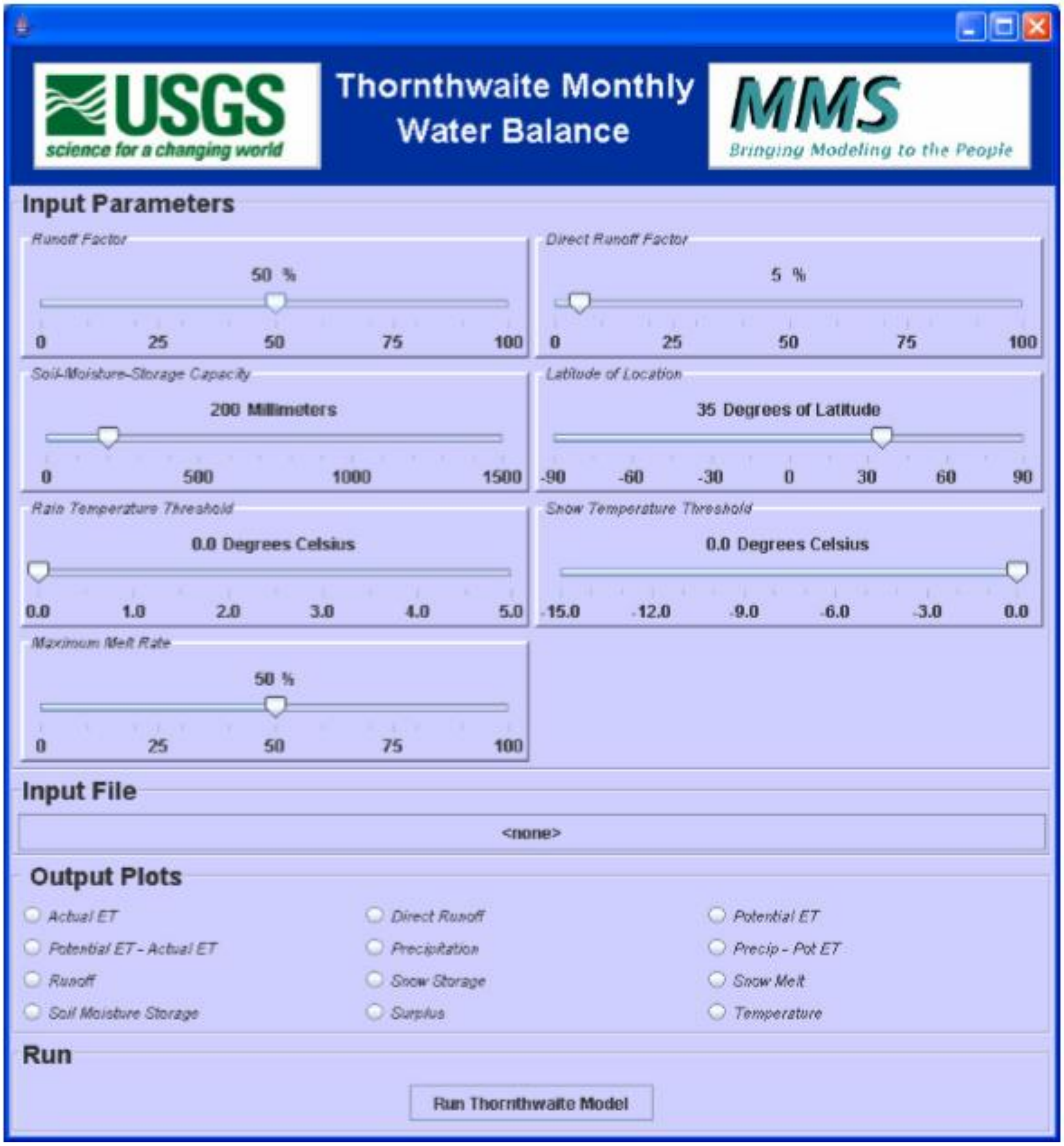
Thornthwaite method requires only air temperature as an index of energy available and adjusted hours of day light for evaporation, so the values tend to be under estimated. Therefore, the calculated annual PET of the study area according to Modified Penman method (1019.89 mm/year) has been considered for the Water Balance analysis.

4.1.2.2. Actual Evapotranspiration

There are several ways of estimating the actual evapotranspiration (AET) and other water balance components. But the following two methods are widely used.

A) Thornthwaite Monthly Water Balance Program

The seven input parameters of the model: (runoff factor, direct runoff factor, soil-moisture storage capacity, latitude of location, rain temperature threshold, snow temperature threshold, and maximum snow-melt rate of the snow storage) can be modified through the graphical user interface (Figure 4.3).



Runoff Factor: 50 %

Direct Runoff Factor: 5 %

Soil-Moisture-Storage Capacity: 200 Millimeters

Latitude of Location: 35 Degrees of Latitude

Rain Temperature Threshold: 0.0 Degrees Celsius

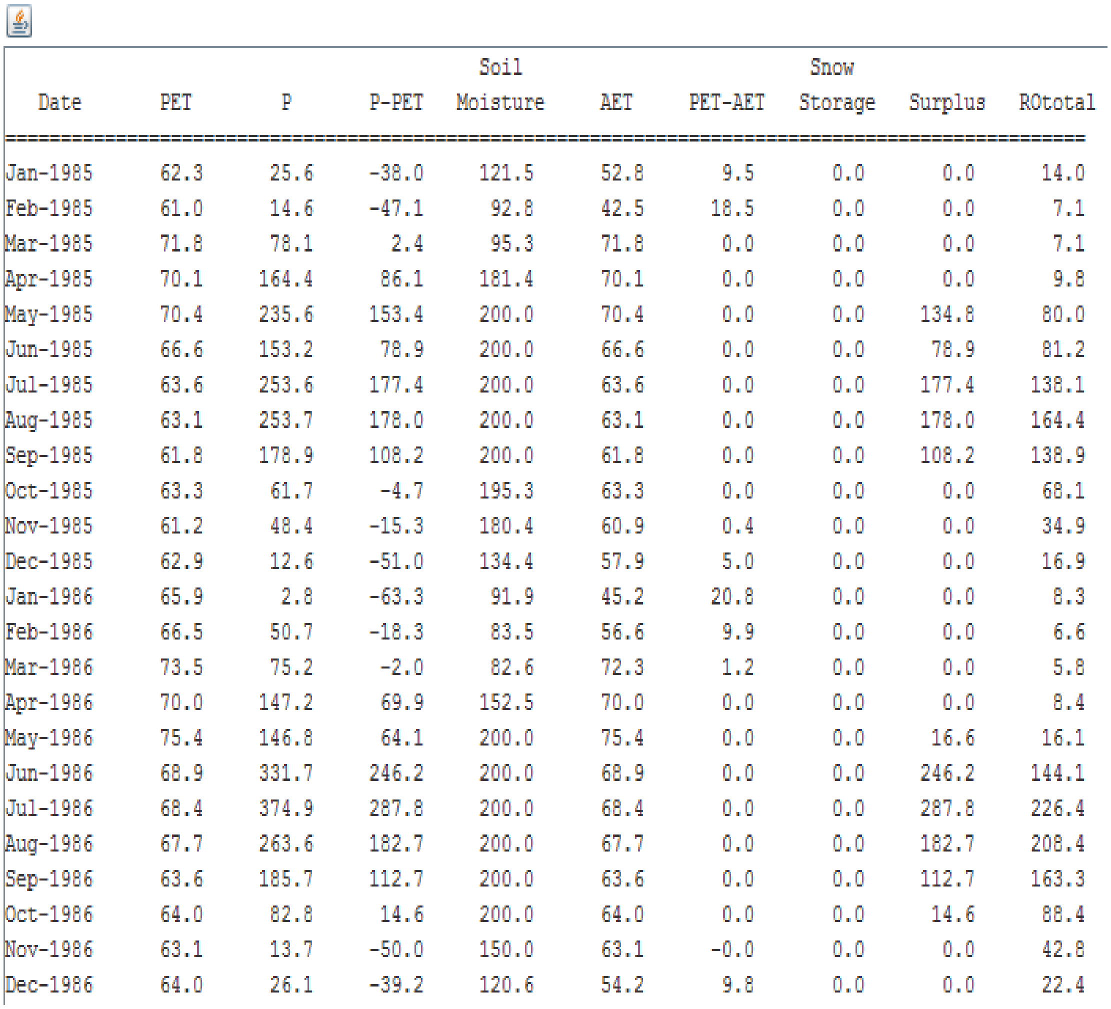
Snow Temperature Threshold: 0.0 Degrees Celsius

Maximum Melt Rate: 50 %

Input File: <none>

Figure 4.3: Screen image of the water-balance model graphical user interface

Actual evapotranspiration (AET) is derived from potential evapotranspiration (PET), P_{total}, soil-moisture storage (ST), and soil-moisture storage withdrawal (STW). Monthly PET is estimated from mean monthly temperature (T). When the model runs, tabular output is written to a popup window (Figure 4.4) and a window will open with the plotted time series (Figure 4.5).



```
                                        Soil                           Snow
  Date      PET       P       P-PET   Moisture    AET     PET-AET   Storage   Surplus  ROtotal
==================================================================================================
Jan-1985    62.3     25.6     -38.0     121.5     52.8       9.5       0.0       0.0      14.0
Feb-1985    61.0     14.6     -47.1      92.8     42.5      18.5       0.0       0.0       7.1
Mar-1985    71.8     78.1       2.4      95.3     71.8       0.0       0.0       0.0       7.1
Apr-1985    70.1    164.4      86.1     181.4     70.1       0.0       0.0       0.0       9.8
May-1985    70.4    235.6     153.4     200.0     70.4       0.0       0.0     134.8      80.0
Jun-1985    66.6    153.2      78.9     200.0     66.6       0.0       0.0      78.9      81.2
Jul-1985    63.6    253.6     177.4     200.0     63.6       0.0       0.0     177.4     138.1
Aug-1985    63.1    253.7     178.0     200.0     63.1       0.0       0.0     178.0     164.4
Sep-1985    61.8    178.9     108.2     200.0     61.8       0.0       0.0     108.2     138.9
Oct-1985    63.3     61.7      -4.7     195.3     63.3       0.0       0.0       0.0      68.1
Nov-1985    61.2     48.4     -15.3     180.4     60.9       0.4       0.0       0.0      34.9
Dec-1985    62.9     12.6     -51.0     134.4     57.9       5.0       0.0       0.0      16.9
Jan-1986    65.9      2.8     -63.3      91.9     45.2      20.8       0.0       0.0       8.3
Feb-1986    66.5     50.7     -18.3      83.5     56.6       9.9       0.0       0.0       6.6
Mar-1986    73.5     75.2      -2.0      82.6     72.3       1.2       0.0       0.0       5.8
Apr-1986    70.0    147.2      69.9     152.5     70.0       0.0       0.0       0.0       8.4
May-1986    75.4    146.8      64.1     200.0     75.4       0.0       0.0      16.6      16.1
Jun-1986    68.9    331.7     246.2     200.0     68.9       0.0       0.0     246.2     144.1
Jul-1986    68.4    374.9     287.8     200.0     68.4       0.0       0.0     287.8     226.4
Aug-1986    67.7    263.6     182.7     200.0     67.7       0.0       0.0     182.7     208.4
Sep-1986    63.6    185.7     112.7     200.0     63.6       0.0       0.0     112.7     163.3
Oct-1986    64.0     82.8      14.6     200.0     64.0       0.0       0.0      14.6      88.4
Nov-1986    63.1     13.7     -50.0     150.0     63.1      -0.0       0.0       0.0      42.8
Dec-1986    64.0     26.1     -39.2     120.6     54.2       9.8       0.0       0.0      22.4
```

Figure 4.4: Screen image of sample output from the water-balance model

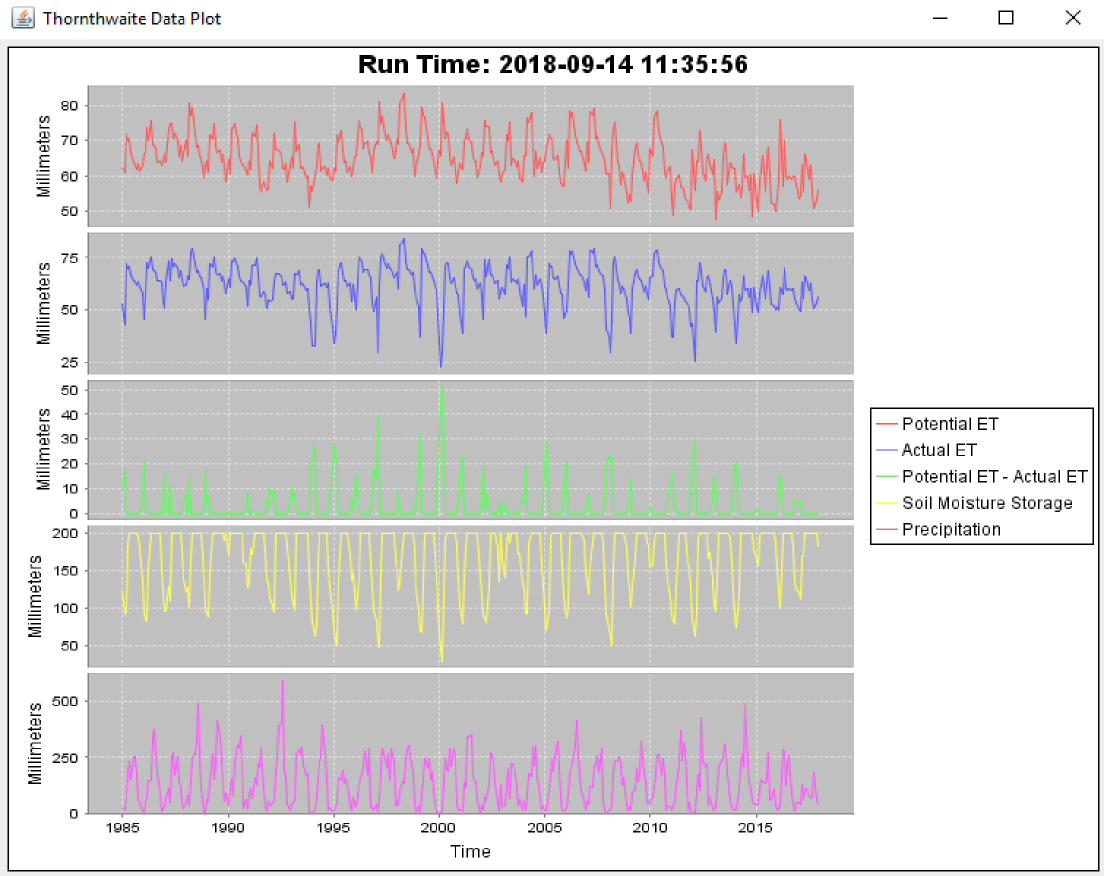


Figure 4.5: Screen image of sample time series plotted by the water-balance model

The model was executed for different soil types of the study area (Table 4.6) and the results are presented in (Appendix 3).

Table 4.6: Available water capacity of root zone and Area coverage of soil types

Soil type	Available water capacity of root zone (mm)	Aerial coverage (km^2)	Area in (%)
Chromic Vertisols and Dystric Nitosols	200	1571	53.4
Dystric Fluvisols	120	445	15.1
Eutric Fluvisols	160	700	23.8
Eutric Nitosols	140	13	0.5
Orthic Arcisols	180	212	7.2
Total		2941	100

Based on the aerial coverage of each soil types in the catchment, the AET and other water balance parameters have been weighted and presented in (Table 4.7).

Table 4.7: Adjusted Thornthwaite Water Balance for the whole study area

	Months												Annual(mm/yr.)
Parameters	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
PET	63.5	61.0	71.2	69.5	72.1	67.0	65.1	64.7	62.2	62.3	59.1	60.0	777.7
P	30.0	36.4	89.3	162.4	204.7	242.9	267.8	260.9	178.7	95.7	43.2	28.1	1640.0
P-PET	-34.9	-26.4	13.6	84.7	122.3	163.7	189.3	183.1	107.6	28.5	-18.0	-33.3	780.3
Soil moisture	93.6	82.2	99.2	155.2	174.2	176.7	176.7	176.7	176.6	165.1	142.1	115.7	1733.9
AET	50.3	45.5	65.6	68.9	72.1	67.0	65.1	64.7	62.2	62.3	57.4	52.5	733.4
PET-AET	13.2	15.5	5.6	0.6	0.0	0.0	0.0	0.0	0.0	0.0	1.7	7.6	44.3
Snow storage	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Surplus	0.0	0.5	2.2	29.4	103.3	161.3	189.3	183.1	107.6	40.0	6.8	0.7	824.2
RO_{total}	13.7	8.2	8.7	25.0	70.3	122.8	163.4	179.6	146.0	93.3	49.8	25.6	906.4

B) WTRBLN (Water Balance model)

The WTRBLN model was executed for different soil types of the study area and the computed AET values for the Chromic Vertisols and Dystric Nitosols, Dystric Fluvisols, Eutric Fluvisols, Eutric Nitosols, and Orthic Arcisols are 921.3 mm/year, 885.69 mm/year, 906.02 mm/year, 896.61 mm/year and 914.18 mm/year respectively (Table 4.8 - Table 4.12).

Table 4.8: WTRBLN for Chromic Vertisols and Dystric Nitosols

	Months												Annual(mm/yr.)
Parameters	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
P	30.5	36.9	90.6	164.8	207.7	246.5	271.8	264.8	181.4	97.1	43.9	28.6	1664.5
DR_O	1.5	1.8	4.5	8.2	10.4	12.3	13.6	13.2	9.1	4.9	2.2	1.4	83.2
P_{eff}	29.0	35.1	86.1	156.6	197.3	234.2	258.2	251.6	172.3	92.2	41.7	27.1	1581.3
PET	89.0	89.8	102.4	92.4	90.9	75.3	66.6	68.5	78.4	91.2	88.3	87.1	1019.9
P_{eff}-PET	-60.0	-54.7	-16.3	64.2	106.4	158.9	191.6	183.1	93.9	1.1	-46.6	-59.9	561.4
A_{cc}PWL	-166.6	-221.4	-237.6	-	-	-	-	-	-	-	-46.6	-106.6	
S_m	86.9	66.1	61.0	125.1	200.0	200.0	200.0	200.0	200.0	200.0	158.4	117.4	
ΔS_m	-30.4	-20.8	-5.2	64.2	74.9	0.0	0.0	0.0	0.0	0.0	-41.6	-41.0	0.0
AET	59.4	55.9	91.3	92.4	90.9	75.3	66.6	68.5	78.4	91.2	83.3	68.2	921.3
SMD	29.6	33.9	11.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.0	18.9	98.6
S	0.0	0.0	0.0	0.0	31.5	158.9	191.6	183.1	93.9	1.1	0.0	0.0	660.0
TAR_O	0.0	0.0	0.0	0.0	31.5	174.6	278.9	322.5	255.1	128.7	64.3	32.2	1287.8
R_O	0.0	0.0	0.0	0.0	15.7	87.3	139.4	161.3	127.6	64.3	32.2	16.1	643.9
DET	0.0	0.0	0.0	0.0	15.7	87.3	139.4	161.3	127.6	64.3	32.2	16.1	643.9
R_OTL	1.5	1.8	4.5	8.2	26.1	99.6	153.0	174.5	136.6	69.2	34.4	17.5	727.1

Table 4.9: WTRBLN for Dystric Fluvisols

	Months												Annual(mm/yr.)
Parameters	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
P	30.5	36.9	90.6	164.8	207.7	246.5	271.8	264.8	181.4	97.1	43.9	28.6	1664.5
DR_O	1.5	1.8	4.5	8.2	10.4	12.3	13.6	13.2	9.1	4.9	2.2	1.4	83.2
P_{eff}	29.0	35.1	86.1	156.6	197.3	234.2	258.2	251.6	172.3	92.2	41.7	27.1	1581.3
PET	89.0	89.8	102.4	92.4	90.9	75.3	66.6	68.5	78.4	91.2	88.3	87.1	1019.9
P_{eff}-PET	-60.0	-54.7	-16.3	64.2	106.4	158.9	191.6	183.1	93.9	1.1	-46.6	-59.9	561.4
A_{cc}PWL	-166.6	-221.4	-237.6	-	-	-	-	-	-	-	-46.6	-106.6	
S_m	29.9	19.0	16.6	80.7	120.0	120.0	120.0	120.0	120.0	120.0	81.4	49.4	
ΔS_m	-19.4	-11.0	-2.4	64.2	39.3	0.0	0.0	0.0	0.0	0.0	-38.6	-32.0	0.0
AET	48.4	46.0	88.5	92.4	90.9	75.3	66.6	68.5	78.4	91.2	80.3	59.1	885.7
SMD	40.6	43.8	13.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8.0	28.0	134.2
S	0.0	0.0	0.0	0.0	67.1	158.9	191.6	183.1	93.9	1.1	0.0	0.0	695.6
TAR_O	0.0	0.0	0.0	0.0	67.1	192.4	287.8	327.0	257.3	129.8	64.9	32.4	1358.7
R_O	0.0	0.0	0.0	0.0	33.6	96.2	143.9	163.5	128.7	64.9	32.4	16.2	679.4
DET	0.0	0.0	0.0	0.0	33.6	96.2	143.9	163.5	128.7	64.9	32.4	16.2	679.4
R_OTL	1.5	1.8	4.5	8.2	43.9	108.5	157.5	176.7	137.7	69.7	34.6	17.6	762.6

Table 4.10: WTRBLN for Eutric Fluvisols

	Months												Annual(mm/yr.)
Parameters	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
P	30.5	36.9	90.6	164.8	207.7	246.5	271.8	264.8	181.4	97.1	43.9	28.6	1664.5
DR_O	1.5	1.8	4.5	8.2	10.4	12.3	13.6	13.2	9.1	4.9	2.2	1.4	83.2
P_{eff}	29.0	35.1	86.1	156.6	197.3	234.2	258.2	251.6	172.3	92.2	41.7	27.1	1581.3
PET	89.0	89.8	102.4	92.4	90.9	75.3	66.6	68.5	78.4	91.2	88.3	87.1	1019.9
P_{eff}-PET	-60.0	-54.7	-16.3	64.2	106.4	158.9	191.6	183.1	93.9	1.1	-46.6	-59.9	561.4
$A_{cc}PWL$	-166.6	-221.4	-237.6	-	-	-	-	-	-	-	-46.6	-106.6	
S_m	56.5	40.1	36.2	100.4	160.0	160.0	160.0	160.0	160.0	160.0	119.5	82.2	
ΔS_m	-25.7	-16.4	-3.9	64.2	59.6	0.0	0.0	0.0	0.0	0.0	-40.5	-37.4	0.0
AET	54.7	51.4	90.0	92.4	90.9	75.3	66.6	68.5	78.4	91.2	82.1	64.5	906.0
SMD	34.3	38.4	12.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	6.2	22.6	113.9
S	0.0	0.0	0.0	0.0	46.8	158.9	191.6	183.1	93.9	1.1	0.0	0.0	675.3
TAR_O	0.0	0.0	0.0	0.0	46.8	182.3	282.7	324.4	256.1	129.1	64.6	32.3	1318.2
R_O	0.0	0.0	0.0	0.0	23.4	91.1	141.4	162.2	128.0	64.6	32.3	16.1	659.1
DET	0.0	0.0	0.0	0.0	23.4	91.1	141.4	162.2	128.0	64.6	32.3	16.1	659.1
R_OTL	1.5	1.8	4.5	8.2	33.8	103.5	154.9	175.5	137.1	69.4	34.5	17.6	742.3

Table 4.11: WTRBLN for Eutric Nitosols

	Months												Annual(mm/yr.)
Parameters	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
P	30.5	36.9	90.6	164.8	207.7	246.5	271.8	264.8	181.4	97.1	43.9	28.6	1664.5
DR_O	1.5	1.8	4.5	8.2	10.4	12.3	13.6	13.2	9.1	4.9	2.2	1.4	83.2
P_{eff}	29.0	35.1	86.1	156.6	197.3	234.2	258.2	251.6	172.3	92.2	41.7	27.1	1581.3
PET	89.0	89.8	102.4	92.4	90.9	75.3	66.6	68.5	78.4	91.2	88.3	87.1	1019.9
P_{eff}-PET	-60.0	-54.7	-16.3	64.2	106.4	158.9	191.6	183.1	93.9	1.1	-46.6	-59.9	561.4
$A_{cc}PWL$	-166.6	-221.4	-237.6	-	-	-	-	-	-	-	-46.6	-106.6	
S_m	42.6	28.8	25.6	89.8	140.0	140.0	140.0	140.0	140.0	140.0	100.3	65.4	
ΔS_m	-22.8	-13.8	-3.2	64.2	50.2	0.0	0.0	0.0	0.0	0.0	-39.7	-34.9	0.0
AET	51.8	48.8	89.3	92.4	90.9	75.3	66.6	68.5	78.4	91.2	81.3	62.1	896.6
SMD	37.2	40.9	13.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	7.0	25.0	123.3
S	0.0	0.0	0.0	0.0	56.2	158.9	191.6	183.1	93.9	1.1	0.0	0.0	684.7
TAR_O	0.0	0.0	0.0	0.0	56.2	187.0	285.1	325.6	256.7	129.4	64.7	32.4	1337.0
R_O	0.0	0.0	0.0	0.0	28.1	93.5	142.5	162.8	128.3	64.7	32.4	16.2	668.5
DET	0.0	0.0	0.0	0.0	28.1	93.5	142.5	162.8	128.3	64.7	32.4	16.2	668.5
R_OTL	1.5	1.8	4.5	8.2	38.5	105.8	156.1	176.1	137.4	69.6	34.5	17.6	751.7

Table 4.12: WTRBLN for Orthic Arcisols

	Months												Annual(mm/yr.)
Parameters	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
P	30.5	36.9	90.6	164.8	207.7	246.5	271.8	264.8	181.4	97.1	43.9	28.6	1664.5
DR_O	1.5	1.8	4.5	8.2	10.4	12.3	13.6	13.2	9.1	4.9	2.2	1.4	83.2
P_{eff}	29.0	35.1	86.1	156.6	197.3	234.2	258.2	251.6	172.3	92.2	41.7	27.1	1581.3
PET	89.0	89.8	102.4	92.4	90.9	75.3	66.6	68.5	78.4	91.2	88.3	87.1	1019.9
P_{eff}-PET	-60.0	-54.7	-16.3	64.2	106.4	158.9	191.6	183.1	93.9	1.1	-46.6	-59.9	561.4
$A_{cc}PWL$	-166.6	-221.4	-237.6	-	-	-	-	-	-	-	-46.6	-106.6	
S_m	71.3	52.6	48.1	112.2	180.0	180.0	180.0	180.0	180.0	180.0	138.9	99.6	
ΔS_m	-28.2	-18.7	-4.6	64.2	67.8	0.0	0.0	0.0	0.0	0.0	-41.1	-39.3	0.0
AET	57.2	53.8	90.6	92.4	90.9	75.3	66.6	68.5	78.4	91.2	82.8	66.5	914.2
SMD	31.8	36.0	11.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.6	20.6	105.7
S	0.0	0.0	0.0	0.0	38.6	158.9	191.6	183.1	93.9	1.1	0.0	0.0	667.1
TAR_O	0.0	0.0	0.0	0.0	38.6	178.2	280.7	323.4	255.6	128.9	64.4	32.2	1302.0
R_O	0.0	0.0	0.0	0.0	19.3	89.1	140.3	161.7	127.8	64.4	32.2	16.1	651.0
DET	0.0	0.0	0.0	0.0	19.3	89.1	140.3	161.7	127.8	64.4	32.2	16.1	651.0
R_OTL	1.5	1.8	4.5	8.2	29.7	101.4	153.9	175.0	136.9	69.3	34.4	17.5	734.2

Where,

P = Mean monthly aerial depth of precipitation

DR_O = Direct runoff

P_{eff} = Effective rainfall

PET = Potential evapotranspiration

P_{eff}-PET = The difference between Effective rainfall and Potential evapotranspiration

$A_{cc}PWL$ = Accumulated potential water loss

S_m = Soil moisture

ΔS_m = Change in Soil moisture

AET = Actual evapotranspiration

SMD = Soil moisture deficit

S = Surplus

TAR_O = Total available water for runoff

R_O = Runoff without direct runoff

DET = Detention

R_OTL = Runoff including direct runoff

All values are in mm.

Based on the aerial coverage of each soil types in the catchment, the AET and other water balance parameters have been weighted. Accordingly, the adjusted AET of the catchment is found to be 911.65 mm/year (Table 4.13).

Table 4.13: Adjusted WTRBLN for the whole study area

	Months												Annual(mm/yr.)
Parameters	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
P	30.5	36.9	90.6	164.8	207.7	246.5	271.8	264.8	181.4	97.1	43.9	28.6	1664.5
DR$_O$	1.5	1.8	4.5	8.2	10.4	12.3	13.6	13.2	9.1	4.9	2.2	1.4	83.2
P_{eff}	29.0	35.1	86.1	156.6	197.3	234.2	258.2	251.6	172.3	92.2	41.7	27.1	1581.3
PET	89.0	89.8	102.4	92.4	90.9	75.3	66.6	68.5	78.4	91.2	88.3	87.1	1019.9
P_{eff}-PET	-60.0	-54.7	-16.3	64.2	106.4	158.9	191.6	183.1	93.9	1.1	-46.6	-59.9	561.4
A_{cc}PWL	-166.6	-221.4	-237.6	-	-	-	-	-	-	-	-46.6	-106.6	
S_m	69.7	51.7	47.3	111.4	176.7	176.7	176.7	176.7	176.7	176.7	135.8	97.2	1573.0
ΔS_m	-27.5	-18.1	-4.4	64.2	65.2	0.0	0.0	0.0	0.0	0.0	-40.8	-38.6	0.0
AET	56.4	53.1	90.5	92.4	90.9	75.3	66.6	68.5	78.4	91.2	82.5	65.8	911.6
SMD	32.6	36.6	11.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.8	21.3	108.2
S	0.0	0.0	0.0	0.0	41.1	158.9	191.6	183.1	93.9	1.1	0.0	0.0	669.6
TAR$_O$	0.0	0.0	0.0	0.0	41.1	179.4	281.3	323.7	255.7	129.0	64.5	32.2	1307.0
R_O	0.0	0.0	0.0	0.0	20.6	89.7	140.7	161.9	127.9	64.5	32.2	16.1	653.5
DET	0.0	0.0	0.0	0.0	20.6	89.7	140.7	161.9	127.9	64.5	32.2	16.1	653.5
R_OTL	1.5	1.8	4.5	8.2	31.0	102.0	154.2	175.1	136.9	69.3	34.4	17.5	736.7

Instead of using the Thornthwaite method to calculate potential evapotranspiration, which is based on air temperature only, more realistic results can be obtained by applying a reference potential evapotranspiration calculated by the Penman or other methods which take into account a more complete range of meteorological observations applied to a reference crop (grass) (Donker, 1987). Hence, potential evapotranspiration calculated by the Modified Penman method was used in WTRBLN model, the results from this model has been considered for water balance analysis.

4.1.3. Runoff

Gilgel Gibe river of the study area has a gauging station at Assendabo at a location of 7.45^{o}N Latitude and 37.11^{o}E Longitude with a drainage area of 2966 km^2. A total of twenty-four years (1990-2013) daily river flow data of Gilgel Gibe river recorded near Assendabo was used for runoff analysis. The mouth or outlet point of Upper Gilgel Gibe watershed is near to Assendabo gauging station and the discharge at the outlet of the watershed is calculated by Drainage-Area ratio. Extrapolation of the discharge rate to the outlet of the watershed is made because of having similar climate, topography and land use land cover. Drainage-Area ratio can be computed as (Emerson *et al.*, 2005):

$$Q_C = \left({}^{A_C}/_{A_G} \right) Q_G \tag{4.13}$$

Where,

Q_C = Discharge from the catchment

A_C = Drainage area of the catchment

A_G = Drainage area of gauging station

Q_G = Discharge at the gauging station

Based on stream flow data record of Gilgel Gibe River near Assendabo for the past 24 years (1990-2013), the mean annual discharge of the river is 1338.44 MCM or 455.10 mm/year. Peak discharge occurs at the month of August.

Table 4.14: Mean monthly discharge of Gilgel Gibe near Assendabo River

Discharge	Recording period (1990-2013)												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
MCM	24.57	18.56	19.31	25.58	54.96	117.1	223.7	311.3	267.2	159.6	77.38	39.12	1338.44
mm/year	8.35	6.31	6.57	8.70	18.69	39.80	76.07	105.8	90.87	54.27	26.31	13.30	455.10
Where, MCM represents Million Cubic Meter.													

4.1.3.1 Rainfall-Runoff-Recharge Relationship

Most natural groundwater recharge is derived directly from rainfall and snow melt that infiltrate through ground surface and migrate to the water table. To quantify recharge from precipitation, it is critical to understand rainfall-runoff relationships (Kresic, 2009).

Estimating runoff or discharge from rainfall measurements is very much dependent on the time scale being considered. For short duration (hours) the complex interrelationship between rainfall and runoff is not easily defined, but for prolonged time the connection becomes simpler (Shaw, 1988).

Table 4.15: Mean monthly Rainfall-Runoff relationships of the study area

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
RF (mm)	30.5	36.9	90.6	164.8	207.7	246.5	271.8	264.8	181.4	97.1	43.9	28.6
R_O (mm)	8.35	6.31	6.57	8.70	18.69	39.80	76.07	105.8	90.87	54.27	26.31	13.30

(Where, RF = Rainfall, R_O = Runoff)

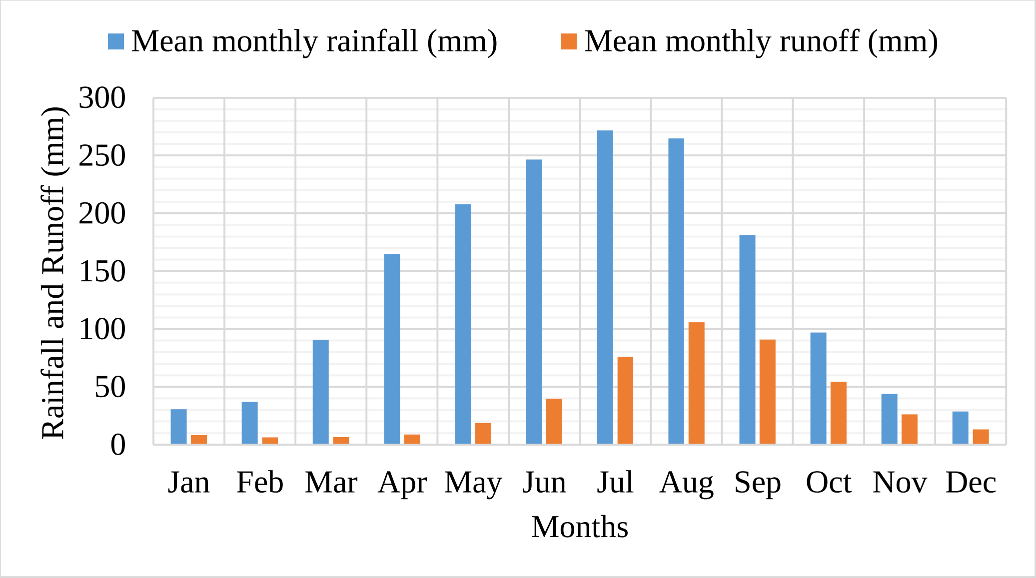


Figure 4.6: Long term Rainfall-Runoff relationship of the study area

4.1.3.2 Base Flow Separation

A surface stream hydrograph is the final quantitative expression of various processes that transform precipitation into stream flow. Separation of the surface stream hydrograph is a common technique of estimating the individual components that participate in the flow formation. Theoretically, they are divided into flow formed by direct precipitation over the surface stream, surface (overland) runoff collected by the stream, near-surface flow of the newly infiltrated water (also called underflow), and groundwater inflow (Kresic, 2009). However, it is practically impossible to accurately separate all these components of stream flow generated in a real physical drainage area. In practice, the problem of component separation is therefore reduced to an estimation of the base flow, formed by groundwater, and surface runoff, which is the integration of all the other components.

In this work, separation of Base flow (Figure 4.7) has been made using a software known as Base Flow Indices (BFI+ 3.0), (see Appendix 4 for stream flow data and Appendix 5 for separated base flow value). The amount of base flow separated by this software was 993.14 MCM or 337.69 mm/year. The method shows that about 74.2% of the flow is contributed from base flow and 25.8% from surface runoff out of the total mean annual flow.

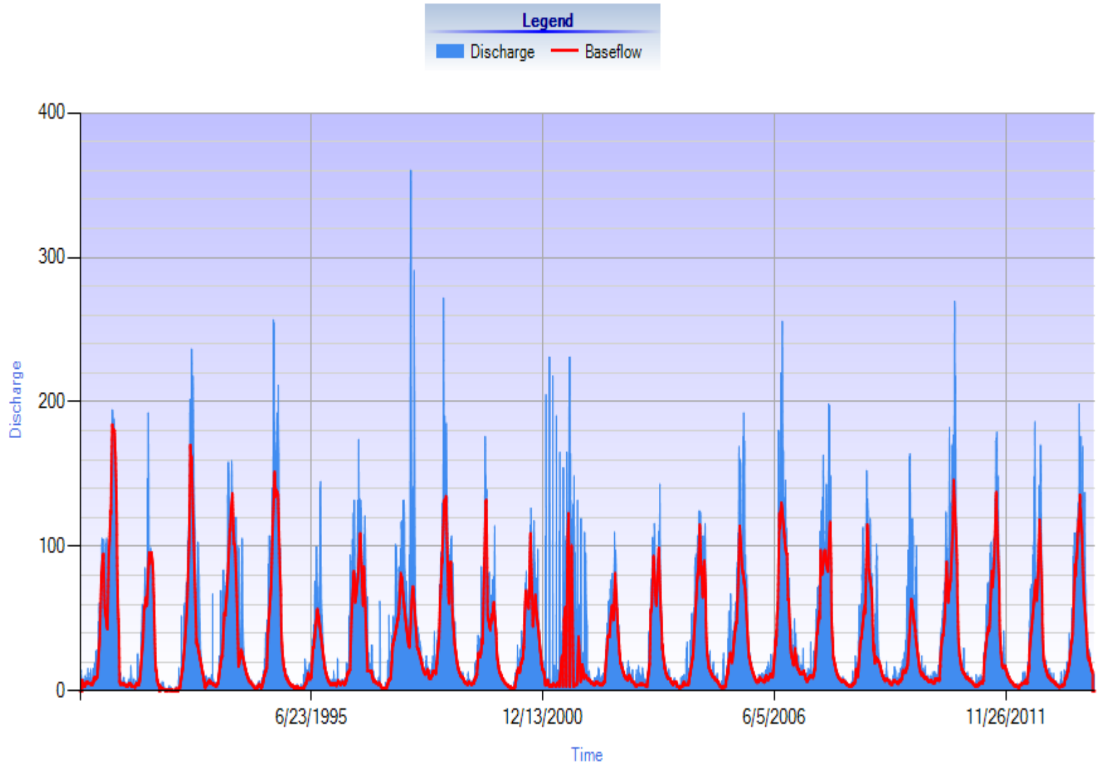


Figure 4.7: Long term Hydrograph of Gilgel Gibe river with separated base flow

4.2. Water Balance and Groundwater Potential Evaluation

The previous calculated values of aerial depth of precipitation and actual evapotranspiration of the catchment are 1664.5 mm/year and 911.6 mm/year. The adjusted value of change in soil moisture was found to be zero and runoff from the catchment was 455.10 mm/year. Substituting the values in the water balance equation (equation 3.4), the total recharge of the study area was 297.8 mm/year. Considering the total area of the catchment as 2941 km^2, the annual groundwater recharge of the Upper Gilgel Gibe catchment was estimated as 875,829,800 m^3/year.

4.2.1. Specific Yield

Specific yield can be estimated using the formula given in equation (3.24). Groundwater abstraction during the recharge period is equal to the volume of water used for domestic use in rainy season. The average per capita water consumption in developing country was estimated to be 5 - 15 l/day/person (Streeter and Portland, 2009). According to report by Central Statistics Agency, CSA (2007), the study area populated as 159.69 people per square kilometer. Upper Gilgel Gibe watershed covers an area of 2941 km^2 of which the population size of the area was estimated to be 469,650. By considering the population growth rate of Oromia region (2.9%), the projected population number of the study area was found to be 605,849. Hence, the amount of water abstracted for domestic consumption was estimated with an average rate of 10 l/day/person, and the abstraction found to be in the order of 2,211,349 m^3/year. The estimation of average water level rise in wet period (Dl_w) done after oral discussion made with farmers and taken as 5 m. The lateral subsurface outflow (Lso) from the catchment is assumed to be equal with the lateral subsurface inflow (Lsi) to the catchment and considered as they balance each other (zero). Using the above mentioned parameters, the specific yield was estimated to be 0.059 or 5.9%.

4.2.2. Exploitable Groundwater Reserve

Estimation of exploitable groundwater reserve (Q_{ed}) was done by using equation (3.25). The estimation of average water level decline in dry period (D_L) done after oral discussion made with farmers and taken as 3 m and putting this value in to equation (3.25), the exploitable groundwater reserve of the catchment was estimated as 520, 557,000 m^3/year.

4.2.3. Safe Yield

In this work safe yield is used as a management concept and is estimated by using equation (3.26). The exploitable groundwater reserve of the catchment and the volume of water used for domestic use in rainy season of the area from the previous estimation are 520, 557,000 m^3/year and 2,211,349 m^3/year. Since the values of recharge due to irrigation returns and sewage infiltration are insignificant, and taken as zero. Thus, the annual safe yield of the catchment was estimated as 522,768,349 m^3/year.

4.2.4. Abstraction

The total amount of withdrawal throughout the catchment consists of irrigation and domestic water uses. Pumping from both hand dug wells and boreholes is the major way by which groundwater is abstracted from the system. The shallow boreholes and hand dug wells fitted with submersible and hand pumps have been serving for domestic water supply for both the urban and rural communities. According to Jimma Zone water, mineral and energy office and Water Sanitation and Hygiene (WASH) report of Jimma Zone, there are about 98 hand dug wells within the study area. The hand dug wells yield on average 0.5 l/s pumping for 8 hours per day. Therefore, groundwater abstraction from this wells was found to be 515,088 m^3/year. In addition to hand dug wells the collected data indicates that, the groundwater of the study area was also abstracted through 56 shallow and deep wells with a total yield of 7,131,170 m^3/year. Report by Water, Sanitation and Hygiene also indicates that there are additional 10 Deep wells and 16 Shallow wells (see Appendix 6). By assuming an average yield of 21.15 l/s and 5 l/s and average pumping hours of 6 hours and 8 hours for Deep wells and Shallow wells respectively, the groundwater abstraction from this wells were found to be 2,508,426 m^3/year. The total groundwater abstraction from the study area was found to be in order of 10,154,684 m^3/year.

Based on the previous estimation, the groundwater recharge, safe yield of the catchment and the total groundwater abstraction or withdrawal was 875,829,800 m^3/year, 522,768,349 m^3/year and 10,154,684 m^3/year respectively (Table 4.16). The total annual inflow of the catchment was greater than the total out flow of the catchment. Thus, the current groundwater abstraction was lower than the safe yield of the aquifers and the annual groundwater recharge of the catchment.

Table 4.16: Estimated water balance components of the study area

Components	Recharge (m^3/year)	Specific yield (%)	Exploitable groundwater reserve (m^3/year)	Safe yield (m^3/year)	Abstraction (m^3/year)
Estimated values	875,829,800	5.9	520, 557,000	522,768,349	10,154,684

4.3. Groundwater Sustainability Indicators

4.3.1. Renewable Groundwater Resources per Capita

Renewable groundwater resource is the average annual flow of rivers and recharge of aquifers generated from precipitation. This can be computed on the basis of the water cycle and represent the long-term average annual flow of rivers. The amount of available groundwater in relation to the number of people using it becomes an important factor for the social and economic development at a catchment level. From previous estimation the values of recharge and number of population in a catchment were found to be 875,829,800 m^3/year and 605,849 respectively. Calculated renewable groundwater resources per capita was found to be 3960.6 l/day/capita which is greater than 1500 l/day/capita and implies low negative impact on groundwater resource of the catchment (Table 3.5).

4.3.2. Total Groundwater Abstraction/Groundwater Recharge

Total groundwater abstraction means the total withdrawal of water from a given aquifer by means of wells, boreholes, springs and other ways for the purpose of public water supply or agricultural, industrial and other usage. Groundwater abstraction as part of the groundwater recharge has been proposed as a catchment level indicator. It considers the natural and induced recharge, and total groundwater abstraction. This indicator may encourage managers to judge the likely level of sustainability through linking the abstraction to groundwater recharge. From previous estimation the values of total groundwater abstraction and groundwater recharge were found to be 10,154,684 m^3/year and 875,829,800 m^3/year respectively. The indicator value for total groundwater abstraction / groundwater recharge was calculated as 0.012 which is less than 0.9 and categorized as under developed groundwater resources.

4.3.3. Total Groundwater Abstraction / Exploitable Groundwater Resources

The indicator relates the groundwater abstraction to exploitable groundwater resource. This indicator may encourage managers to link the total volume of groundwater that can be abstracted annually to groundwater recharge and recognize possible over-abstraction. This indicator tells whether groundwater abstraction is sustainable or not. From previous estimation the values of total groundwater abstraction and exploitable groundwater resources were found to be 10,154,684 m^3/year and 520, 557,000 m^3/year. respectively. The indicator value for total groundwater abstraction / exploitable groundwater resources was calculated as 0.019 which is less than 0.9 and also categorized as under developed groundwater resources.

4.4. Groundwater Management Strategies

Groundwater management strategies have been focused on the development of groundwater resource while projects of various types and scales have been developed and managed in response to the growing demand for water by communities and industries. With the increase in demand, the resource is being over exploited in many areas resulting in a permanent depletion of the aquifer system and associated environmental consequences like land subsidence and water quality deterioration. If groundwater resources are to be developed and managed sustainably so that they can continue to contribute as long term water supply sources, the following important management strategies should be implemented.

4.4.1. Understanding of Resources Availability and its Vulnerability

Efficient management of groundwater has to start with an understanding of the occurrence and behavior of groundwater and groundwater quality. It must include consideration of aquifer capabilities, water needs and water quality requirements. Identification and control of sources of contamination are necessary to limit impacts on groundwater quality, control on the location and construction of wells and the withdrawal of water at appreciable rates are necessary to prevent aquifer depletion and to avoid the occurrence of adverse environmental consequences. In this regard, a close cooperation and coordination are essential among the various governmental and non-governmental organizations dealing with groundwater.

4.4.2. Proactive Management and Control of Groundwater Resources

With increasing demand for water, dependence on groundwater has increased considerably in different parts of the world and therefore, the groundwater issues become a part of the social, legislative and scientific conscience. However, the ensuing problems of over exploitation and environmental degradation are not reflected as major concerns in the development policy of many nations. Thus, more proactive management and protection of groundwater resources are urgently required to avoid permanent depletion of the resource in both quantity and quality aspects. This implies that an effective control on groundwater exploitation is necessary. In many situations, institutional and regulatory measures need to be strengthened to implement necessary controls. Moreover, proper monitoring and evaluation are to be undertaken to check the effectiveness of various control measures adopted as well as to identify new or emerging threats. For these efforts to be successful there is a need of coordination and collaboration of different agencies dealing with technical, administrative, regulatory and legislative aspects for implementation of methods for groundwater protection.

4.4.3. Protecting Groundwater from Pollution

Management of groundwater quality requires both the protection of aquifers and groundwater from entrance of pollutants, and also the remediation or treatment of polluted resources. However, treatment of polluted groundwater is complex, expensive, and often only partially successful and it may take many years. Groundwater quality management should be pro-active and attempt to prevent the contamination of groundwater resources.

4.4.4. Managing Catchment Abstraction

This is a means of providing information on water demands and availability of resources on a local scale for achieving the sustainable management of water resources within a catchment or group of catchments. The objectives of this strategy are; providing a consistent and structured approach to local water resources management by recognizing both the reasonable needs of users for water and environmental needs, and providing the opportunity for greater public involvement in the process of managing abstraction at a catchment level.

4.4.5. Creating Awareness

Since groundwater is an invisible resource, its limitations and threats are often not well understood. Special efforts are required to create awareness about groundwater and its use so as to use the resource sustainably. Water users play a dual role in sustainable development: on the one hand they are the ultimate beneficiaries, but on the other hand they are the ultimate managers, whose behavior plays a dominant role. Any control to be imposed on water withdrawal and on land use planning to ensure sustaining the available resource for future generations will have an immediate impact on the present water users. In this regard, the effectiveness of any regulation will certainly depend on the acceptance and credibility attached to the decisions by the water users. As such, the knowledge and information on the groundwater system and its interaction with the environment gained by the authorities should be transferred to the users in a form that they can understand. A wide variety of awareness creating methods can be used ranging from basic knowledge to detailed information that actively engages water user groups. The groundwater awareness of the communities can be increased through providing groundwater management trainings, preparing workshops dealing on groundwater.

4.4.6. Considering Different Aspects of Groundwater Resources

Technical aspects: First, it is important to identify the characteristics of resources in the basin, including the land, the rainfall, the runoff, the stream and river flows and the groundwater. Technical aspects of planning involve: Predicting changes in land use/covers and economic activities at watershed and river basin levels, Estimation of the costs and benefits of any measures being and to be taken to manage the basin’s water resource, and Identification and evaluation of alternative management strategies and also alternative time schedules for implementing those measures.

Economic and Financial aspects: groundwater should be treated as an economic commodity to extract the maximum benefits as well as to generate funds to recover the costs of the investments and of the operation and maintenance of the system. Water had been treated for long as a free commodity. In management policies, financial viability should be viewed as a constraint that must be satisfied.

Institutional aspects: Successful project implementation needs an enabling environment. National, provincial and local policies, legislation and institutions are crucial for implementation of the decisions.

4.4.7. Scientific Development of Groundwater

Scientific development of ground water involves a proper understanding of the local groundwater availability, its behavior and demand centric development with scientific planning. The need for scientific development of groundwater under different hydrogeological conditions comprises:

Development of Deep aquifers: In many parts of the country deep aquifers are not fully developed which implies under-utilization of available groundwater resources. This under-utilization from deep aquifers may cause a near stagnant condition at depths and may provide the required time factor for the deterioration in quality of groundwater.

Development of groundwater in non-developed areas: Policy makers often pay attention to the regions where groundwater development has great potential and neglect other areas with hidden potential. Naturally, some farmers find it problematic to increase agricultural production due to non-availability of water. There is wide scope for development of groundwater in the study area.

4.4.8. Regulation of Groundwater Development

One of the vital strategies for sustainable management of groundwater is regulation of groundwater development in critical areas. Over development of groundwater resources is increasingly being recognized as a most important problem. Hence, the tendency towards over development of groundwater resources is rooted in the rapid spread of energized pumping technologies, resource characteristics, demographic shifts and government policies, regulations of groundwater development should be established. However, it is not easy to implement the legislations without people's support and awareness creation.

4.4.9. Stakeholders Communication and Engagement

Effective public engagement invites individuals or organizations to get involved in deliberation, dialogue, and action on public issues. It helps leaders and decision makers better understand the perspectives, opinions, and concerns of users and stakeholders. Public engagement helps people weigh a variety of perspectives and listen to each other's views, builds common understanding, manages differences, and establishes direction for moving ahead on tough issues, builds trust and improves communication between the public and leaders, and creates opportunities for everyone to become involved in public problem solving and decision making.

Generally, when seeking to achieve sustainable groundwater development, First, the successful adoption of any strategy must ensure that it is flexible enough to deal with current and future conditions. Second, removing institutional obstacles to obtaining financial resources may significantly influence achievement of a more sustainable environment. Third, innovative approaches to sustainable groundwater management are necessary in order to balance conflicting demands. Fourth, there is a need to bridge the divide that exists between the approaches advocated by governmental authorities and the perceptions of local users. To tackle these challenges, local educational programs in collaboration with groundwater regulators are required to strengthen public awareness.

5. CONCLUSION AND RECOMMENDATIONS

5.1. Conclusion

The groundwater potential in the study area was estimated based on the water balance approach which is a viable method of establishing the rainfall-recharge relationship and for quantification of groundwater recharge. For proper assessment of potential, present use and additional exploitability of water resources at optimal level, a water balance study is necessary.

In the study area, precipitation was identified as major recharging component of groundwater aquifer. Whereas, Evapotranspiration (the principal cause of water loss from precipitation), runoff, and house hold consumptions discharges the system. However, net groundwater inflow and outflow from the basin, effluent seepage to rivers and recharge from irrigated field were not assumed as it is difficult to analyze those components and their effect may compensate each other. According to the water balance analysis of the study area, the annual groundwater recharge of the study area is estimated as 875,829,800 m^3. The present annual groundwater abstraction is obtained as 10.15 MCM per year. The estimated specific yield, exploitable groundwater reserve and safe yield of the catchment are 5.9%, 520,557,000 m^3/year and 522,768,349 m^3/year respectively. The estimated value of groundwater sustainability indicators is 3960.6 l/day/capita, 0.012 and 0.019 for renewable groundwater resources per capita, total groundwater abstraction/groundwater recharge, and total groundwater abstraction/exploitable groundwater resources respectively.

The current groundwater abstraction is much lower than the safe yield of the aquifers, the annual groundwater recharge of the catchment and the exploitable groundwater resources. This indicates under developed groundwater resources of the study area. The available groundwater resource of the study area can support the total inhabitants as domestic water supply. In order to utilize the existing groundwater resources, appropriate management and rules should be applied at large in different groundwater resource potential zones of the country. In the study area, there is enough amount of the groundwater resources potential for planning and implementation of different groundwater resource development projects. Groundwater potential evaluation across the river basin plays a vital role in case of groundwater quality control, occurrence, extraction and management of the resources in the study area.

Protection of groundwater from depletion and pollution, reduction of negative ecological effects, and economic efficiency need to be considered when exploiting groundwater. Hydrological investigations are a basis for determination of exploitable groundwater resources. These investigations demand usage of a mathematical model of groundwater system to analyze and solve the problems. The study of water balance remains as a precondition for groundwater modelling. Finally, it is essential to study both unsaturated and saturated flow for finding the recharge components from rainfall and from percolation in groundwater basins. The return flow of irrigation under diverse crops, soils, and irrigation practices has to be quantified, and groundwater quality of many groundwater basins need to be assessed in detail.

5.2. Recommendations

Based on the results and conclusions of the study, the following recommendations have been made:

- In this study, subsurface inflow and outflow, influent seepage from river, effluent seepage to rivers, and canal recharge were not assumed. However, the contribution of these components may be significant on the result obtained. Therefore, it is recommended for further research in the area to estimate groundwater recharge considering the indicated components.
- In this study, groundwater level fluctuation during wet and dry seasons was taken by simple oral discussion with local farmers. But, this needs a detail study and field measurement. Because, it affects the estimated values of groundwater potential of the study area significantly.
- When conducting this research, the main problem was availability of borehole data. Therefore, governmental and non-governmental organizations working on groundwater development should pay a great attention to collect and organize data during construction and provide them to different researchers.

- Since the available groundwater resource is sufficient, concerned governmental and non-governmental bodies should utilize water effectively by considering sustainability of the resources.
- Finally, as individuals, we cannot depend only on legislation for delivering sustainability. Each of us should implement the precautionary principle in which we use water and handle our raw materials and waste in such a way as to decrease demand and restrict the probability of pollution of water resources.

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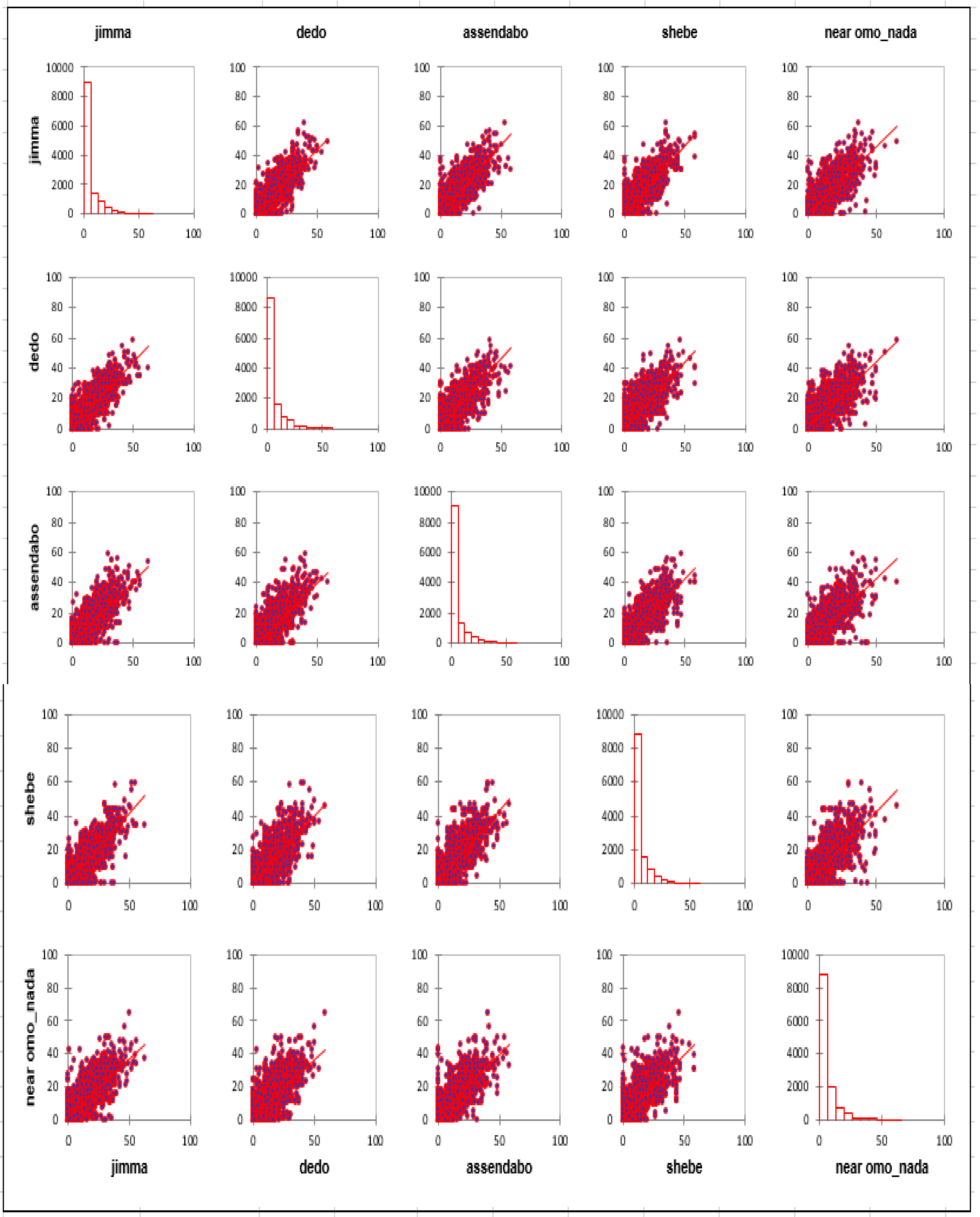
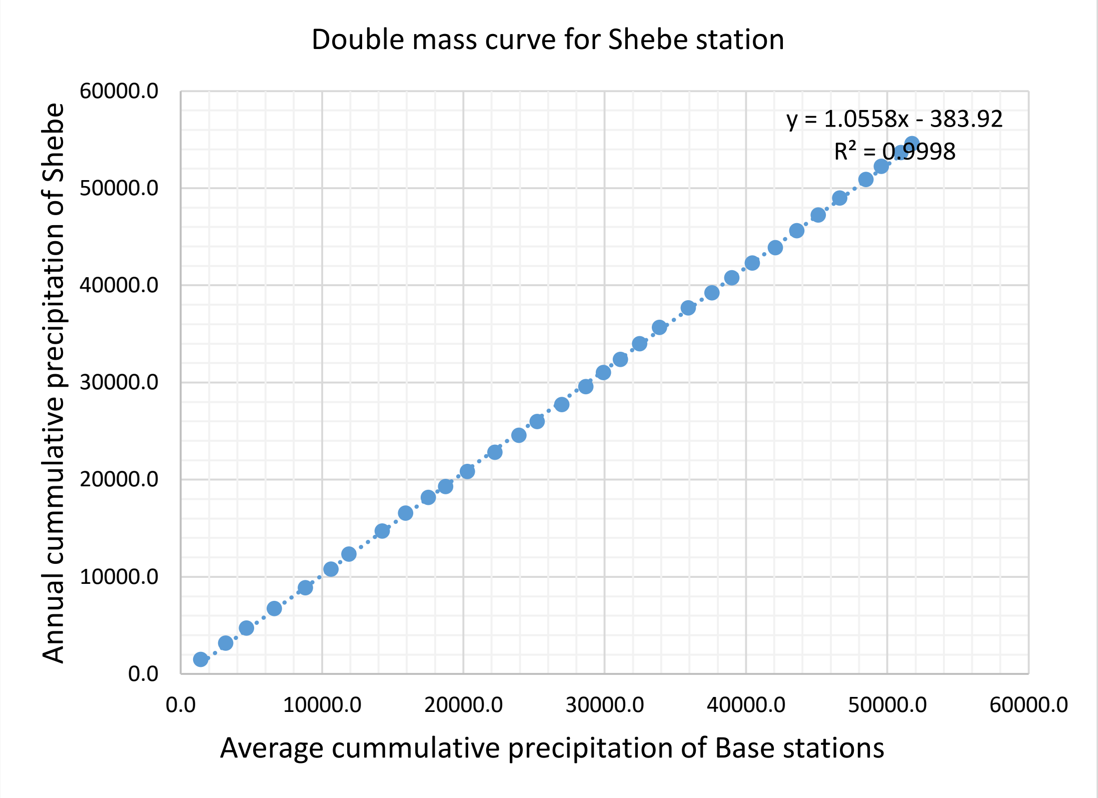
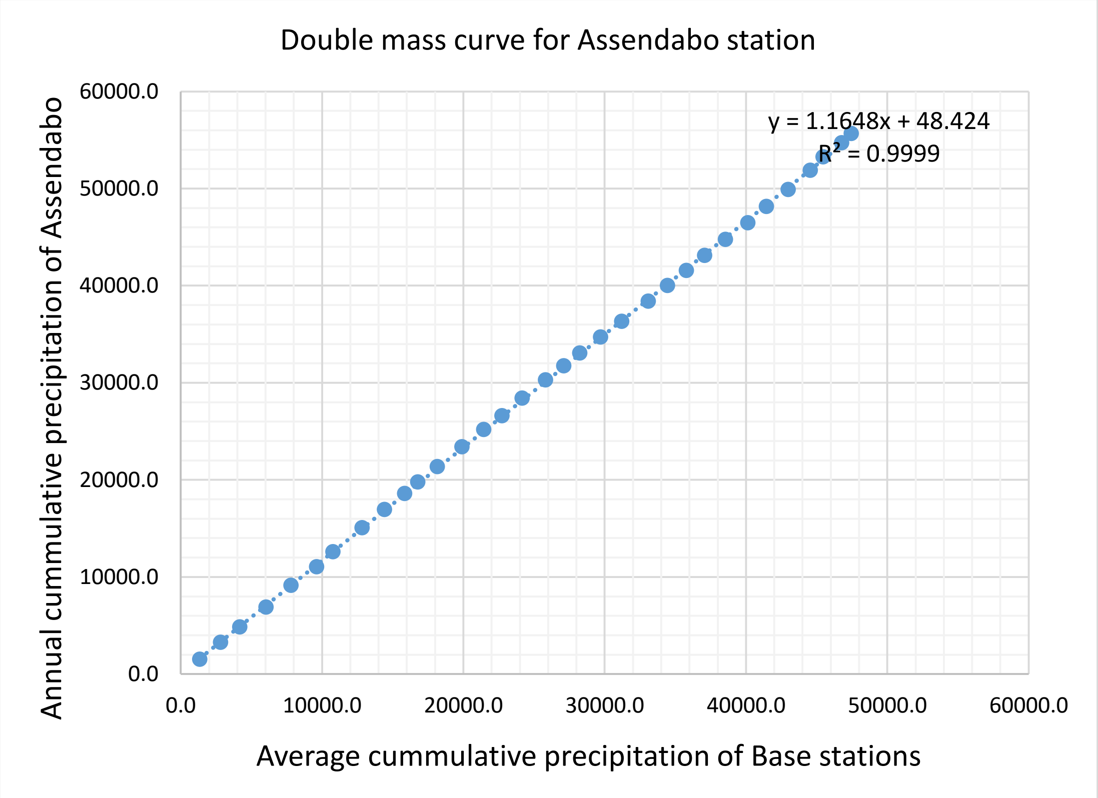
7. APPENDICES

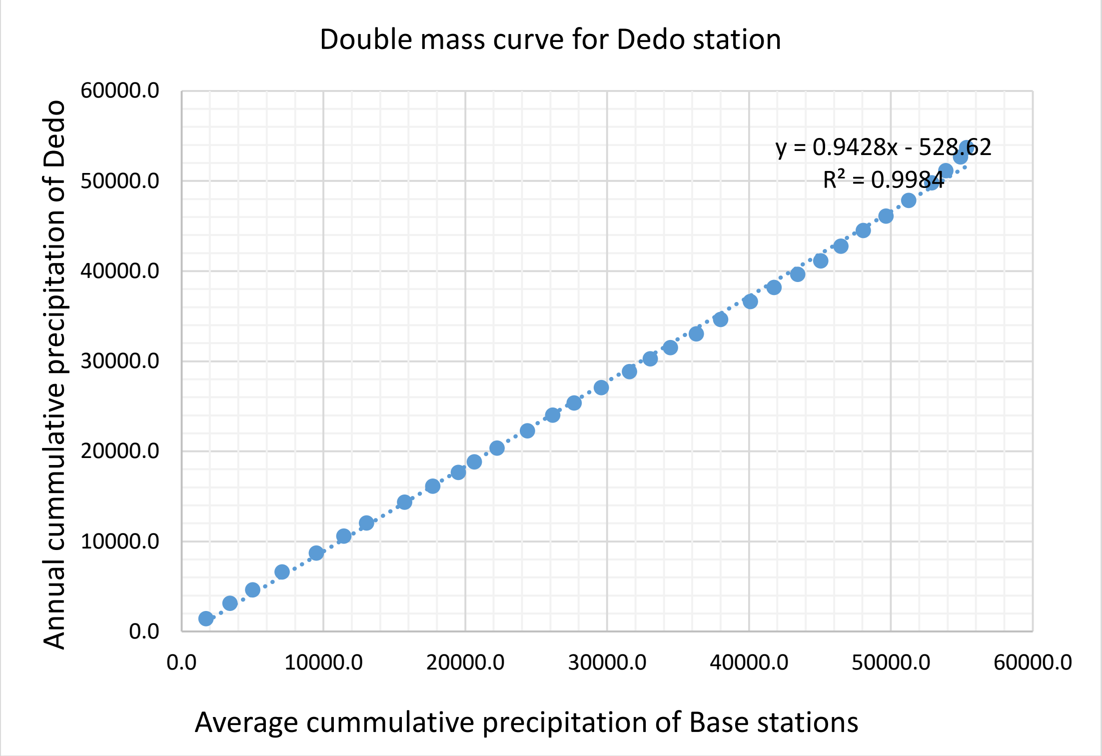
Appendix 1: Scatter plots of correlation test between variables

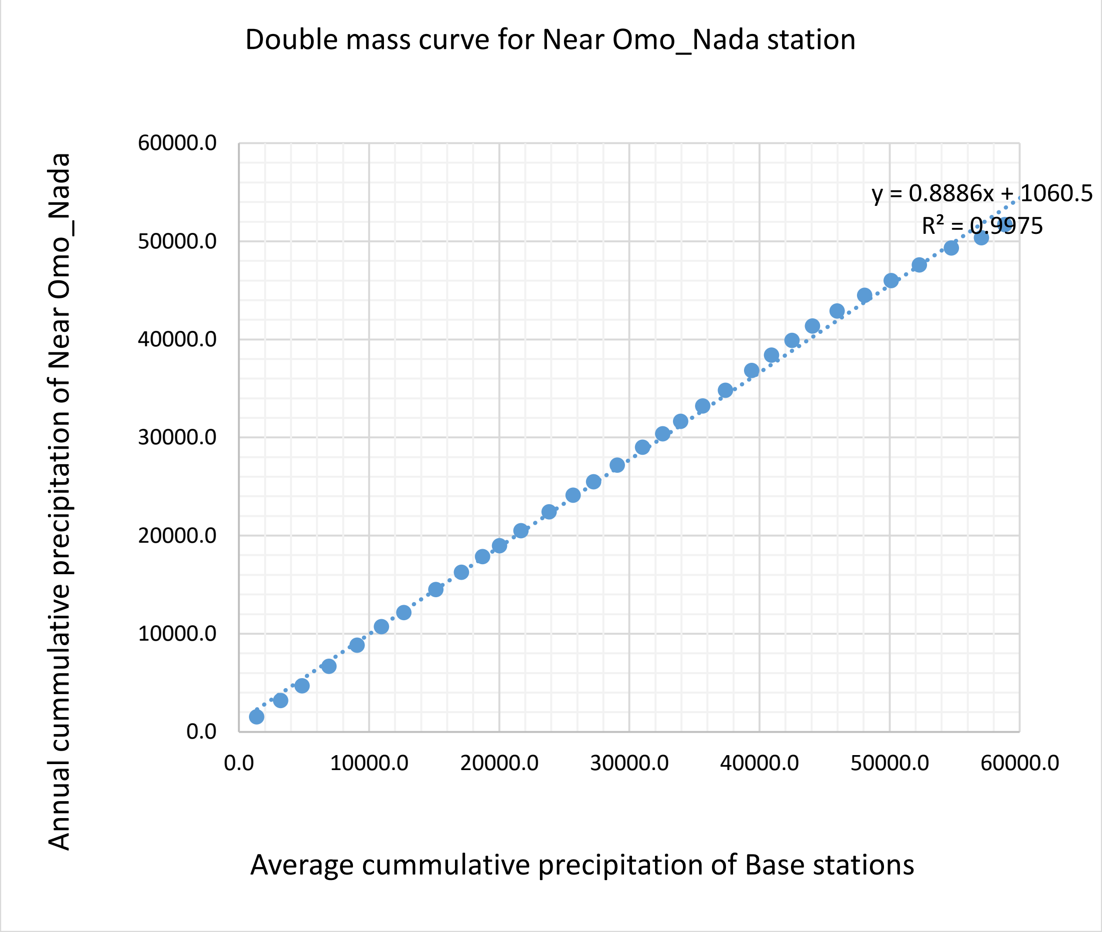


Appendix 2: Double mass curves for different stations






Double mass curve for Dedo station
Annual cummulative precipitation of Dedo
Average cummulative precipitation of Base stations
y = 0.9428x - 528.62
R² = 0.9984
0.0
10000.0
20000.0
30000.0
40000.0
50000.0
60000.0


Double mass curve for Near Omo_Nada station
Annual cummulative precipitation of Near Omo_Nada
Average cummulative precipitation of Base stations
y = 0.8886x + 1060.5
R² = 0.9975
0.0
10000.0
20000.0
30000.0
40000.0
50000.0
60000.0

Appendix 3: Thornthwaite Water Balance for different soil types of the study area

Table 1: Chromic Vertisols and Dystric Nitosols

	Months												Annual(mm/ yr.)
Parameters	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
PET	63.5	61.0	71.2	69.5	72.1	67.0	65.1	64.7	62.2	62.3	59.1	60.0	777.7
P	30.0	36.4	89.3	162.4	204.7	242.9	267.8	260.9	178.7	95.7	43.2	28.1	1640.0
P-PET	-34.9	-26.4	13.6	84.7	122.3	163.7	189.3	183.1	107.6	28.5	-18.0	-33.3	780.3
Soil moisture	113.5	100.6	117.3	175.2	197.4	200.0	200.0	200.0	200.0	188.5	165.2	137.7	1995.4
AET	51.7	46.9	66.0	68.9	72.1	67.0	65.1	64.7	62.2	62.3	57.6	53.5	738.2
PET-AET	11.8	14.1	5.2	0.6	0.0	0.0	0.0	0.0	0.0	0.0	1.4	6.5	39.5
Snow storage	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Surplus	0.0	0.5	2.1	27.4	100.2	161.1	189.3	183.1	107.6	40.0	6.8	0.7	818.8
RO_{total}	13.7	8.2	8.7	23.9	68.2	121.7	162.8	179.3	145.9	93.3	49.8	25.6	901.0

Table 2: Dystric Fluvisols

	Months												Annual(mm/ yr.)
Parameters	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
PET	63.5	61.0	71.2	69.5	72.1	67.0	65.1	64.7	62.2	62.3	59.1	60.0	777.7
P	30.0	36.4	89.3	162.4	204.7	242.9	267.8	260.9	178.7	95.7	43.2	28.1	1640.0
P-PET	-34.9	-26.4	13.6	84.7	122.3	163.7	189.3	183.1	107.6	28.5	-18.0	-33.3	780.3
Soil moisture	46.4	39.0	57.0	106.9	118.0	120.0	120.0	120.0	120.0	108.5	86.1	62.7	1104.6
AET	46.3	41.5	64.4	68.7	72.1	67.0	65.1	64.7	62.2	62.3	56.7	49.4	720.3
PET-AET	17.2	19.5	6.9	0.8	0.0	0.0	0.0	0.0	0.0	0.0	2.4	10.6	57.4
Snow storage	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Surplus	0.0	0.5	2.4	35.6	111.2	161.8	189.3	183.1	107.6	40.0	6.8	0.8	839.1
RO_{total}	13.7	8.2	8.9	28.1	75.8	125.8	164.9	180.4	146.4	93.5	49.9	25.7	921.3

Table 3: Eutric Fluvisols

	Months												Annual(mm/ yr.)
Parameters	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
PET	63.5	61.0	71.2	69.5	72.1	67.0	65.1	64.7	62.2	62.3	59.1	60.0	777.7
P	30.0	36.4	89.3	162.4	204.7	242.9	267.8	260.9	178.7	95.7	43.2	28.1	1640.0
P-PET	-34.9	-26.4	13.6	84.7	122.3	163.7	189.3	183.1	107.6	28.5	-18.0	-33.3	780.3
Soil moisture	78.8	68.2	85.6	140.7	157.7	160.0	160.0	160.0	160.0	148.5	125.5	99.6	1544.6
AET	49.5	44.6	65.3	68.8	72.1	67.0	65.1	64.7	62.2	62.3	57.3	51.9	730.9
PET-AET	13.9	16.3	5.9	0.7	0.0	0.0	0.0	0.0	0.0	0.0	1.8	8.1	46.8
Snow storage	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Surplus	0.0	0.5	2.1	30.4	105.3	161.4	189.3	183.1	107.6	40.0	6.8	0.7	827.2
RO_{total}	13.7	8.2	8.7	25.4	71.6	123.5	163.7	179.8	146.1	93.4	49.8	25.6	909.5

Table 4: Eutric Nitosols

	Months												Annual(mm/ yr.)
Parameters	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
PET	63.5	61.0	71.2	69.5	72.1	67.0	65.1	64.7	62.2	62.3	59.1	60.0	777.7
P	30.0	36.4	89.3	162.4	204.7	242.9	267.8	260.9	178.7	95.7	43.2	28.1	1640.0
P-PET	-34.9	-26.4	13.6	84.7	122.3	163.7	189.3	183.1	107.6	28.5	-18.0	-33.3	780.3
Soil moisture	62.2	53.1	70.8	123.6	137.8	140.0	140.0	140.0	140.0	128.5	105.8	81.0	1322.7
AET	48.0	43.2	64.8	68.8	72.1	67.0	65.1	64.7	62.2	62.3	57.0	50.8	726.1
PET-AET	15.4	17.8	6.4	0.7	0.0	0.0	0.0	0.0	0.0	0.0	2.1	9.2	51.6
Snow storage	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Surplus	0.0	0.5	2.2	32.7	108.0	161.6	189.3	183.1	107.6	40.0	6.8	0.7	832.6
RO_{total}	13.7	8.2	8.8	26.6	73.5	124.6	164.3	180.0	146.2	93.4	49.9	25.6	914.8

Table 5: Orthic Arcisols

	Months												Annual(mm/ yr.)
Parameters	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
PET	63.5	61.0	71.2	69.5	72.1	67.0	65.1	64.7	62.2	62.3	59.1	60.0	777.7
P	30.0	36.4	89.3	162.4	204.7	242.9	267.8	260.9	178.7	95.7	43.2	28.1	1640.0
P-PET	-34.9	-26.4	13.6	84.7	122.3	163.7	189.3	183.1	107.6	28.5	-18.0	-33.3	780.3
Soil moisture	95.9	84.1	101.1	158.2	177.5	180.0	180.0	180.0	180.0	168.5	145.3	118.6	1769.3
AET	50.7	45.9	65.7	68.9	72.1	67.0	65.1	64.7	62.2	62.3	57.5	52.8	734.8
PET-AET	12.7	15.1	5.5	0.6	0.0	0.0	0.0	0.0	0.0	0.0	1.6	7.2	42.9
Snow storage	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Surplus	0.0	0.5	2.1	28.3	103.0	161.3	189.3	183.1	107.6	40.0	6.8	0.7	822.7
RO_{total}	13.7	8.2	8.7	24.4	69.9	122.6	163.3	179.6	146.0	93.3	49.8	25.6	904.9

Appendix 4: Streamflow of Gilgel Gibe River near Assendabo

	Months												Annual (MCM)
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
1990	22.1	15.7	26.0	23.2	44.0	126.8	246.8	205.6	315.7	485.0	243.6	25.6	1780.3
1991	16.9	12.8	20.1	12.0	28.4	90.3	181.4	305.8	221.1	54.7	8.0	7.0	958.4
1992	1.7	3.6	0.4	3.4	32.1	110.1	231.0	507.8	310.6	201.9	51.9	20.9	1475.3
1993	19.6	25.8	12.0	52.8	143.9	203.4	346.1	322.0	220.3	163.2	86.6	27.5	1623.1
1994	15.9	7.8	11.7	13.0	57.8	183.8	353.2	455.4	326.4	73.5	29.5	15.7	1543.6
1995	8.7	7.4	6.8	21.1	31.8	39.6	121.7	175.2	205.0	50.5	20.8	16.7	705.3
1996	18.8	21.7	17.3	28.0	125.0	236.4	229.0	335.2	235.4	125.2	45.0	23.9	1440.9
1997	17.6	30.5	6.5	44.6	70.6	183.6	189.0	283.5	187.7	360.2	363.0	144.5	1881.3
1998	74.1	39.3	43.9	30.6	56.0	78.5	229.9	466.3	260.1	229.2	89.0	40.3	1637.0
1999	27.0	14.2	19.6	15.7	44.4	92.1	213.2	291.1	154.4	194.4	67.4	29.5	1162.9
2000	17.0	9.3	6.4	18.9	53.3	77.2	168.5	221.7	227.6	202.1	94.6	41.2	1137.9
2001	61.4	57.0	66.1	62.1	97.9	175.4	314.9	285.4	200.9	133.5	77.2	134.4	1666.2
2002	26.2	14.2	19.4	25.2	19.1	77.0	154.7	204.6	158.7	58.7	31.7	33.8	823.4
2003	28.5	12.8	24.1	26.0	15.4	63.0	216.9	228.1	245.2	82.4	33.0	26.5	1001.8
2004	17.3	12.0	11.0	17.4	36.0	84.5	174.6	265.4	247.9	208.2	53.0	35.4	1162.6
2005	24.5	11.7	27.5	22.8	109.0	90.0	182.1	346.7	325.9	139.0	51.1	26.5	1356.8
2006	20.6	22.3	26.2	31.4	38.6	93.1	324.3	452.8	282.2	139.4	76.5	62.9	1570.4
2007	40.8	37.1	25.0	39.7	56.0	149.8	263.0	309.0	358.5	176.1	43.6	25.0	1523.4
2008	19.5	14.4	10.2	17.6	42.3	117.5	213.7	304.2	240.4	85.0	144.0	38.1	1247.1
2009	26.9	20.9	17.1	25.3	23.4	38.9	99.3	290.5	204.9	152.0	41.2	38.3	978.5
2010	25.4	18.9	22.7	27.8	85.0	185.3	269.1	324.5	456.8	112.6	43.5	31.4	1602.9
2011	23.2	14.4	15.7	17.2	38.3	130.0	194.3	269.1	355.0	88.4	61.4	30.1	1237.1
2012	17.4	9.9	9.6	18.4	21.1	81.0	209.9	269.5	332.9	108.0	39.1	27.7	1144.5
2013	18.6	11.4	18.1	19.9	49.9	102.0	242.8	352.8	340.1	207.8	62.3	36.1	1461.9
Average	24.6	18.6	19.3	25.6	55.0	117.0	223.7	311.3	267.2	159.6	77.4	39.1	1338.4
Flow expressed in depth (catchment area = 2941 km^2) = 455.10 mm/year													

(Source: Ministry of Water, Irrigation and Energy office, MoWIE).

Appendix 5: Base flow separated using Base Flow Indices (BFI+ 3.0) software

	Months												Annual (MCM)
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
1990	15.0	11.2	14.4	15.2	24.9	103.4	217.6	144.3	310.7	475.8	241.4	21.9	1595.7
1991	11.8	9.6	10.9	8.4	14.8	64.8	157.8	226.7	219.3	54.7	8.0	3.2	790.0
1992	1.4	1.7	0.4	1.2	17.1	72.0	198.2	400.1	202.5	77.5	41.2	11.9	1025.2
1993	16.7	12.3	10.6	31.7	91.9	165.6	292.9	308.0	149.5	65.1	50.8	26.9	1222.0
1994	14.4	6.1	8.9	9.5	32.3	115.4	262.3	376.2	268.5	73.4	26.2	14.2	1207.5
1995	8.1	6.2	4.3	6.8	22.5	30.5	95.3	138.1	92.3	44.8	19.1	12.8	481.0
1996	12.6	14.1	14.2	19.5	54.1	177.8	189.3	253.3	181.8	69.5	33.7	18.8	1038.7
1997	14.2	7.0	4.8	14.9	55.9	103.8	155.6	191.7	122.2	101.3	166.6	103.0	1041.0
1998	64.0	35.4	35.0	24.6	34.5	66.3	202.9	332.1	213.1	186.1	78.7	39.7	1312.4
1999	24.5	13.8	14.8	13.8	32.0	65.6	164.4	246.2	122.2	142.8	65.2	29.3	934.5
2000	16.6	8.9	6.2	12.3	37.0	57.3	154.1	206.2	159.3	150.1	82.6	35.9	926.7
2001	15.3	9.0	11.1	11.8	36.0	97.6	193.2	139.2	11.9	56.9	33.3	26.1	641.4
2002	20.3	12.5	14.6	12.4	13.7	64.5	120.9	163.6	138.3	56.4	29.6	24.4	671.0
2003	20.8	11.3	11.2	11.6	10.4	41.9	189.1	191.4	204.0	78.9	30.7	20.9	822.3
2004	14.4	10.9	7.6	12.7	13.0	42.1	119.5	236.1	213.7	178.7	48.2	29.1	926.1
2005	20.9	10.8	7.5	19.4	58.4	75.7	150.2	266.5	198.3	111.7	45.8	26.0	991.2
2006	18.7	18.5	21.8	23.2	31.4	85.9	256.6	322.6	245.6	123.6	57.2	54.3	1259.5
2007	34.2	29.4	21.3	26.4	38.8	113.9	217.1	246.7	246.2	155.8	43.0	24.6	1197.3
2008	18.1	13.2	9.5	11.9	30.9	75.8	136.4	249.0	188.7	76.9	55.1	37.8	903.3
2009	21.5	17.4	14.4	17.1	16.5	27.4	39.1	105.1	141.7	89.7	40.2	28.1	558.2
2010	21.4	16.1	16.9	21.0	68.3	139.1	194.9	255.7	315.4	112.6	39.4	27.5	1228.4
2011	21.2	13.1	10.2	13.0	30.5	92.8	158.0	241.5	283.5	87.6	42.4	28.8	1022.6
2012	17.0	9.6	8.2	12.6	16.5	56.1	137.5	189.4	256.6	100.3	34.3	23.4	861.5
2013	16.7	9.5	8.6	15.1	37.3	83.6	203.8	302.9	267.5	135.5	57.9	39.0	1177.5
Average	19.1	12.8	12.0	15.3	34.1	84.1	175.3	238.9	198.1	116.9	57.1	29.5	993.14
Flow expressed in depth (catchment area = 2941 km^2) = 337.69 mm/year													

Appendix 6: Borehole Data

No	Site name	X-Easting	Y-Northing	Z-Elevation	Source type	Depth (m)	GW Level (m)	SWL (m)	yield (m^3/day)
1	Magala Seka	248258	840654	1784	BH	105	1782	2.3	483.84
2	Bake Gudo	231370	844536	2153	BH	123	2153	0	691.2
3	Sombo	237487	835696	1954	BH	96	1938	15.7	432
4	Sheki	259784	830242	1880	BH	110	1875	5.2	820.8
5	Ula Uke	242290	837702	1913	BH	105	1897	16	518.4
6	Sarbo	280625	857813	1693	BH	150	1692	1.09	604.8
7	Bulbul	289579	852662	1692	BH	140	1692	0	1209.6
8	Gibe	300230	858036	1699	BH	35	1699	0	864
9	Gello	293745	854518	1712	BH	100	1702	9.69	604.8
10	Dimtu 2	287611	861764	1716	BH	121	1736	20	691.2
11	Besale	289543	851687	1708	BH	47.7	1699	9.15	155.52
12	Boneya	287886	854839	1707	BH	50	1730	1.1	622.08
13	Dimtu	290027	865342	1721	BH	82	1704	17.5	155.52
14	wadeye	291189	854314	1713	BH	96	1676	36.55	388.8
15	Site 4	291956	853094	1713	BH	87.3	1699	14.4	408.8
16	Busase	291540	854783	1756	BH	73.3	1747	9.1	102.82
17	Farsi	289315	854867	1788	BH	53.3	1769	18.8	432
18	Site 5	292043	853401	1785	BH	60	1768	16.65	180.58
19	Kaka	287304	854049	1721	BH	90	1703	17.62	93.31
20	Marewa	268960	851314	1788	BH	110	1787	1.19	622.08
21	Ale	294694	842729	1818	BH	92	1778	40.1	285.12
22	Degani	285196	840653	1750	BH	83	1728	21.6	1866.2
23	Chalte	302018	855322	1730	BH	78	1726	4.35	216
24	Lucho	303739	855322	1730	BH	68	1715	15.46	172.8
25	Kereyu	286082	840532	1777	BH	78	1747	30.13	72
26	Ale well	293855	842841	1777	BH	83	1777	0	432
27	Nada well	292473	843257	1789	BH	85	1789	0	391.39
28	JU Sport field 1	262907	849066	1741	BH	152	1691	50	302.4
29	JU Sport field 2	262907	849066	1741	BH	121.5	1735	6.42	432
30	JUW #3	259850	847764	1634	BH	110	1631	2.8	216
31	JUW #5	262181	847875	1823	BH	165	1822	1.15	328.32
32	JUWR#3	261232	848310	1705	BH	187	1660	45	276.48
33	Ginjo school	263253	848896	1746	BH	108	1746	0	172.8
34	Kito No.1	258935	850447	1729	BH	121.5			406.08
35	Kito No.2	259051	849890	1723	BH	152			475.2
36	Kito No.3	259168	849265	1712	BH				350.2
37	Jimma Airport well	259253	848000	1716	BH	165.7		3.8	275.6
38	Somodo	260160	856095	1976	BH	136	1960	16	604.8
39	Nyeha	246942	839039	1876	SW	85	1869	16	86.4

40	Fulale	246968	839565	1552	SW	66.7	1542	7	86.4
41	Oyana	236358	836090	2018	SW	48.5	2006	10	43.2
42	Yabo	237178	838766	1990	SW	53.05	1990	12	259.2
43	Sheshemane	240000	837421	1936	SW	57.6	1903		172.8
44	Melko	255026	846168	1798	SW	71.25	1781	35	259.2
45	ONSW-2	289619	839793	1843	SW			4.2	86.4
46	ONSW-3	289293	840938	1799	SW			4	129.6
47	ONSW-4	291698	845715	1768	SW			6	86.4
48	ONSW-5	285452	845468	1727	SW			8.5	30.2
49	ONSW-6	283547	845616	1732	SW			16.5	32.8
50	ONSW-16	300083	852429	1749	SW			21	51.8
51	ONSW-17 (Dry well)	300013	848742	1834	SW				0.0
52	Uno	285171	842558	1739	SW			21	259.2
53	Billoarebo pri.school	290629	847319	1742	SW			27	129.6
54	Gerbi	288662	848257	1735	SW			17	86.4
55	Qoreagelo pri.school	296182	850249	1743	SW			40	34.6
56	Lalo	297633	850107	1749	SW			11	345.6
57	Seka	249668	841364	1818	HDW	17.5		16.95	
58	Sombo	238173	836477	2037	HDW	10.5		8.05	
59	Gura	238513	834965	1946	HDW	7		6	
60	Waktola	303848	856872	1766	HDW	4.5		3.9	
61	Kudo	290310	843697	1773	HDW	17		13	
62	Serbo	276948	852443	1693	HDW	6		5.4	
63	Dedo	265405	830283	2222	HDW	10		8.5	
64	Jimma Town	260651	848497	1697	HDW	11.3		10	
(Source: Jimma zone water, mineral and energy office and previous study by Dereje Belay)									
65	Ashewa	289497	853065	1704	DWD				
66	Basalz	289758	852901	1707	DWD				
67	Brburse chofe	277522	854019	1755	DWD				
68	Gibe	247732	841403	1773	DWD				
69	goshu	300227	858039	1695	DWD				
70	kilisher	289686	852980	1705	DWD				
71	Korke	286203	835741	1822	DWD				
72	Wacho	285195	840655	1757	DWD				
73	WASCH-0112279 of Dimtu 1	289934	852989	1715	DWD				
74	WASCH-0112282 of Dimtu 2	289862	853058	1712	DWD				
75	Abe	286911	837969	1810	SW				
76	Abulu	292317	843619	1763	SW				
77	Alle school	294687	842733	1824	SW				
78	Allee Megala	294463	843148	1806	SW				
79	brbersa chofa	277435	853412	1760	SW				

80	Dego	288128	844744	1729	SW				
81	Doyu	283608	844449	1736	SW				
82	Harirorobde	293810	842787	1775	SW				
83	kombo Jarso	262070	840243	1766	SW				
84	Merti Ber	248988	840309	1726	SW				
85	Sega	286209	839583	1772	SW				
86	Waachee	285194	839282	1765	SW				
87	wajo 1	296757	855822	1747	SW				
88	WASCH-0099265 of Lalo	279146	851439	1765	SW				
89	WASCH-0109380 of Lilo	294914	843324	1789	SW				
90	WASCH-0112118 of Burka	286092	841894	1748	SW				
91	A/Zebene	298329	844227	1819	HDWNP				
92	Aba Diga Aba Roro	300526	859971	1795	HDWNP				
93	aba zinab	237623	835905	1933	HDWNP				
94	Abase	278853	853411	1770	HDWNP				
95	AdOama Ber Sefer	297688	843051	1807	HDWNP				
96	Alga	287188	847423	1724	HDWNP				
97	Alliaco	293249	861809	1896	HDWNP				
98	B/Kara	263441	857346		HDWNP				
99	B/Kossa	262519	859784		HDWNP				
100	Badey well	276827	850639	1782	HDWNP				
101	Badi 1	294033	854751	1732	HDWNP				
102	Badi 2	285637	843179	1789	HDWNP				
103	Befira	303930	854165	1770	HDWNP				
104	Benba	295485	853924	1709	HDWNP				
105	Biirii	254658	840352	1741	HDWNP				
106	BIRISHE AHIMED	272601	849639	1772	HDWNP				
107	Chila	300812	845400	1839	HDWNP				
108	Dansero	303204	853523	1773	HDWNP				
109	Dega gara	279975	856222	1756	HDWNP				
110	derese	236953	836599	1952	HDWNP				
111	digo	295716	845168	1809	HDWNP				
112	Dimetu	299758	849324	1809	HDWNP				
113	Dimseta	264913	841376	1784	HDWNP				
114	GALE	276351	846687	1766	HDWNP				
115	gamina	238040	834522	1967	HDWNP				
116	Gamona	300834	849970	1810	HDWNP				
117	Gejera	298676	841322	1927	HDWNP				
118	Gito	296630	841462	1818	HDWNP				
119	Gollobbu	252145	841106	1756	HDWNP				

120	Gono	262409	844611	1723	HDWNP				
121	guraa	238513	834965	1946	HDWNP				
122	Guta	300098	849195	1850	HDWNP				
123	Hajii	300153	843916	1852	HDWNP				
124	HDW	279162	836938	1763	HDWNP				
125	Health post 1	255725	854703		HDWNP				
126	Health post 2	252089	847480		HDWNP				
127	Jimate Health Post	252452	854525		HDWNP				
128	kala'o	237549	834225	1989	HDWNP				
129	Kammbo gibe	261539	841266	1732	HDWNP				
130	Keye	299176	843713	1860	HDWNP				
131	Kimsa	303454	856865	1738	HDWNP				
132	Kiramu	302620	850854	1798	HDWNP				
133	Kuba	254636	852854	1946	HDWNP				
134	Lale well	275215	850370	1787	HDWNP				
135	lefa geba	237469	835712	1945	HDWNP				
136	Maddo	253919	843768	1798	HDWNP				
137	Malkahobe	270466	831254	1970	HDWNP				
138	MANSUR	276457	855499	1773	HDWNP				
139	Masi	294428	838246	1824	HDWNP				
140	Megala Kerigu	294284	843416	1791	HDWNP				
141	Mesera	279438	852452	1749	HDWNP				
142	Migira	253523	844411	1823	HDWNP				
143	mirate Pamp	270245	834630	1737	HDWNP				
144	Morowa	301806	849966	1812	HDWNP				
145	Oucho	283772	828524	1842	HDWNP				
146	Qudo'o	290310	843697	1773	HDWNP				
147	Sadacha	287641	845145	1758	HDWNP				
148	sarye	273206	850998	1801	HDWNP				
149	Sebero Oda	301009	846107	1825	HDWNP				
150	Sh/Ahimed	263957	826456	2303	HDWNP				
151	Siba	297735	862453	1978	HDWNP				
152	Sigalu	263435	826639	2408	HDWNP				
153	site	298831	856260	1688	HDWNP				
154	Tarba	295203	845773	1777	HDWNP				
155	Tergi	300204	849552	1806	HDWNP				
156	Tulama	295658	842030	1810	HDWNP				
157	Tull	249635	839844	1822	HDWNP				
158	Ture	292664	853443	1708	HDWNP				
159	wajo 2	297232	856454	1734	HDWNP				
160	WASCH-0098477 of Jarso	265576	827634	2331	HDWNP				
161	WASCH-0098789 of	262044	845157		HDWNP				

	School 1								
162	WASCH-0099033 of Lemlem	268721	849967	1795	HDWNP				
163	WASCH-0099141 of Beye	263270	827800	1827	HDWNP				
164	WASCH-0099303 of FTC 1	269614	863207	2190	HDWNP				
165	WASCH-0103009 of School 2	292641	876459	1616	HDWNP				
166	WASCH-0104056 of warsu	237467	834791	1989	HDWNP				
167	WASCH-0105182 of NULL 1	277429	852675	1774	HDWNP				
168	WASCH-0105328 of NULL 2	277180	852553	1777	HDWNP				
169	WASCH-0109373 of Lilo	294744	843473	1805	HDWNP				
170	WASCH-0109393 of site 2	299163	854994	1691	HDWNP				
171	WASCH-0109538 of Lalo	297755	859526	1847	HDWNP				
172	WASCH-0111719 of Abdi Guddina	303974	855401	1756	HDWNP				
173	WASCH-0114289 of Shashemene	240584	836313	1910	HDWNP				
174	Welda gibe	300683	854780	1689	HDWNP				
175	Welda hando	301306	856815	1702	HDWNP				
176	Wenji	303848	856872	1766	HDWNP				
177	Wodeyi	294030	852178	1707	HDWNP				
178	worabi	295020	853522	1712	HDWNP				
179	Yebo	292225	854754	1747	HDWNP				
180	Yebo Mosqeau	297601	859840	1848	HDWNP				

(Source: Water, Sanitation and Hygiene, WASH report of Jimma zone)

BH: Borehole, DWD: Deep Well with Distribution, HDW: Hand Dug Well, HDWNP: Hand Dug Well with Normal Pump, and SW: Shallow Well