Groundwater Resource Potential Assessment in the Wama Catchment, East Wollega Zone, Western Ethiopia

A Thesis Submitted to the School of Earth Sciences of Addis Ababa University in Partial Fulfillment of the Requirements for Degree of Master of Science in Hydrogeology.

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DECLARATION

I, the undersigned, declare that this thesis is my original work and has not been presented for a degree on any other university.

All sources of materials used for the thesis have duly acknowledged.

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ABSTRACT

This study aims to evaluate the groundwater resource potential of Wama catchment based on hydrometeorological, hydrogeological, and hydrochemical data analysis. Wama Catchement is the major tributary of Didessa Sub-basin and is situated between 36º 24′ 0″E to 37º 24′ 0″E longitudes and 8º24′0″N to 09^0 0′ 0″N latitudes. The total area of the watershed is about 3385.5km^2. It is characterized by highly rugged topography, dendritic drainage pattern, and tropical to sub-tropical climate condition. Elevation of the area varies from 1300 to 3100 m.a.s.l.

From the long term mean monthly rainfall data, annual precipitation of the catchment is calculated as 1715 mm/ year. The PET value obtained by Penman method is estimated to be 1059.1 mm/yr. AET obtained from Turc and soil-water balance methods are 717mm/yr. and 860mm/yr., respectively.

The annual groundwater recharge estimated from water balance and chloride mass balance methods were 481mm and 204mm respectively. The wetSpass model have simulated the average annual long-term groundwater recharge, actual evapotranspiration and surface runoff in the catchment. The results are found to be 333.5 mm/ year, 908.2mm/ year and 473.3 mm/year respectively.

Lithologic units in the catchment include, granite, Quaternary sediment (Alluvial and Eluvium), Tertiary volcanics (Lower, Middle and Upper basalt, Lower and Upper Silicics, Trachyte flows and plugs) and Mesozoic Sedimentary rocks (Getema and Wama sandstone). Tertiary volcanic rocks are the most extensive lithology in the study area.

Based on qualitative and quantitative analysis of aquifer/aquitard characteristics, the basin is categorized in to moderately productive porous aquifers, moderately productive fissured aquifers, moderately productive mixed porous and fissured permeability aquifers, low productive fissured crystalline rock and aquitards. The fractured and weathered volcanic rocks are the main water bearing unit in the catchment. From the existing borehole data, the higher values of discharge, hydraulic conductivity and transmissivity zones are mapped at or near fractured regions.

Water flows from surrounding highland to the discharge areas following low hydraulic gradient and regional groundwater flow is generally toward the southwestern direction.

The hydrochemical analysis result shows that Ca and HCO_3 are dominant cation and anion, respectively. Based on graphical plots, the major water type found in the area is Ca-HCO_3 and Ca-Na/Mg-HCO_3 with low TDS and EC value in highland areas (recharge zone) and Na-Ca/Mg-HCO_3 with relative high TDS and EC value compared with the recharge area. Most of the water samples quality result shows the area is suitable for domestic and irrigation purpose.

Key words: Groundwater potential, Hydrochemistry, Wama catchment, Water quality, WetSpass

TABLE OF CONTENTS

CONTENTS **PAGE**

LIST OF FIGURES

LIST OF TABLES

LIST OF ANNEXES

CHAPTER ONE

INTRODUCTION

1.1 Background

Water is the main source of life on Earth and is abundantly supplied by nature. This natural resource is used for irrigation, industries, domestic, agriculture, and plant growth. Although fresh water is one of the limited resources, its demand is increasing as a result of an increase in population growth and modern civilization all over the world.

In order to use large scale development, it is essential to have a reliable estimate of groundwater potential. The largest amount of water on Earth (97.2 %) is contained in the oceans and seas as a saline or salty water but only small amount of it (2.8 %) exists as fresh water on land. This fresh water found on land is distributed as ice caps and glaciers (76.43 %), groundwater and soil moisture (21.96 %), fresh-water lakes (0.32%), saline-lakes (0.29 %) and very small amount of it as a streams channel (0.004 %) (Fetter, 2001).

The demand for groundwater in the catchment area is increasing at an alarming rate with the fast growth of population. Climatic change which affects the components of hydrologic cycle has greatly resulted in lowering of water table, which also enhance demand of water supply.

To manage the resource in a more sustainable manner, knowing the spatial distribution and assessing of groundwater resource is of vital importance. This activity increases the chance of planning productive ground water development activities which is used for potable water supply and can also used for agricultural activities.

The study area hosts rural community whose life is based on poorly developed farming practices. As planned in the second growth and transformation plan (GTP II) of Ethiopia, all farmers have to use small and medium scale irrigation to escape out rain fed agricultural system. However, this can be achieved through proper groundwater development which in turn requires good understanding of hydrogeological system that determines and controls the water resource potential. Therefore, groundwater resource studies on the availability, sustainability and quality of the resource is very important for utilization of the resource.

1.2 Statement of the problem

There is rising of population number in and around the catchment which in turn requires adequate quantity and quality of water. Currently, in addition to large scale irrigation of sugar cane plantation for Wama, there is newly irrigation scheme of earth dam now on construction progress nearby Wama river confluence.

In addition to this, Diga dam from which population of Nekemte town (part of the study area) and its surrounding have been using water for domestic and other purpose is now about to finish its service because of sedimentation and high evaporation rate. Due to this, substantial part of the area's water supply comes from groundwater has taken great attention. Despite water requirement is increasing very rapidly with the growth of human population and irrigation in the area, there is no significant research conducted to know the groundwater resources.

On the basis of this concept, this study is proposed to give some detail picture on groundwater characteristics by applying hydrometeorological, hydrogeological and hydrogeochemical methods to come up with reasonable result with respect to the potentialities of the resource.

1.3 Research objectives

1.3.1 General Objective

The main objective of the thesis is to assess the groundwater resource potential of the Wama catchment.

1.3.2 Specific objectives

The specific objectives of the research include the following.

- To estimate groundwater recharge and major hydrologic components involving in the catchment.
- To determine aquifer productivity zone based on hydraulic characteristics, and produce hydrogeological map of the catchment area.
- To differentiate recharge and discharge areas, and to determine ground water flow direction.
- To assess the water quality from domestic and agricultural point of view.

1.4 Previous work

There is no detail work done on groundwater potential assessment to mention in the study area. From hydrogeological point of view, the region has not been well studied except some limited regional and localized studies by private companies and town water supply, only for locating borehole sites. Otherwise, none of these studies shows groundwater potential of the catchment by applying quantitative and qualitative computation of the most important hydrogeologic parameters.

One of the regional hydrogeological studies, which include the Wama catchment is that of Chernet (1993) as part of hydrogeology of Ethiopia and water resource development estimate the annual groundwater recharge and categorized the country into four recharge zone. Since this is a small-scale representation of the regional recharge conditions the author envisaged that there is a greater amount of direct recharge from the rainfall in the highlands and a lesser amount in the lowlands. In this manner, the area in the vicinity of study area has a recharge of 150-250mm/yr. Actually, this estimation was applied to get an insight about the amount of recharge in the regional context and estimated value may be modified depending on the nature of study area.

Water Work Design and Supervision Enterprise (WWDSE, 2007) has made feasibility studies on Arjo-Didessa irrigation project through hydrogeologic investigation. During study the annual mean rainfall calculated by Arithmetic is 1453mm. The study has computed evapotranspiration using Turc method and obtained 944.6mm/yr. The annual groundwater recharge estimated by applying both base flow separation and water balance technique was 196.6mm and 297.5mm respectively. Many boreholes drilled around dam site with maximum depth of 92m revealed that fresh fractured and weathered trachyte basalt dominate the investigated area.

GSE (2014) produced hydrogeological and geological map of Arjo area at scale of 1:250,000. This study confirmed the presence of different rock unit (metamorphic, sedimentary, volcanic and recent deposit) in the area. The annual rainfall was estimated using arithmetic method and obtained value is 1848 mm.

The geology of Nekemte area (NC 37- 9) is compiled by (Solomon Gera and Mulugeta Hailemariam, 2000). Detailed geologic description is forwarded by this work. The geological map of Nekemte area is presented by (GSE, 2003) at 1:250,000 scale.

Apart from these, borehole completion reports performed by water resources offices of East Wollega Zone reports on water supply project proposals of rural communities of the same zones are worth mentioning.

In general, published researches and scientific exercises could not be found in the catchment that cause a lack in detail and sub-detail information.

1.5. Methodology and Materials

1.5.1 Methodology

In order to achieve the objectives of the research, the following methods were used.

Desk study: Prior to field work published and unpublished materials were collected and reviewed in order to get the detailed awareness on geology, hydrogeology, and hydrochemistry of the area. This includes water resources study reports, water points completion reports (borehole, hand dug wells, springs, pump test data, geophysical reports or any other literature regarding the catchment area and its surrounding.)

It also includes the collection of hydrometeorological data, regional geologic map, obtaining of SRTM (Shuttle Rader Topography Mission) derived DEM (30-m resolution) from United State Geological Survey (USGS) website free of charge, collection of scanned topographic maps of the area (purchased from Ethiopian Mapping Agency) with appropriate scale, and soil map and land use land cover map of the area from FAO.

Meteorological data were collected from National Meteorological Agency (NMA) from 15 stations having 20 to 33 years records. The main objective of this data is to determine evapotranspiration whose result is further used to calculate water balance of the catchment which in turn help for developing and managing its water resource through determining recharge.

During field work: At this stage, water samples for chemical analysis were collected. In doing this, systematic sampling of representative water samples of different water sources (deep wells, shallow wells, hand dug wells, and springs) in the study area have been collected. During sampling, the sample bottles were carefully cleaned with distilled water and have been washed in the field by the water to be sampled. Sampling from some wells was carried out right on borehole using leakage but for others it is just near the well head before entering the reservoir.

Some properties of water, such as in situ measurement of pH, temperature and electrical conductivity (EC) have been done in the field with the help of (pH, EC and Temp.) meter. In-situ measurement was conducted due to change of the physical properties of water which is time sensitive until it reaches in the laboratory for analysis. In order to fill the gap where there were data scarcity, water samples are taken from 17 water point of which eleven deep wells, four spring samples and two hand dug well samples were collected. The samples were sent to laboratory of Oromia Water and Energy Resource Development Bureau for analysis.

Field photographs are captured for documentation and interpretation. Borehole data and inventoried water points were collected from regional water bureaus, NGO's and private drilling companies. Groundwater level was determined from elevation of boreholes and its static water level, and was used to produce groundwater depth map that is used as one of input parameter in the WetSpass model.

After field work: Finally, data from literature review of geological, hydrogeological and hydrochemical as well as field work were combined. After a complete laboratory chemical analysis of collected water samples, the physico-chemical behavior of the groundwater and its usage for drinking, agriculture and industrial purpose were determined by comparing with local and international standards.

The spatially distributed water balance model, WetSpass-M 1.3 (2016, released date) has been used in estimation of the amount of recharge for the catchment. As the model requires data as a map prepared by the required format, all the required physical and hydro metrological data sets have been prepared to the appropriate format.

Based on the qualitative and the very limited quantitative data (the yield of springs and boreholes) and geological description, classification of the hydrogeologic units with their areal extent has been made.

Generally, result obtained by different study approaches throughout the thesis work were organized, analyzed and interpreted using appropriate software such as, ArcGIS 10.3, Aquachem 2014.2, Surfer 15, Global Mapper 12 and spatially distributed water balance model (WetSpass-M 1.3) and the results are presented by tables and maps.

1.5.2 Materials

During field and throughout the phases of the research work, different relevant software and material were used including instrumentation used in the laboratory analysis. Materials used during field work are topographic map of the area, Global Positioning System (GPS) and Compass, bottles for collecting water samples for laboratory analysis, (pH, Temperature, and Electrical Conductivity (EC)) meter.

The analytical method and instrumentation used in physico-chemical analyses of the collected water samples are listed below in (Table 1.1)

Table 1.1 Analytical method and instrumentation used.

Parameter	**Analytical method and instrumentation used**
pH, TDS, and T	Potentiometric, pH meter (model 107),TDS and Temperature meter
Electrical conductivity (EC)	Potentiometric method
Calcium (Ca^{2+})	Titration/volumetric method using EDTA solution (0.01M), sodium hydroxide (IN) and murexide indicator.
Magnesium (Mg^{2+})	Calculation method using the volume of EDTA used in Determination of calcium and total hardness.
Bicarbonate(HCO_3)	Titration method using hydrochloric acid (0.1N), methyl orange indicator, phenolphthalein indicator and sodium Carbonate (0.1N).
Chloride (Cl^-)	Titration method/volumetric method using silver nitrate (0.02N) and potassium chromate (5%)
Sulphate (SO_4^{2-})	DR 5000 spectrophotometer method using (APHA 1992) Standard procedure.
Sodium (Na^+) and Potassium (K^+)	Atomic absorption spectrophotometer (AAS) method, model 210 VGP using (APHA 1992) standard procedure, Sodium at 589nm and potassium at 766.5nm.

CHAPTER TWO

GENERAL OVERVIEW OF THE STUDY AREA

2.1 Location and Accessibility

The study area, Wama Catchement, which is the major tributary of Didessa Sub-basin, is bounded between 36º 24′ 0″E to 37º 24′ 0″E longitudes and 8º24′0″N to 09^{0} 0′ 0″N latitude, and is located in the East Wollega Zone of Oromia region, Western Ethiopia. It is situated at about 281km west of Addis Ababa and it includes major parts of Nekemte town which is the capital city of East Wollega Zone. The watershed, which has a total area of 3385.5km^2, is accessible through Addis Ababa → Ambo → Nekemte asphalt road. Weather and seasonal gravel roads which connects different town of woreda are also available in the catchment.

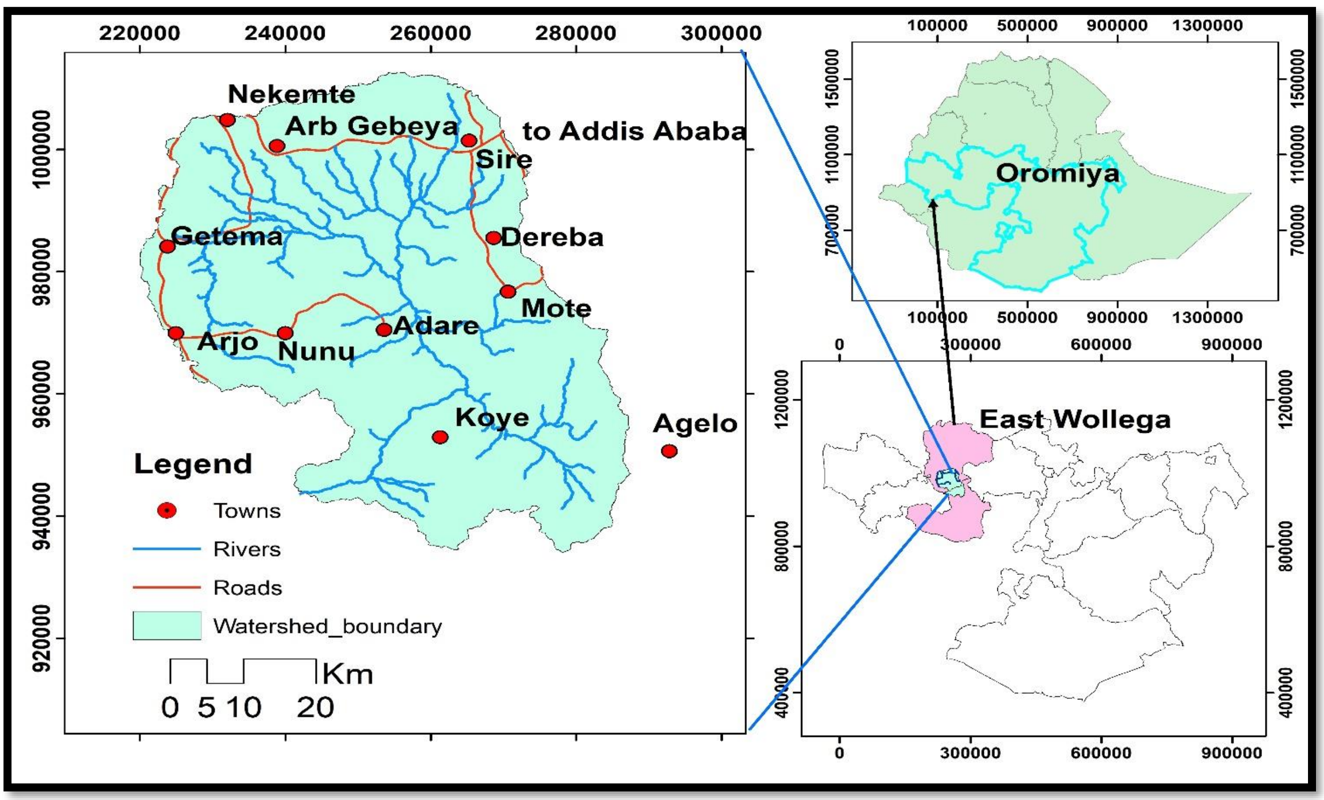


Figure 2.1 Location map of the study area

2.2 Climate

Climate of Wama catchment varies from tropical to subtropical climatic condition. The variation is largely a function of altitude and vegetation cover.

The mean annual rainfall is from 1,040.6 mm/year around Agelo area to 2,480 mm/year around Dereba. The catchment is characterized by unimodal rainfall pattern and rainy season is from April to October (Figure 2.2). On the basis of rainfall distribution, climate of the study area can be categorized into two broad seasons; the dry season (winter) and the wet season (summer) with autumn and spring receiving a small amount of rain. The catchment has annual mean temperature of 19.23^{O}C. The maximum temperature was recorded in the months of March and April while minimum temperature was recorded in the month of September. Generally, study area has high temperature during dry season and low temperature in rainy season.

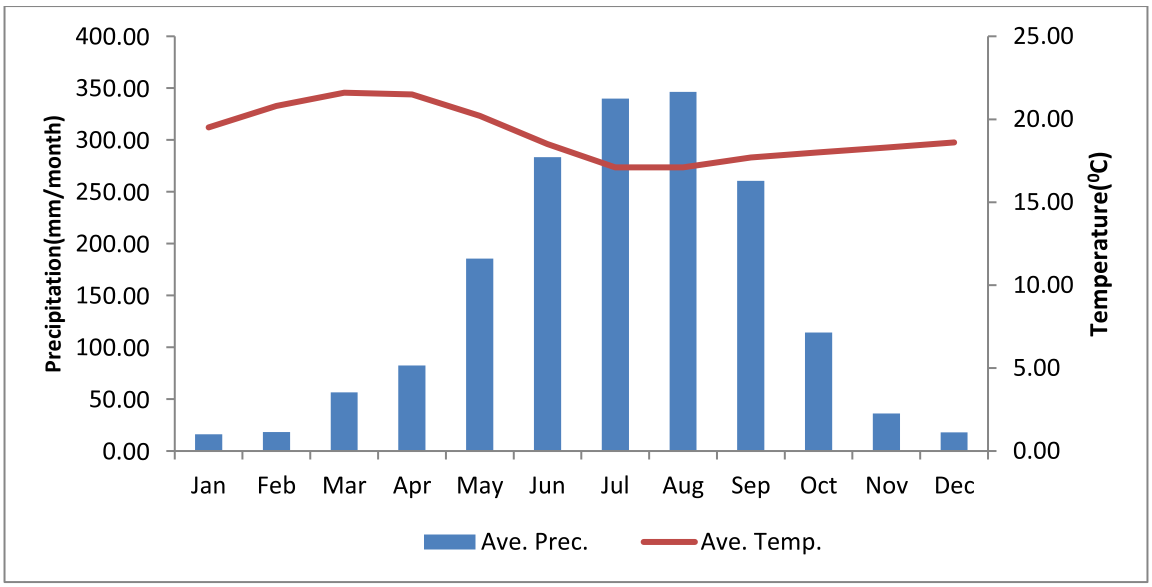


Figure 2.2 Monthly temperature and rainfall of the catchment.

2.3. Physiography

The present geomorphology of the area is the result of volcano-tectonic activities that occurred in the past with slight modification by recent deposition in low lying area. The catchment is known by its extensive tertiary volcanism which gave rise to the peculiar geomorphology of volcanic environments to the area. Such that it is mountainous, highly rugged and dissected topography with steep slope while the valley floor with flat to gentle slopes characterizes the lower part of the catchment particularly around Wama Adare area and adjacent to the area, Arjo Didessa. As the result a number of streams emerged from either side of the bisected plateau feed the Wama River.

Generally, study area is rugged terrain with deeply cut and dissected morphology with undulating topography and flat plain with variable slopes. The elevation of the study area is varying from around 1,300 m.a.s.l. to more than 3,100 m.a.s.l.

In general study area consists of the following land forms:

• Mountainous volcanic plateau with uneven surface.

• Low plateau with moderate to high relief hills and flat top ridge

• Plains occupied by recent deposits and undulating land forms.

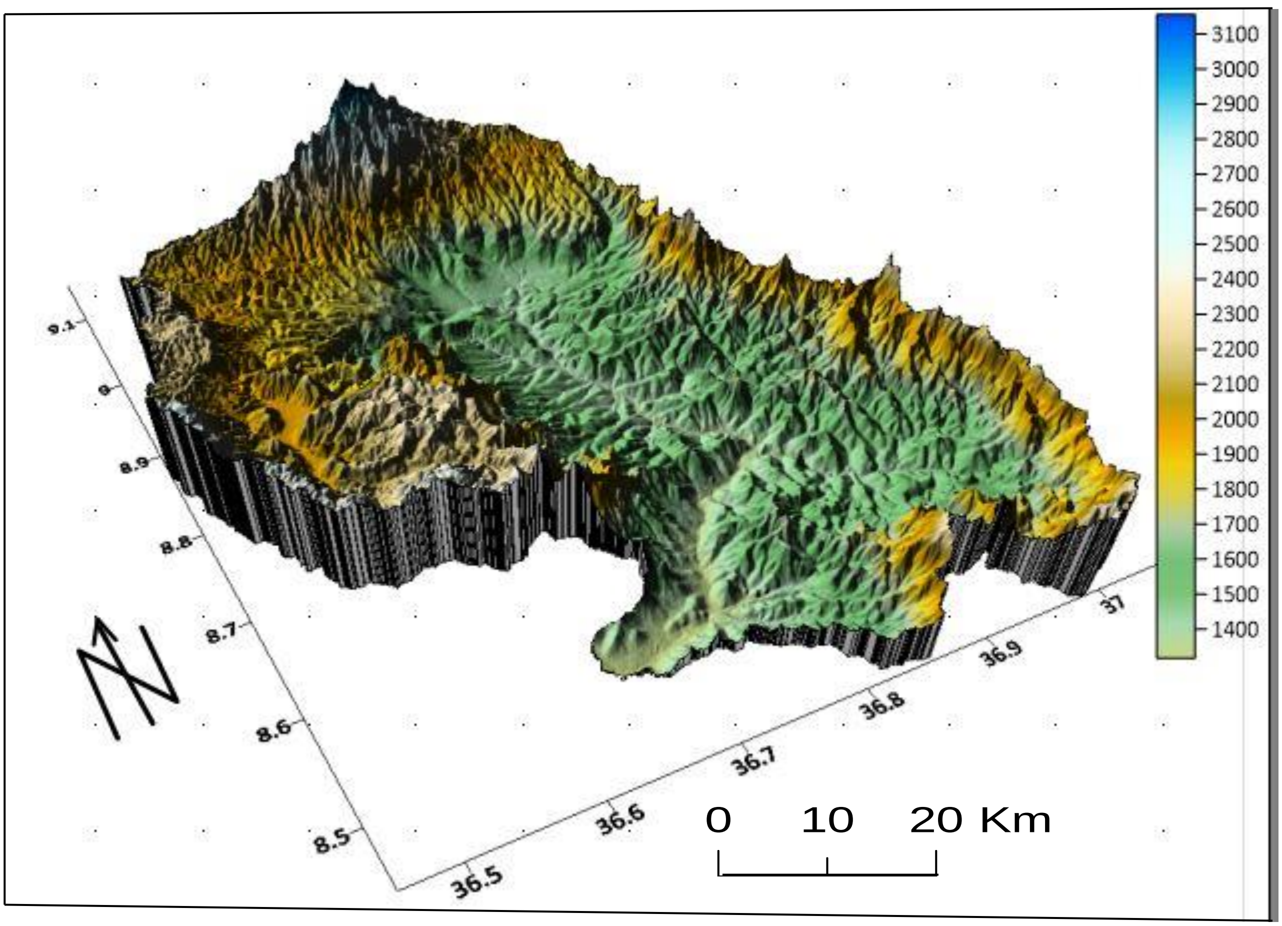


Figure 2.3 3D Physiographic map of the study area

2.4 Drainage

Drainage is a reflection of slope, relief, geology, geomorphology and structures. It is the spatial arrangement of streams and is, in general, very characteristic of rock structure and lithology. From the northern, Negeso and Indris, and another river from the southern are some of the major tributaries which drain to the southwest and form Wama River, following the regional topography.

Wama catchment is extensive drainage system arising from mountain Komto, Getema-Arjo highlands, Mote, Atnango and Koma rigde. The streams networks of study area commonly show dense dendritic drainage pattern in the upstream areas and sub parallel pattern in the down course indicating homogeneous and mountainous relief with more dissected nature. Tributaries feeding Wama River have flow in three major trends: NE-SW, N-S, and NW -SE. Drainage is relatively denser in northern and northwestern part of the catchment area.

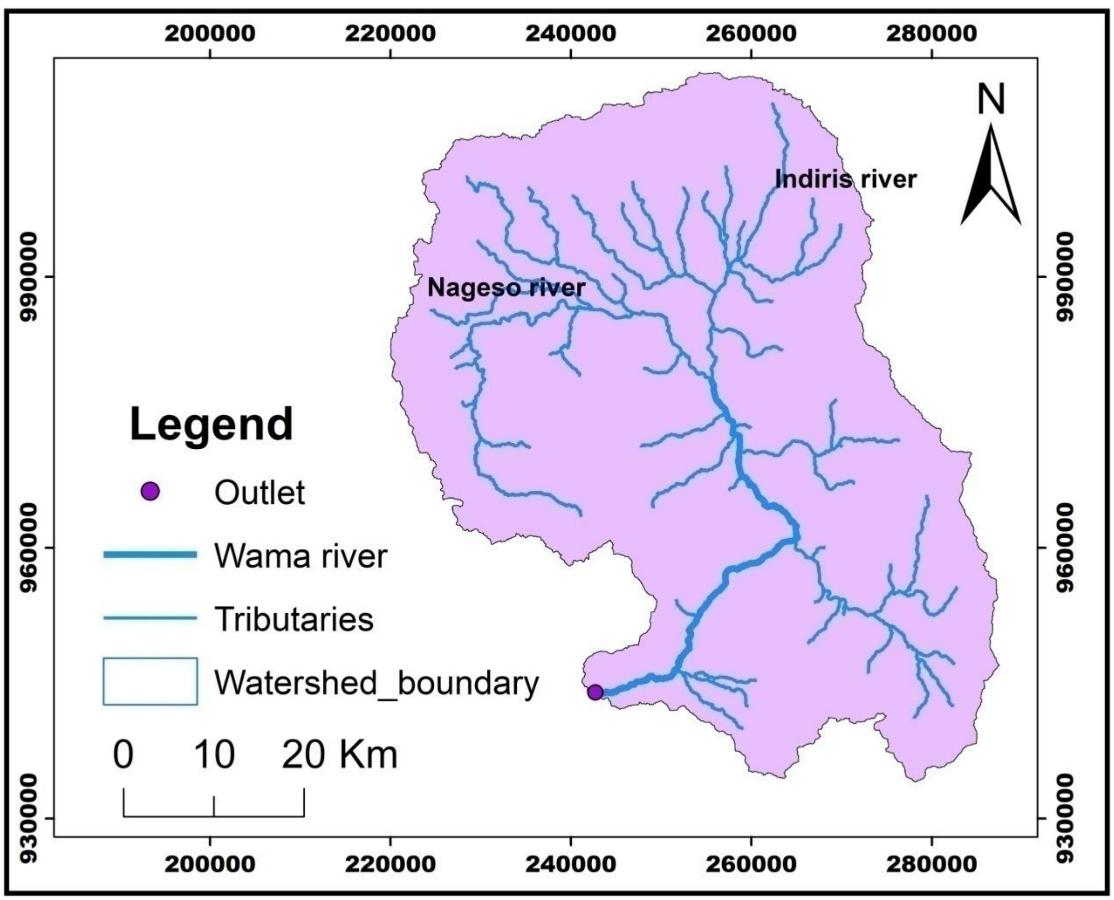


Figure 2.4 Drainage map of study area

2.5 Soil

The most governing factor affecting the water holding capacity, infiltration and runoff characteristics of soils is texture. Soil type distribution and characteristics depends on variation in geology, topographic setting, slope gradient, climatic conditions, land use land cover and agricultural practices. Soils derived from coarse grained rocks inherit a coarse texture, whereas those derived from fine grained rocks are characterized by a fine texture. This indicates that soils resemble their origin.

Soil stores rainwater in its pores before it infiltrates to greater depths and recharges the aquifer system. Water stored in thin soils evaporated directly before feeding the aquifer. Soil water that is stored in thick layers either join saturated zone or absorbed by vegetation roots and then transpires to atmosphere. The ability of soil to store and transport water is controlled by soil texture, soil structure and soil moisture content. Therefore, amount of evapotranispiration is different for every soil type. Deeper soil has a larger soil moisture reserve than thinner soil, which can supply more water to evaporate. Hence, soil has sound role in determining hydrogeology of the area.

According to the soil map adopted from food and agricultural organization, study area is covered by two types of soil texture called loam and clay. Along the river flood plains (i.e., Wama and its main tributaries Indiris, and Nageso), clay is the dominant texture. The left parts of the catchment are covered by loam. The reality of this texture classification is questionable. This depicting that there is no detail scientific study conducted in the catchment.

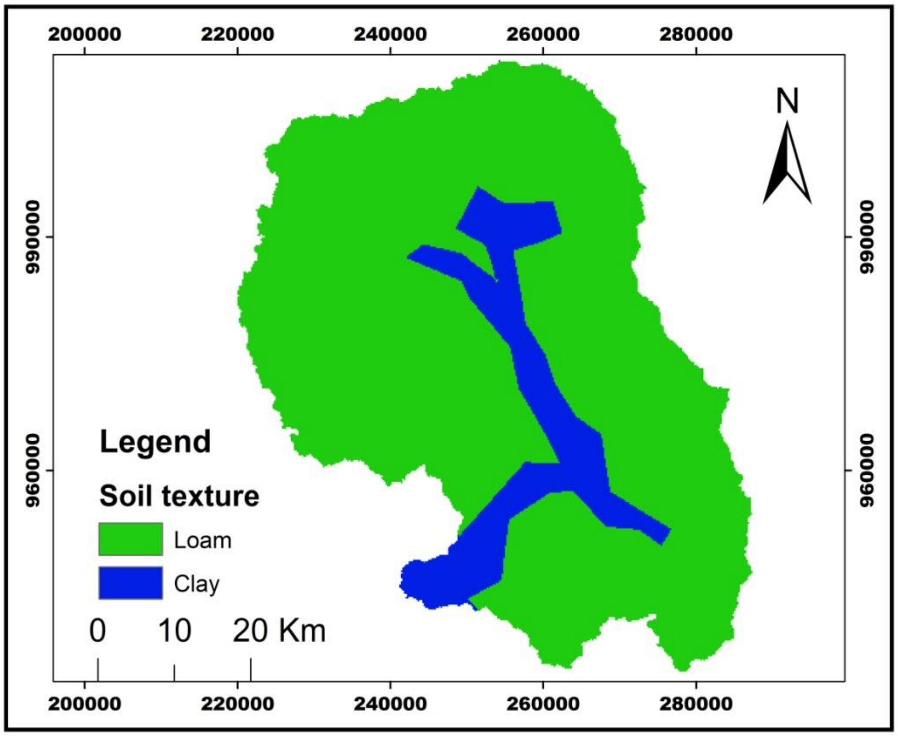


Figure 2.5 Soil map of the study area (FAO, 2018)

2.6. Land use/Land cover (LULC)

Majority of the catchment is generally used for agricultural purpose, including perennial and seasonal crops plantation, residence and grazing land.

The major farming system prevailed around the catchment is the mixed farming system of annual and perennial crop production and livestock husbandry. Major crops grown include maize, sorghum, Teff, coffee, barley, peas and bean. All crops are grown under rain fed conditions, mostly in one main season (May to October). The Arjo-Didessa and Wama irrigation for sugar factory is under perennial crop cover which is dominated by sugar cane plantation. The irrigation uses high amount of water from Wama River throughout the year except the rainy months. Farmers commonly use fertilizers of different types (DIAP and UREA) from farm to farm. Herbicide, Insecticides & fungicides are also another popular chemical applied to the crops.

Vegetation cover play important role in minimizing water loss through surface run off and increasing infiltration of water to soil and to ground water table. Major natural vegetations found in the catchment are bushy wood land, shrubs, open woodland, natural forest, coffee, forest plantation, woodland and Elephant grasses. Riverine trees and vegetations are also dominant along the course of main rivers; Indris, Nageso and Wama. Even though the area was highly vegetated during the past, currently it is sparsely vegetated, due to increasing number of populations. Along with population number, deforestation increases because of the high demand for wood, charcoal and construction materials.

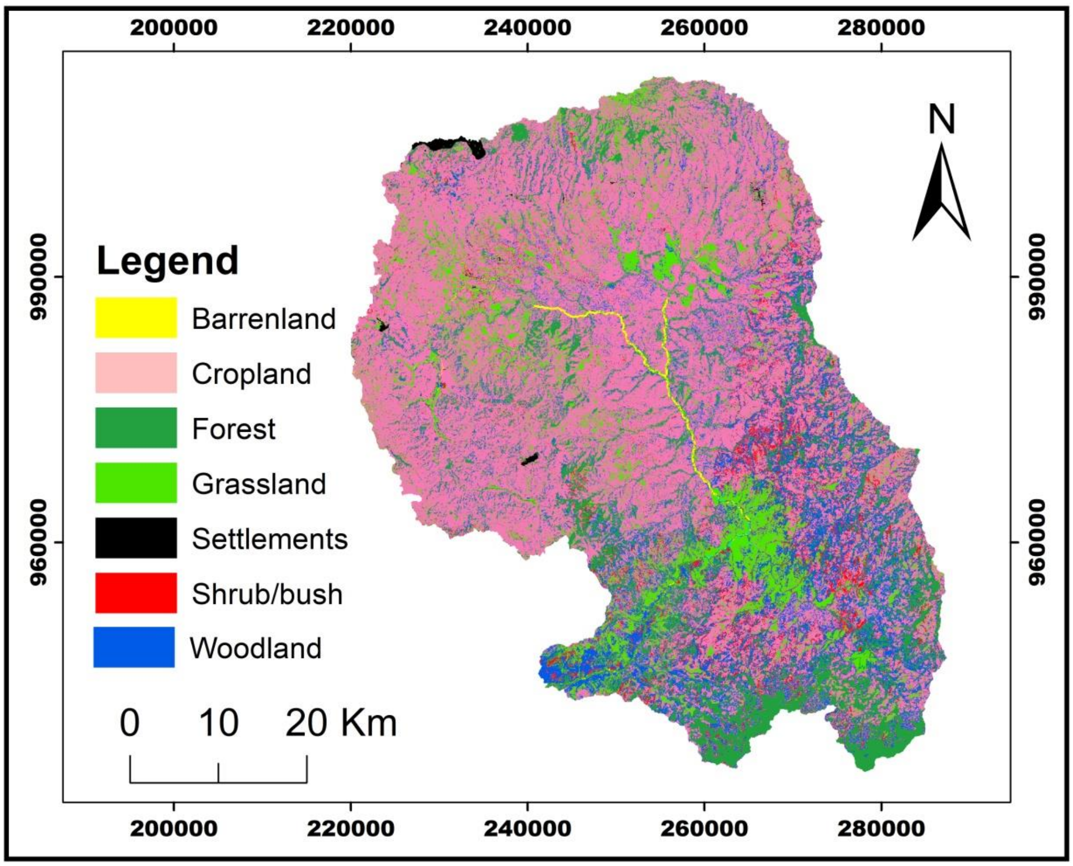


Figure 2.6 Land use/Land cover map of the study area (FAO, 2018)

CHAPTER THREE

GEOLOGY

3.1 Regional geology

The area is situated in the Western Ethiopian plateau and underlain mainly by Eocene-Pleistocene (Solomon, 2000) volcanic rocks and small portion of Mesozoic sedimentary and metamorphic basement rocks. It is contained in the Abay basin, major tributary of Didessa Sub-basin, particularly the Wama river catchment. Geology of Western Ethiopia has complex tectonic history starting from Precambrian and Phanerozoic sedimentation to tertiary volcanic activity resulted in exposure of metamorphic, sedimentary and volcanic rocks. The Western basement terrain is considered to contain lithological components common to both the Arabian-Nubian shield (ANS) and Mozambique Belt (MB) (Kazmin et al., 1978, 1979). Recent studies have divides tectonic evolution of the Western Ethiopian shield into Gore-Gambella area which comprise Birbir, Baro and Geba domains (Ayalew, 1997) as well as Tulu Dimtu belt that comprises five domains from East to West; Didessa, Kemashi, Dengi, Sirkole and Daka domains (Allen and Tadesse, 2003).

The Didessa domain extends from approximately 5km East of Didessa River in Wollega area covering about 70km to 25km west of Gimbi town. Didessa domain is characterized by moderate grade gneiss, intruded by Neoproterozoic intrusive rocks like poly deformed gabbroic and granitoids bodies and post-kinematic mafic and felsic plutons (Allen and Tadesse, 2003). The western Precambrian basement is overlain either by Paleozoic-Mesozoic sandstone or tertiary volcanic product. Sandstone is supposed to be southwestern extension of central Ethiopian (Abbay) sedimentary succession (Geological Survey of Ethiopia, 2000). The tertiary volcanics covering western Ethiopia is commonly trap series which constitute majority of the Ethiopian plateaus. The Ethiopian volcanic plateau is divided into west and southeast plateau.

However, the regional and wide E-W oriented rift transversal structure called Addis Ababa Nekemte tectonic line (Abbate et al., 2015) or Yerer-Tulu Wollel Volcano Tectonic Lineament (YTVL) (Abebe et al., 1998) has divided the western plateau volcanics into Northwestern and Southwestern Plateau. The southwestern plateau, of which the study area is part, is characterized by thicker volcanic rock.

This volcanic sequence is resting directly on the crystalline basement or rarely, on the Eocene basalts. The succession of this volcanic begins with a hundred meters of mildly alkaline basalts (Omo Basalts), capped by a thick unit, up to 1,000 m, of rhyolite, acidic tuffs, and subordinate. Jimma volcanic comprises trachyte basalts and rhyolite which covers most part of the southwestern Ethiopian plateau. The Wollega Basalts resting on the basement or on the tilted Omo Basalts and Jima Volcanics is consist of predominant columnar alkaline basalt flows interbedded, particularly in the upper portion, with acidic tuff and loose fluvial deposits.

The sedimentary rocks of the catchment area are the southwestern extension of the West central Ethiopian sedimentary succession. These rocks are exposed around Beda Sire, Fungan Sire localities and Finca'a valley (Nekemte map sheet) (Solomon Gera and Mulugeta, 2000). It consists of thick lower sandstone succession that is overlain by thin remnants of transitional beds. The late Paleozoic and Mesozoic sediments are uncomfortably overlain by thick massive flood lavas, mainly of basalt; which is classified as Trap series by (Mohr, 1962).

These rocks cover the northwestern plateau. The volcanic rocks in the catchment area are the Southern extension of these rocks. These volcanic rocks are generally post - Oligocene- Quaternary (Berhe,et al., 1987; Conticelli et,al, 1999) which have stratified nature, built up of various succession of flood basalts. Quaternary volcanic activities with the formation of lava flow, trachyte plugs and scorea cones are also recorded (Mengesha, et al., 1996).

3.2 Local Geology and Stratigraphy

The geology of the Wama catchment is constituted by the rocks ranging in age from Precambrian to recent time (GSE, 2014). It includes metamorphic, sedimentary, igneous and recent deposit (Figure 3.1) and is described below. Even though it includes a variety of rocks, volcanic rocks are the most extensive lithology in the study area.

Basic regional geology and field checking have indicated the occurrence of three major types of rocks in the catchment area. These are Precambrian crystalline basement rocks, Mesozoic sedimentary rocks, Tertiary volcanic rocks and associated plugs and Quaternary soils.

3.2.1 The Precambrian Basement Rock

3.2.1.1 Granite (Circular to sub-circular)

The deformed granitoid are sub-circular to elliptical in shape and which is located about 5 km south of Chewaka settlement. It forms northwesterly elongated body of about 48 km and having moderate to high relief. Granite, which represents the dominant part of the Demeksa granitoid, is grayish to reddish pink, medium- to coarse-grained and in equigranular. This granitoid is situated in the central part of the area and it is pink to grayish pink in color. The total area coverage of this unit is 137.5 km^2. It covers about 4.06% of the study area.

3.2.2 Mesozoic Sedimentary Rock

The Mesozoic rocks of study area are comprised of continental clastic sediments represented by Getema Sediments and Wama Sandstones. In the vicinity of study area particularly around Gute and Sire (Solomon and Mulgeta, 2000) discussed the presence of both lower and upper sandstone that have thickness of 470 m and 300 m respectively. This unit consists of rock fragments containing mainly sandstone and siltstone of the Lower sandstone and laid directly on basement.

Around Gute and Sire it also unconformably underlain by the Paleozoic sandstone without clear unconformity (Solomon and Mulgeta, 2000). Getema sediments which covers about 8.5km2 (0.25%) of the area unconformably overlie the Precambrian rocks, and underlie the Tertiary volcanics, which attains a maximum thickness of 250m. It is dominantly sandstone with intercalations of siltstone, conglomerate, mudstone, clay stone and shale. Good exposure of these rocks exposed along Aleltu stream and Getema-Ambelta road cut exposure.

Another sandstone unit is Wama Sandstone named after Wama River, which is the major tributary of Didessa River along which sandstone is clearly exposed. Wama Sandstone is comprised of commonly red and pinkish red with minor grayish yellow and white sandstone with minor conglomeratic interbeds, which is attaining a maximum thickness of 100 m (GSE, 2014). It covers about 179.4km^2 (5.3%) of the study area.

Regionally Getema sediments may be correlatable with the Enticho sandstone whereas Wama sandstone with the Adigrat Sandstone of Northern Ethiopia (Kazmin, 1975).

Figure 3.1 Wama river from which the Wama sandstone is derived

3.2.3 Tertiary Volcanic Rocks

Tertiary volcanic rocks cover nearly 83% of the catchment area. These rocks cover wide range of the catchment area. Northern, North eastern, Eastern; southeastern, south western and the southern part of the catchment is extensively covered by these rocks (Figure 3.7). There are seven mapable units, which are categorized on the basis of Stratigraphy and mode of occurrence. These are:

3.2.3.1 Lower basalt (Tlb)

This unit consists of Lower basalt which described as (Tlb) with its respective localities in geologic map of the area. It is forms gentle slope and steep cliffs and covers wide portion of the catchment area which is estimated to be 1559.7 km^2 (46.07%) of the total mapped area and exposed in Western ,Northwestern, Northern and Southern direction of the catchment. This unit rests unconformably either on the basement or Mesozoic sedimentary successions **(**Solomon, 2000). It rests on Mesozoic sedimentary around Sire area. In the catchment, it is visible around Arjo, Limu, Jibat, and Gibe localities.

3.2.3.2 Middle basalt (Tamb)

This unit occupies a higher topography and characteristically forming flat top ridges and plateau. The flow attains an average thickness of 50 to 60 m, but thicker to the west, which attains a maximum thickness of 175 m around Meko area (Tadesse Alemu and Yonas Hageresalam, 2005).

In the southwestern part of the catchment area, around Arjo with areal coverage of 282.35km^2 (8.34%), this unit is exposed. The top part of the flow is highly weathered and laterized. At places, especially on the Dega-Meko road soils measured in thickness up to 1 m are seen. The basalt is gray to grayish black and aphanitic to locally amygdaloidal.

3.2.3..3 Upper basalt (Tub)

This unit crop out as Northwest trending discontinuous dome-like ridges and hills, which locally formed cones and isolated peaks. This The rock is light gray to grayish black and varying in texture from aphanitic to phyric, but locally porphyritic. It is columnar and platy jointed. This unit covers small part of the Northern catchment area and it is exposed around Arjo, Limu, and Jibat. It covers a total area of 566.4km^2 (16.73%) in the catchment.

3.2.3.4 Trachyte flows and plugs

This rock unit is evenly distributed at southern, eastern, and central part of the study area by having the physical properties of sub circular to elongated and dome like shape. At Mote area, it shows highly weathered and slightly fractured and porphyritic properties, but around the road Mote to Bilo, massive trachyte flow forming dome shape. The flows are light gray to grayish white and pinkish gray. The borehole data shows that this unit have yield of 1l/s. The total area coverage of this unit is 85km^2 (2.5%). Depending on quantitative and qualitative properties, hydro geologically it is classified as low productive fracture aquifer.

3.2.3.5 Upper trachyte flow and pyroclastic rocks (Tup)

The trachyte and pyroclastic rocks of the upper volcanics cover 83km^2 (2.45%) of the total mapped area. It is exposed in the northern part of the study area as lenses on the ridge sides between the Lower and Upper basalts in many localities, such as Biloyi, Kara, and Jobira. (Solomon etal., 2000) described that the unit attains a maximum thickness of 500 m around Jobira area. Generally, this unit consists of trachyte flow, pyroclastic rocks of various types such as ignimbrite, ash fall and tuff, volcanic breccias and lahar, and plagioclase phyric- basalt.

The trachyte flow is light, medium grained, porphyritic and shows flow layering. Some minerals occur as microphenocrysts within cryptocrystalline and glassy matrix. The ignimbrite is light gray to greenish gray, medium grained and compact. It is composed of plagioclase, and rock fragments.

3.2.3.6 Lower silicics (Tlls)

This unit is represented by varying proportions of trachyte, rhyolite and pyroclastic rocks. Either it directly overlies the Gibe group or separating from the underlying Gibe group by deposition of Tertiary sediments (Limu and Boter Becho sediments). It attains a maximum thickness of 350 m at Akote-Gilgel Gibe section and a minimum of 175 m at Limu Seka section (GSE, 2014)

This unit covers an area of 132km^2 which is about 3.9% of the study area. It is exposed in the southern part of the area. It is generally pink to pinkish grey, fine- to medium-grained, weathered and fractured.

3.2.3.7 Upper silicics (Tlus)

The Upper silicics are comprised of dominantly trachyte with subordinate rhyolite and pyroclastics, which formed plateaus and flat top ridges. This unit covers about 102km^2 (3%) of the area and it occurs in the southeastern part of the study area. The thickness ranges from 80 to 100 m, but it attains a maximum thickness of 300 m at Akote-Gilgel Gibe section (GSE, 2014). The trachyte which represents the largest part of the unit is greyish green to greenish grey fresh colour and greyish brown to greyish white weathered color. It is represented by aphanitic and porphyritic varieties.

3.2.4 Quaternary sediments (Qs)

3.2.4.1 Alluvial Deposit

This unit distributedly found in the area but dominantly exposed in the southern and south western part of the study area. From the borehole data and field observation the unit overlies highly productive lower basalt with an average yield of 6.63l/s and middle basalt which is moderate to highly fractured and weathered basalt. It shows reddish brown and black soil, sandy soil and silty soil. From the field inventoried data there is thick alluvial deposit around the so-called village- Silk Amba. Topographically the unit is located at the flat gentle slope, dispersly vegetated and along many perennial rivers, especially Nageso and Wama river. This deposit covers a total area of 61 km$^{2.}$ (1.8%). Considering the qualitative observation, this unit is classified under low productive intergranular aquifer.

3.2.4.2. Elluvium (Qel)

This unit is represented by red to reddish brown soils that are developed from the surrounding basaltic flows. This unit covers a total area of 189.6km^2 (5.6%). The exposure of this soil around Shogle area shows a thickness of 5 to 20 m thick with a general topographic setting of the area is flat undulating, but the spring emerges through thick soil at the deep gorge with a spring yield 0.2l/sec; considering the qualitative and quantitative data, this unit is classified under low productive intergranular aquifer.

3.3 Geologic structures

Structurally, Wama catchment is found in the vicinity of regionally deformed tectonic structure known as Yerer Tullu Wolel volcanic lineament (YTVL). The YTVL is an East–West trending regional structure with a length of 800 km and diameter of 80 km that partly crosses Abbay basin and certainly dividing western Ethiopian plateau into Northwestern and Southwestern. There are two major lineaments in the YTVL zone (Abebe et al., 1998): Didessa Lineament (DL) and Ambo-Butajira Lineament (ABL). These lineaments are deep faults and lineaments that cut across the YTVL and are fed by dykes and aligned volcanic plugs. Within this deformed zone, the lineament known as Ambo fault belt also starts from the western escarpment of the rift and extend further to Wollega (Mengesha et al., 1996).

The other prominent structure in the YTVL is Didessa lineament whose name seems derived from Didessa River, which is the outlet of Wama river, a river under investigation around which many manifestations of the lineament easily observed. Didessa lineament crosses the catchment from SE-NW direction. Some of the local lineaments have aligned parallel to this lineament. The orientation of lineament and spring in the catchment depict that lineament has considerable effect on groundwater. Since the lineament is a kind of deep fault structure, the water circulates at great depth and evolve into high TDS, Na^{2+}, HCO_3^- and SO_4^{2-}. This property of thermal spring indicates pronounced water-rock interaction supplemented by long and wide lineament.

On the other hand, there is agreement between lineament and groundwater flow direction of the catchment. As observed from groundwater depth location in chapter 5, groundwater flow is toward the southwestern similar to lineament which shows the positive effect on regional groundwater flow.

Another geologic structure, columnar joints are among the structures prevailed in the study area**.** The joints observed on volcanic rock out crops are prominent. They act as recharging conduit. There is a columnar joint on basaltic unit (Figure 3.2) around Malaya Nunu (GPS location of X-240117E and Y-970645N, at elevation of 2452m). These are the most widely prevailed structures, but because of vegetation cover they are observed at a few localities. Generally, they act as recharging conduit and the occurrence of many springs especially in steep area may be a result of these joints.

Figure 3.2 Malaya Nunu columnar basalt

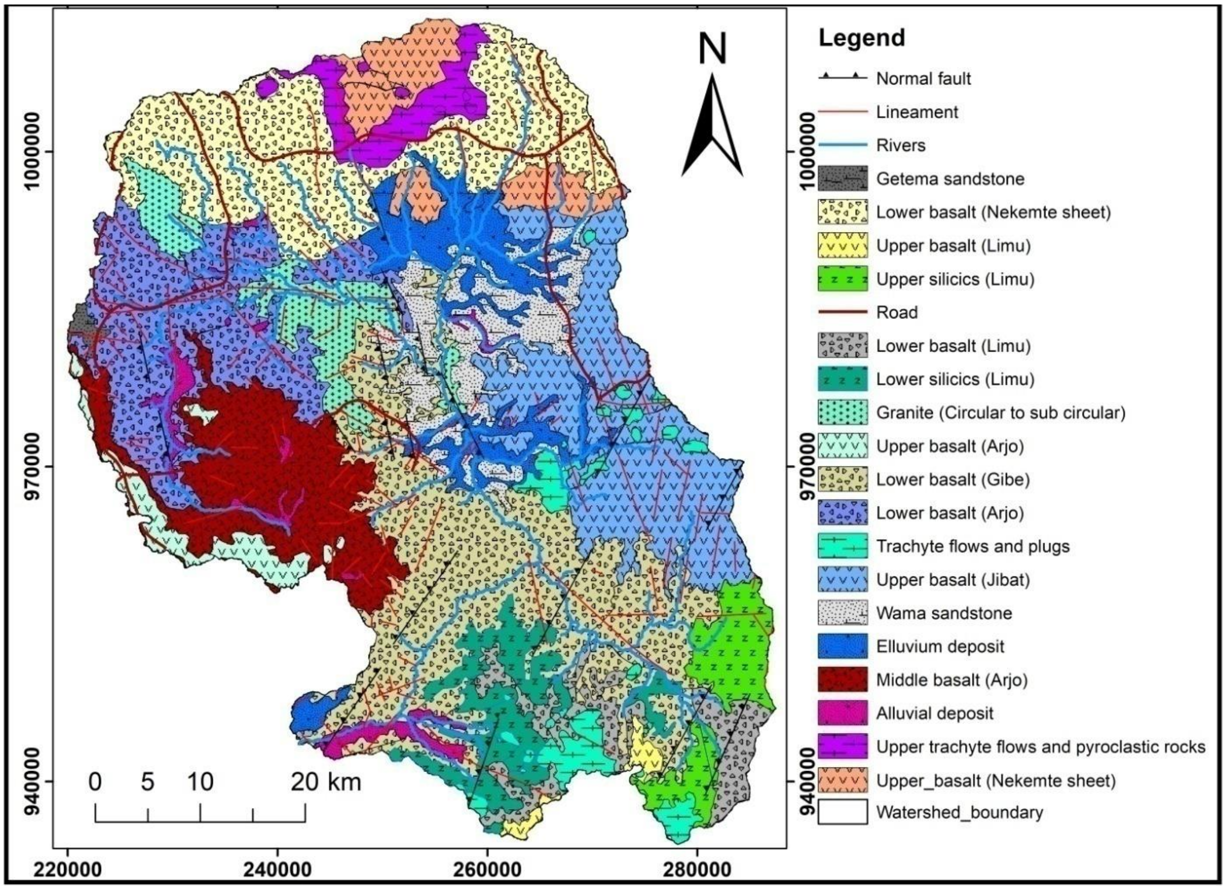


Figure 3.3 Geological map of the study area (Source: Modified from GSE, 2014)

CHAPTER FOUR

HYDROMETEOROLOGY

4.1 General

Hydrometeorology is a science which links hydrology and meteorology. It studies the hydrological cycle which involve processes in the atmosphere and at the earth's surface (Shaw, 1994). The most useful hydrometeorological elements are precipitation, wind speed, evapotranspiration, sunshine hours, humidity, and air temperature. The main objectives of analyzing hydrometeorological data is to determine evapotranspiration whose result is further used to calculate water balance of the catchment which in turn help for developing and managing its water resource through determining recharge.

For the analysis of various components of hydrologic cycle long term meteorological data have been obtained from Ethiopian National Meteorological Agency (ENMA). Totally there are 14 metrological stations within and in the vicinity of the study area. Among them, 6 stations are principal station while remaining are ordinary stations. More information about meteorological data and meteorological station's location is annexed in (Annex 1 and Annex 12 respectively).

4.2 Sunshine

The length of Sunshine hour and intensity varies depending on altitude, cloud, vegetation and variation of seasons which are responsible for absorption, scattering and reflection of incoming solar radiation. Sunshine hour has direct relationship with evapotranspiration. In the study area there are seven stations with available sunshine hour record. The data shows seasonal variation in relation to weather condition. The computed value increases from minimum (3.11) in July to the maximum (9.04) in February. During rainy season atmosphere is usually unclear because of fog and cloud cover so that only little time is available for sunshine to reach surface. As a result, study area gets high sunshine hour in dry season when sky is clear and become low in extreme rainy (Kiremt) months. The area has mean monthly sunshine hour value of 6.37. Available monthly mean sunshine hour is given in (Annex 2).

Table 4.1 Long term mean monthly sunshine hours of the study area.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean	7.48	7.85	7.5	7.49	7.08	6.2	4.7	4.9	6.63	7.7	7.69	7.53	6.37

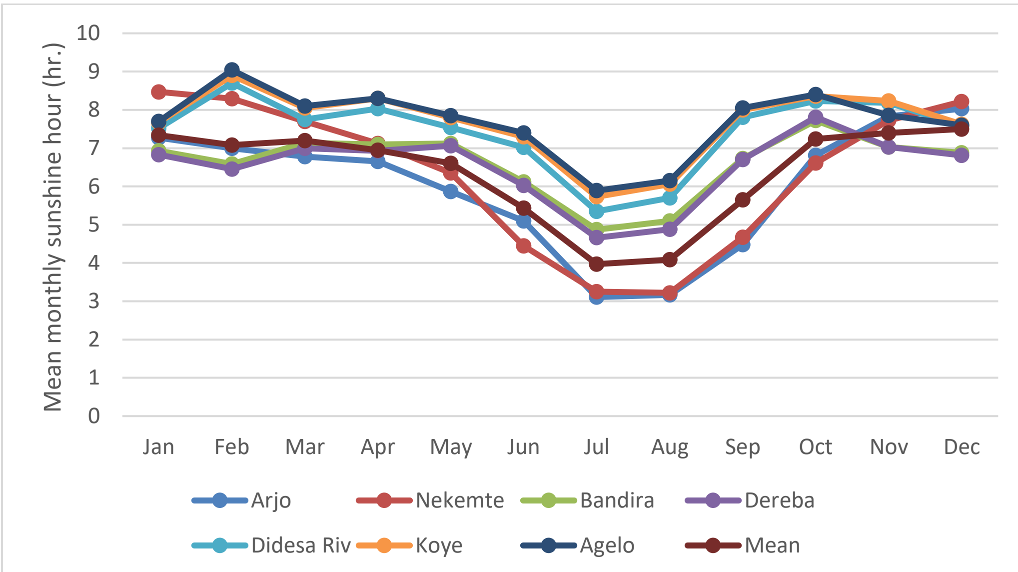


Figure 4.1 Mean monthly sunshine hour for available stations in the study area

4.3 Wind speed

Wind speed is about the fastness and slowness of the air movements controlled by pressure. The movement of air and moisture transfer depends on wind speed and turbulence. The decrease in wind speed results in a decrease in the rate of evaporation because the saturated vapor above the surface could not be removed instantaneously.

The wind speed data measured at height of 2 m above the ground level obtained from six stations (Arjo, Bandira and Dereba, Koye, Agelo and Didessa River) show spatial variation. Higher wind speed is recorded in Arjo and Dereba while Koye show low wind speed record relative to them. This variation is directly linked with the topographic altitude of the stations as Arjo and Dereba are highly elevated area of the catchment and tend to have high speedy wind than the others. The wind speeds in the catchment become high at the beginning of the spring season rain.

This is a usual phenomenon in western region of the country at the early start of rainy season. During this time, moisture carrying wind from different direction commonly the westerly trade wind blows highly toward the study area to bring the spring rainfall. It is these months when catchment experience its maximum wind speed. But it slowly decreases as spring ends and close to summer rain. In general, the mean monthly wind speed of the area varies from 0.88 m/s in November to 1.26 m/s in April with average value of 1.07 m/s. The mean monthly wind speed of available stations is given in (Annex 3)

Table 4.2 Long term mean monthly wind speed (m/s) at 2 m above ground of the study area.

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Arjo	1.38	1.57	1.67	1.79	1.72	1.59	1.59	1.49	1.26	1.15	1.1	1.15	1.45
Didessa River	1.44	1.56	1.65	1.74	1.63	1.3	1.15	1.1	1.17	1.4	1.43	1.42	1.41
Bandira	1.38	1.48	1.56	1.67	1.6	1.3	1.2	1.1	1.16	1.4	1.45	1.4	1.39
Dereba	1.53	1.59	1.62	1.61	1.55	1.35	1.2	1.13	1.2	1.5	1.6	1.57	1.45
Koye	1.32	1.42	1.5	1.5	1.4	1.2	1.07	1.02	1.08	1.26	1.3	1.29	1.28
Agelo	1.67	1.76	1.77	1.68	1.53	1.3	1.16	1.12	1.21	1.49	1.6	1.64	1.49
Mean	1.45	1.56	1.62	1.67	1.57	1.34	1.23	1.16	1.18	1.36	1.4	1.41	1.41

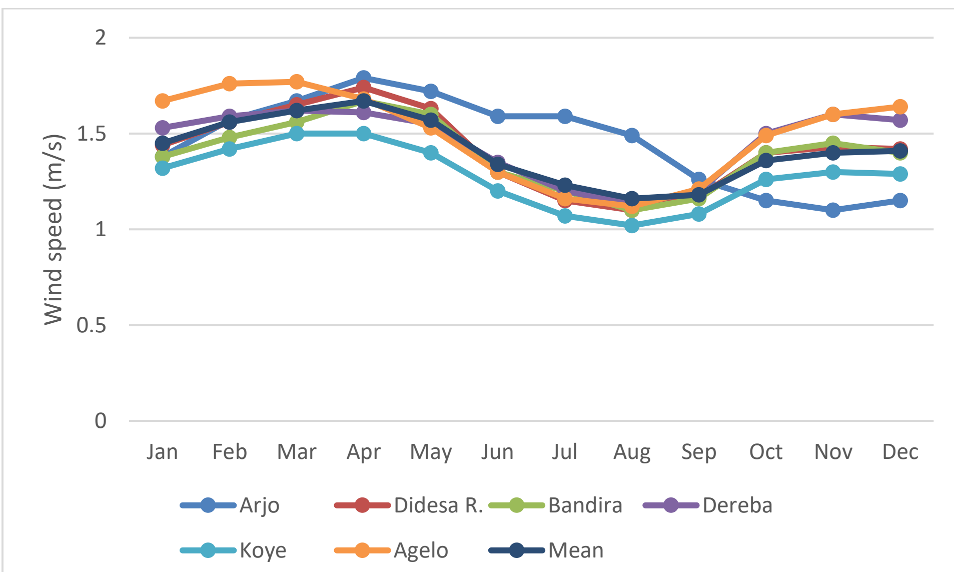


Figure 4.2 Mean monthly wind speed.

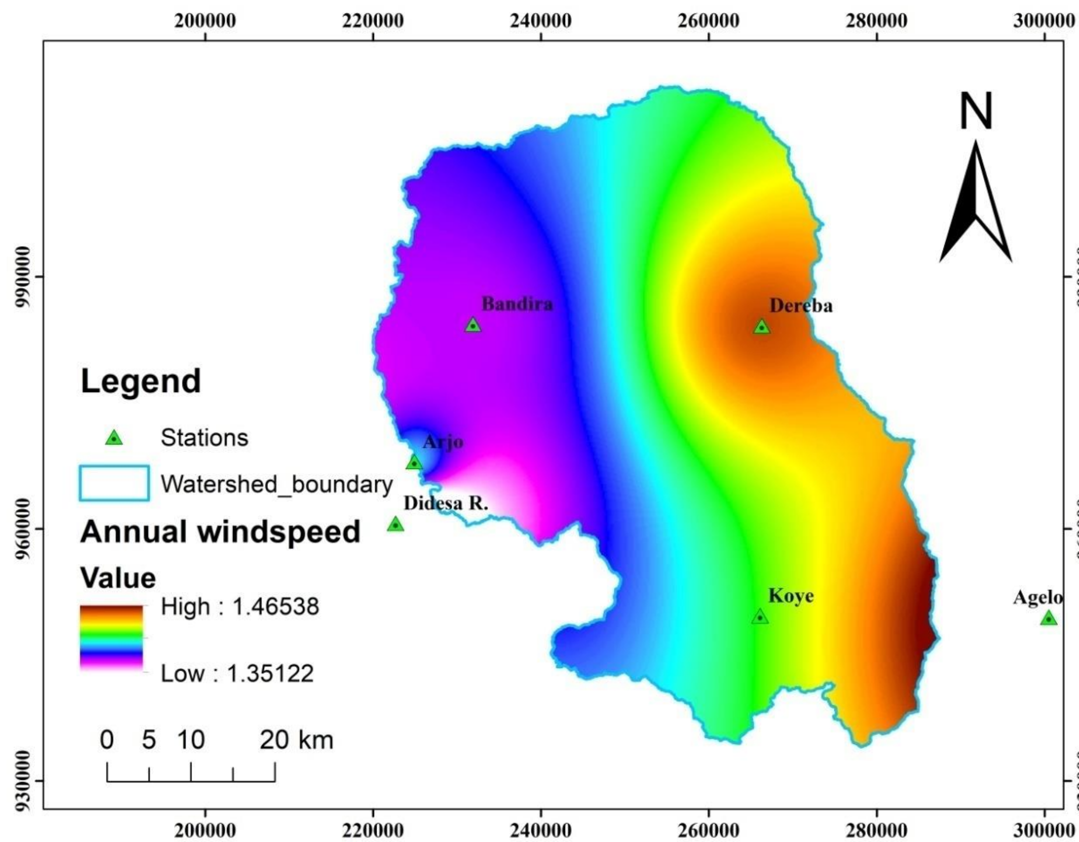


Figure 4.3 Annual wind speed (m/s) map

4.4 Temperature

Temperature governs the rate at which water molecules leave evaporating surface and enter the overlying air as water vapor. It is one of the hydrometrological variables that actively affect water resource. Area with high temperature has low amount of water for recharge than area with less temperature because water lost to vapor rapidly before percolation.

The water stored in a surface pond as well as in soil (unsaturated) zone gradually feed the groundwater system but high temperature leads to evaporation at rate higher than recharge. In high temperature condition, vegetation absorbs more amount of water through root zone and provides much water for transpiration. Therefore, temperature determines how much water can be available for groundwater recharge. This indicates temperature affect groundwater resource by lowering recharge which in turn lowers groundwater potential.

In the study area, there are 10 metrological stations with available temperature records. Temperature varies spatially and increases with a general trend of decreasing with altitude. The mean monthly temperature is computed as average of the daily temperature of all the days in the month. As can be seen from (Figure 4.3), high temperature is in the months of March and April while minimum temperature is in the month of July, August and September.

The annual mean temperature spatially varies from 16.5 ^{o}C to 20.9^{o}C at Arjo and Bandira respectively with the catchments annual mean of 19.23^{o}C. From the ground truth, the maximum temperature is expected around Didessa river valley. However, due to lack of well recorded time series temperature data for Didessa station, Bandira was considered as area of highest mean annual temperature. The monthly mean temperature of stations is annexed in (Annex 4).

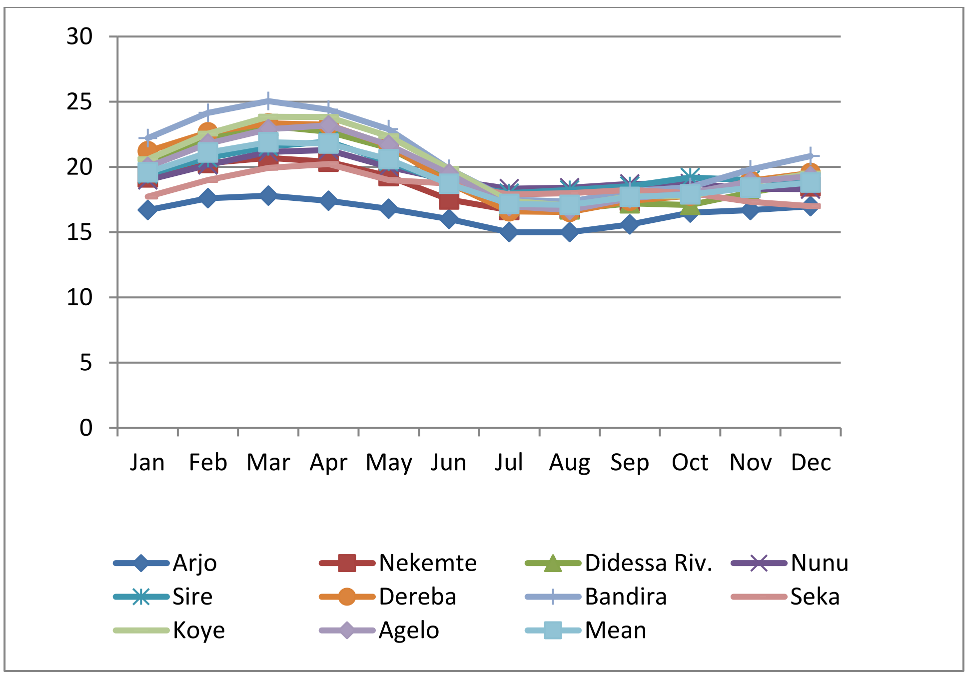


Figure 4.4 Mean monthly temperatures

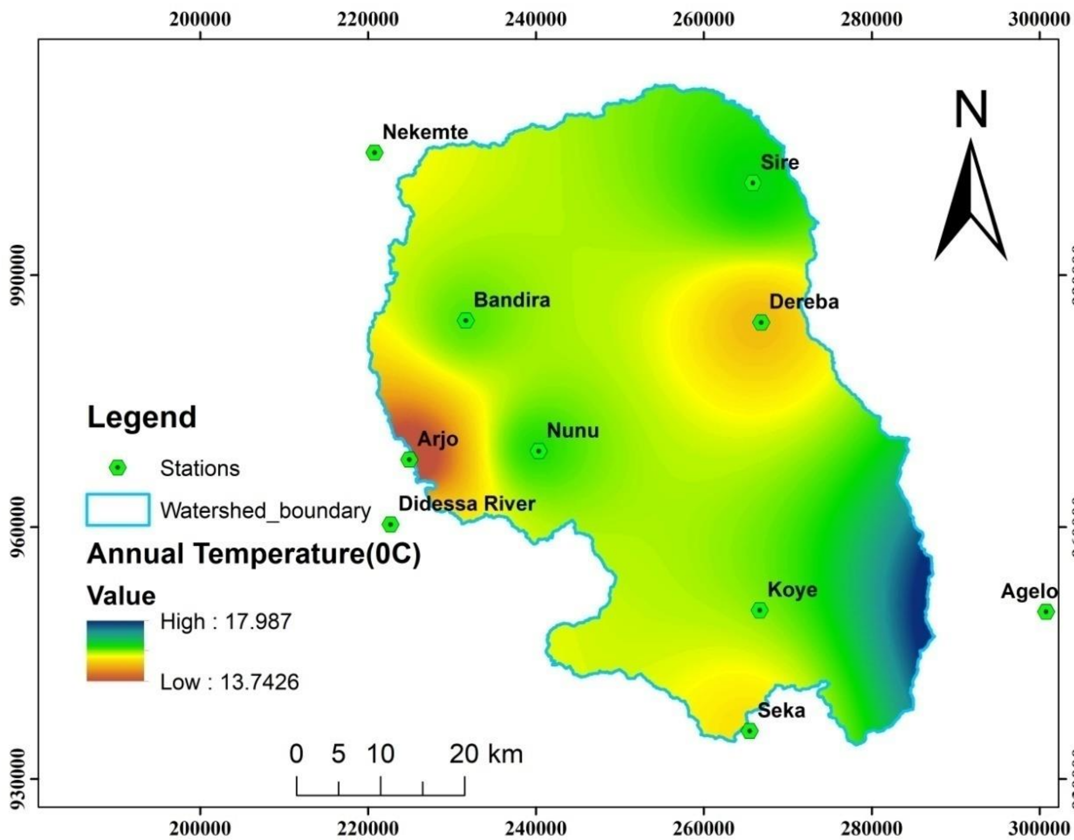


Figure 4.5 Annual temperatures (^{0}C)

4.5 Relative humidity

Relative humidity is the relative measure of the amount of moisture in the air to the amount needed to saturate the air at the same temperature (Shaw, 1994). Higher values indicate that the air is nearer to saturation point, and lower values shows that the air consists less water vapour in the atmosphere. It is expressed as the percentage of the ratio of actual to saturation vapor pressure. Evaporation takes place more rapidly in dry air than in air with a high humidity. Study area has seven relative humidity recording station at Nekemte, Arjo, Bandira, Koye, Agelo and Dereba and Didessa River as annexed in (Annex 5). The annual relative humidity computed for the catchment is 66.9%. The little spatial variation in humidity between different stations is linked with altitude and exposure to moist wind.

As the general, relative humidity of the catchment reaches its peak value in the summer during cloudy weather condition and become low in dry months. As relative humidity approaches 100% evaporation ceases. Mean monthly relative humidity of the study area is given in (table 4.4). It is estimated from the Metrology station in the area and nearer to the area.

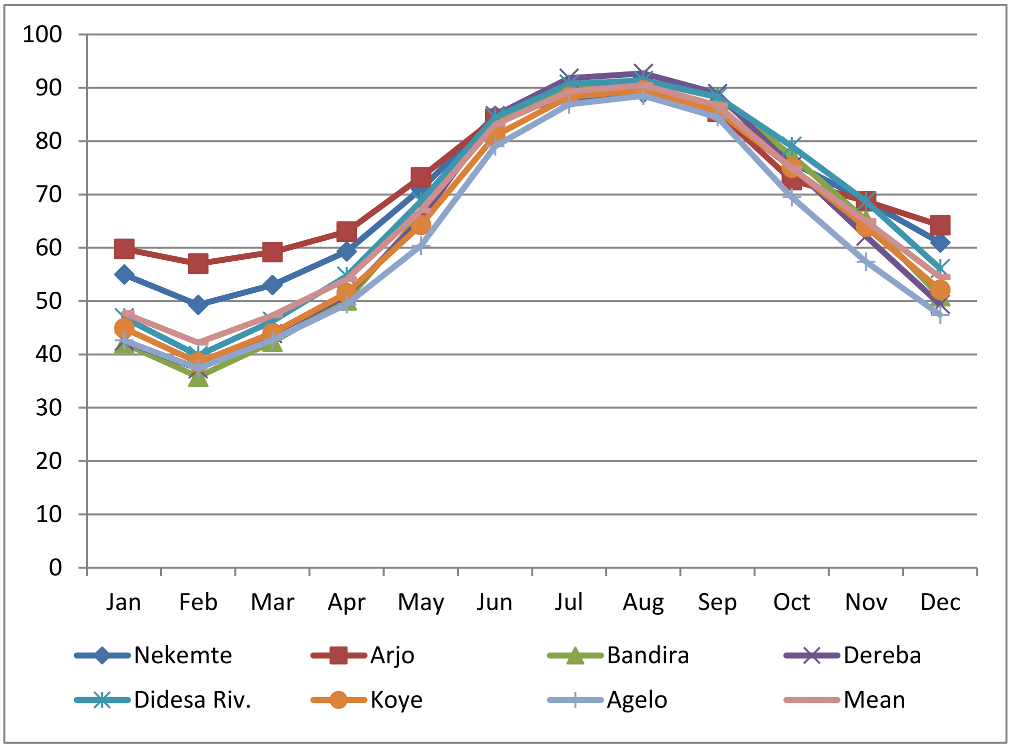


Figure 4.6 Mean monthly relative humidity

Table 4.3 Long term mean monthly relative humidity (%) of the study area.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean (%)	47.7	42.2	47.3	54.1	67	83.1	89.3	90.5	86.7	74.9	65	54.5	66.9

4.6 Rainfall

Seasonal and spatial variation of precipitation has significant effect in hydrology in the case it is a decisive factor for the river flow, groundwater dynamics and groundwater recharge. It is known that distribution and intensity of rainfall in Ethiopia is influenced by oscillation of the surface position of the Inter-Tropical Convergence zone.

In its fluctuation between north and south of the equator, ITCZ crosses over Ethiopia twice a year and this movement from one place to other gives rise to slight difference in the wind flow arrangements over the country with the onset and withdrawal of winds from north and south (Alemayehu, 2006). When ITCZ migrate to northern Ethiopia, the whole southwestern highland is under the influence of Equatorial Westerlies from South Atlantic Ocean (Kebede, 2004).

During this period, Wama catchment receives most of its annual rainfall up to more than 75% when south westerly wind brings rains from the Atlantic Ocean. When ITCZ migrate to Southern Ethiopia, Wama catchment gets its remaining Belg/Spring rainfall (March–May) from southerly wind of Indian Ocean.

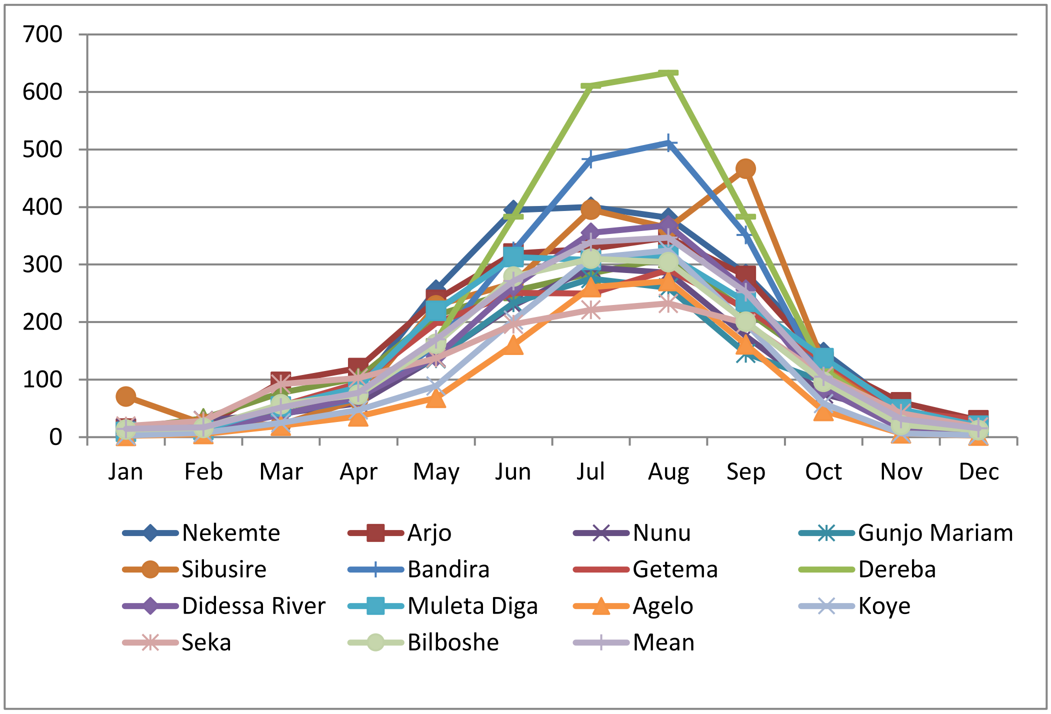


Figure 4.7 Mean monthly precipitation of the study area.

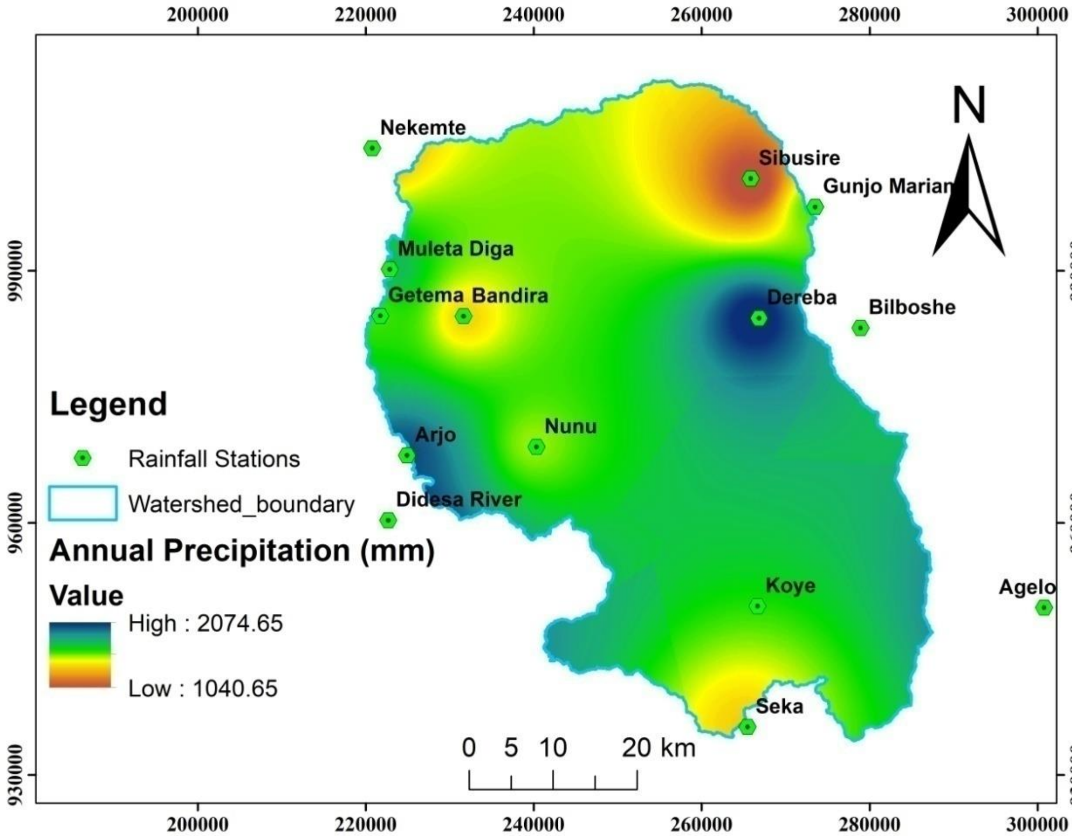


Figure 4.8 Annual precipitations (mm)

4.6.1 Determining aerial depth of rainfall

Precipitation can be defined as the total amount of water falling from the atmosphere in the form of rain, snow, sleet, mist and etc. The rainfall measured by a rain gauge is a point observation which gives depth of rainfall only at a particular geographic point where it is set up, not the aerial rainfall that can represent the whole Area of interest. Thus, some method of obtaining effective depth of rainfall should be implemented. In this work, aerial depth of rainfall of study area was obtained by the following three methods.

A) Arithmetic method

B) Theissen polygon method and

C) Isohytal method

4.6.1 .1 Arithmetic method

Arithmetic mean is the simplest method of computing aerial depth of rainfall and more reliable for relatively flat area where gauging stations are closely and evenly spaced. It is computed by dividing the sum of the rainfall measured at all gauging stations located only within study area in which the variation of individual gauge record from the mean is not too large (Wilson, 1983). By taking this into account stations within and very nearby study area were averaged to get annual depth of rainfall and obtained value is 1693mm**.** The mean monthly rainfall of stations in study area is provided in (Annex 6)

$$\mathbf{P_a} = \frac{\mathbf{P1+P2+P3+\cdots+Pn}}{\boldsymbol{n}}$$

Where, Pa is average depth of precipitation

P1P2…Pn are rainfall recorded at each station 1, 2, etc. and 'n' is the number of rain gauge Stations in the area of interest.

4.6.1 .2 Theissen polygon method

This is another graphical technique which calculates station weights based on the relative areas of each measurement station in the Theissen polygon network. By this method polygons are constructed over rain gauges to mark the area of influence by each gauge. The individual weights are multiplied by the station observation and the values are summed to obtain the areal average precipitation. The mean rainfall depth of the catchment is estimated by using 13 rain gauges in and around the catchment.

Pa=$\frac{PiAi}{A}$, Where, P_a= mean aerial depth of precipitation

Ai= Area of polygon corresponding to gauges

P_i= mean rainfall measurement at i th gauge.

A= total area of the catchment.

The value obtained by this method is 1759.3mm/yr.

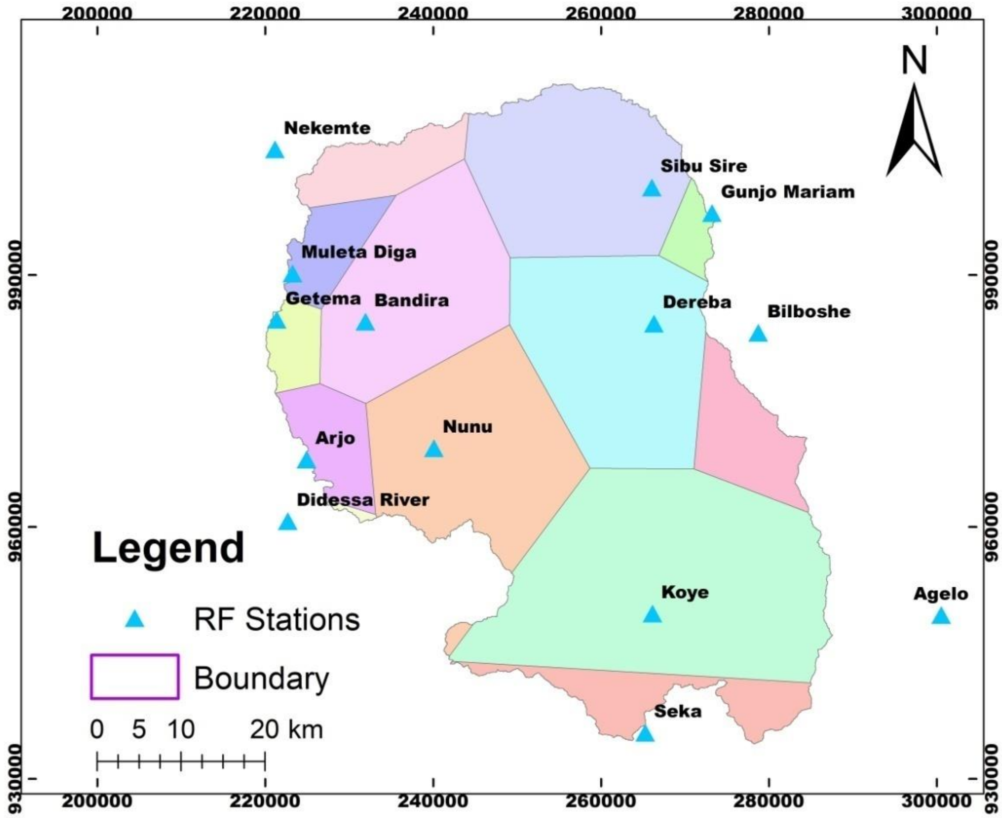


Figure 4.9 Theissen polygons and location of metrological stations

Table 4.4 Mean annual depth of precipitation obtained from Theissen polygon method.

Stations	Polygon area (Km^2)	Mean Precipitation (mm)	Weighted area (%)	Weighted rainfall (mm)
Arjo	109.3	1982	0.032	64.0
Bandira	419.8	2084	0.124	258.4
Biloboshe	147.9	1547	0.044	67.6
Dereba	486.5	2481	0.144	356.6
Didessa River	4.8	1615	0.001	2.3
Getema	59.3	1597.5	0.018	28.0
Gunjo Mariam	43.0	1354.2	0.013	17.2
Muleta Diga	90.6	1759.5	0.027	47.1
Koye	839.1	1276	0.248	316.3
Nekemte	120.0	2089	0.035	74.0
Nunu	482.1	1409	0.142	200.6
Seka	148.8	1392	0.044	61.2
Sibu Sire	434.2	2074.6	0.128	266.1
Total	3385.5		1.000	1759.3

4.6.1.3 Isohytal method

The method is employed by preparing an Isohytal map by drawing contours of equal precipitation using ArcGIS 10.3. In this method, the area between two successive isohyets is multiplied by the average rainfall value of the two adjacent isohyets. The method has advantage in that, the stations do not necessarily need to be equally spaced and also it takes into account the influence of physiographic parameters like distance from the coast, slope, elevation and exposure to rain bearing wind (Shaw, 1994). Therefore, the result produced by this method is believed to be more accurate than the preceding two. By this method, value of computed rainfall depth is 1692mm as given below.

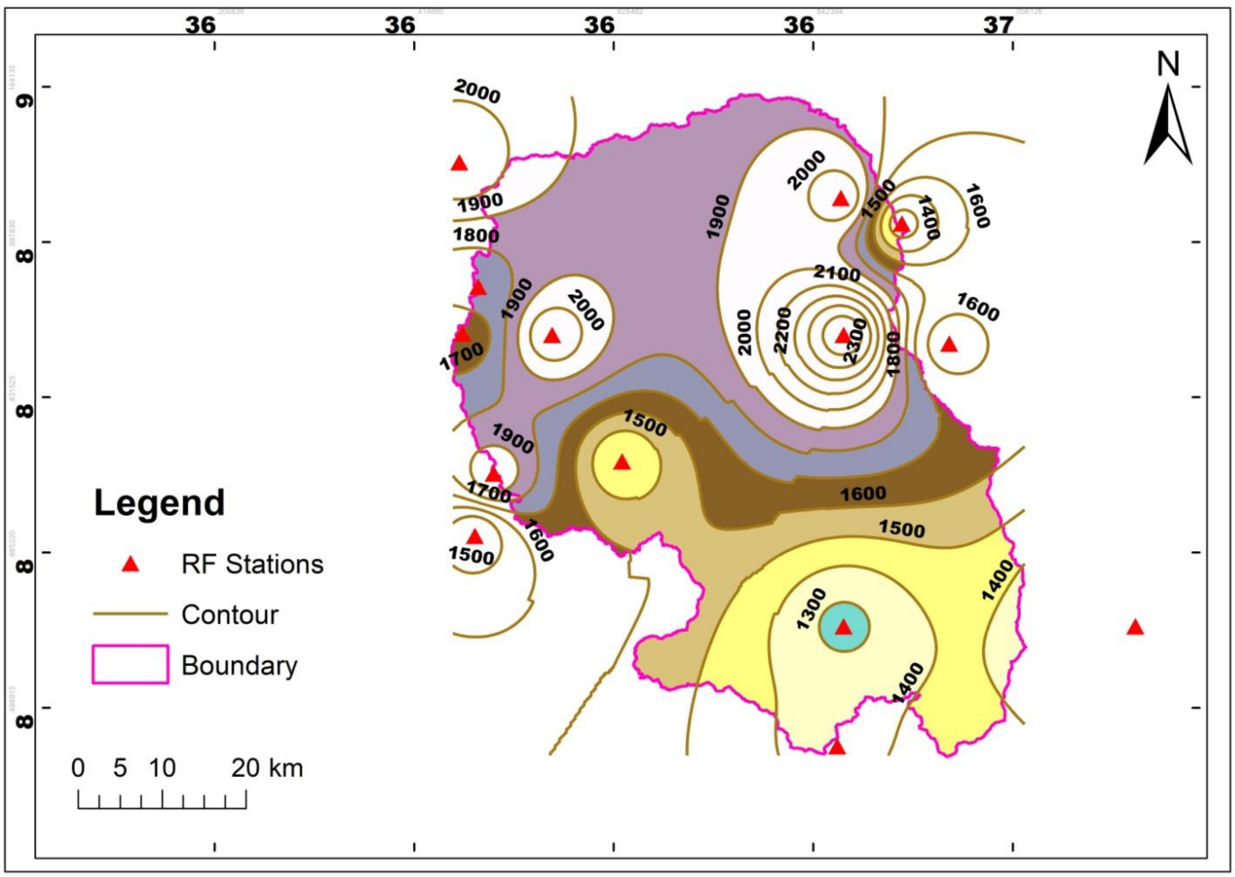


Figure 4.10 Isohytal rainfall depth map of the study area

Table 4.5 Mean annual depth of precipitation obtained from Isohyetal method

Isohyetal range	**Precipitation (mm)**	**Enclosed area (Km^2)**	**Enclosed area (%)**	**Weighted Rainfall(mm)**
<1400	1350	359.8	0.106	143.5
1400-1500	1450	442.4	0.131	189.5
1500-1600	1550	314.9	0.093	144.2
1600-1700	1650	427.9	0.126	208.5
1700-1800	1750	505.7	0.149	268.9
1800-1900	1850	3.7	0.001	2.1
1900-2000	1950	971.3	0.287	530.8
>2000	1900	364.3	0.108	204.4
Total		3385.5		**1692**

Generally, the result obtained using above three methods is slightly similar and very satisfactory with respect to the annual rainfall expected for Wama catchment from the previous work. According to Alemayehu (2006), Southwestern Ethiopia is the region of heaviest rainfall in the country with mean annual rainfall of about 2500 mm, and it is over 2800 mm in Ilu Ababora and parts of Arjo in Wollega.

In this work, because the difference between results obtained from them is not significant, the average value of Arithmetic, Theissen and Isohytal methods (i.e., 1715mm) is considered as annual rainfall of the catchment and is used for further analysis.

4.8 Temporal variability of Rainfall

It is apparent that rainfall is not uniform throughout the year. Some months are rainy month some are extremely rainy and others are dry. In the catchment, months in the given hydrologic year can be partitioned in to rainy and dry month based on the values of rainfall coefficients. Rainfall coefficient is the ratio between mean monthly rainfall depth and one twelfth of the mean yearly rainfall (Gemechu, 1977). On the basis of this value the distribution of rain fall in the year can be analyzed as follows.

$$\mathbf{RC} = \frac{\mathbf{12Pm}}{\mathbf{Pa}}$$

Where RC = rainfall coefficient (unit less)

Pa = mean annual rainfall depth

Pm = mean monthly rainfall depth

Based on this value months in a year can be considered as:-

Dry month when RC <0.6 and

Rainy month when RC ≥0.6

Table 4.6 Classification of rainfall based on rain fall coefficient

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Pm	14.5	16.9	51.5	77.2	170	271.4	339.3	346.8	252	105.2	31.6	15.6	1693
R.c	0.10	0.12	0.37	0.55	1.23	1.93	2.38	2.43	1.79	0.76	0.23	0.11	

On the basis of the rainfall coefficient values, months in a water year are classified as:

i) Dry month: November, December, January, February, March and April

ii) Small rainy month: October.

iii) Big rainy month: May, June, July, August and September. The following table gives abroad classification of months of water year (After Gemechu, 1977)

Table 4.7 Monthly rainfall scheme

Dry month		Rainy month		
	Small rain		Big rain	
		Moderate concentration	Higher concentrati on	Very high concentration
Rc < 0.6	0.6≤ Rc ≤0.9	1≤Rc≤1.9	2≤ Rc≤ 2.9	Rc ≥ 3
Nov	Oct	May	Jul	
Dec		Jun	Aug	
Jan		Sep		
Feb, Mar and Apr				

Accordingly, rainy month has about 87.6% contribution for total mean annual rainfall whereas dry month contribute only 12.4% for study area.

4.9 Evapotranspiration

Evapotranspiration is the conversion of water molecules to vapor by evaporation (open water body/bare land) and transpiration (plants) away from the watershed surface to the atmosphere (Axon, 1982). It is the additive value of both evaporation and transpiration. The process happens when the water molecules have absorbed enough energy to escape from the surface tension that holds them in the liquid or solid state.

Since it is difficult to separately measure both, they treated together as evapotranispiration. The term thus includes evaporation of liquid water from rivers and lakes, ice and snow surface, bare soil and vegetative surface; evaporation from and within the leaves of plants (transpiration). Evapotranspiration is controlled by Metrological conditions, the type of vegetation, and the supply of water. It is a primary process affecting hydrological cycle.

In managing and planning the distribution of water resources, thorough understanding of the evapotranispiration process and knowledge about the spatial and temporal rates of evapotranispiration is required. Direct measurement of evapotranispiration over an area is much more difficult and expensive and is usually impractical due to the unsecure parameters we have to take into account. Thus, an array of empirical methods has been developed for estimation of evapotranispiration based on measurement of more readily measured quantities

4.10 Estimation of Potential Evapotranspiration (PET) and Actual Evapotranspiration (AET)

4.10.1 Estimation of PET

Potential evapotranispiration is the amount of water which could have evaporated if the soil had had an infinite amount of water to evaporate (Thornthwaite, 1955). There are different method of estimating potential evapotranispiration but depending on available data, the following empirical formulas were applied.

4.10.1.1 Thornthwaite method

Thornthwaite produced a formula for calculating PET based on temperature with an adjustment being made for the latitude location and number of daylight hours. The method is based upon the assumption that Potential evapotranispiration is dependent only on meteorological conditions and air temperature is an index of energy available for evapotranispiration.

However, the method devised by Thornthwaite is still useful. The necessary factors to input are: mean monthly air temperature, latitude, and a month. Latitude and month yield average monthly sun shine. The potential evapotranispiration obtained by this method is 864.7mm/yr.

$PET_m = 16N_m \frac{(10Tm)^a}{I}$ (Shaw, 1988)

N_m- Monthly adjustment factor related to hours of day light

T_m- monthly mean temperature C°

$I = \sum im = \sum(Tm/5)^{1.5}$ for m=1, 2….12, and

$a = 6.7x10^{-7}I^3 – 7.7x10^{-5}I^2+1.8x10^{-2}I+0.49$

Nm – is the monthly adjustment factor related to hours of daylight and obtained by dividing the possible sunshine hours for the appropriate latitude by 12 (in this case 10°N)

Table 4.8 Mean PET of study area based on Thornthwaite method

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
T (°C)	19.6	21.1	21.9	21.8	20.6	18.7	17.15	17.1	17.7	17.9	18.4	18.8	
N	11.6	11.8	12	12.3	12.6	12.7	12.6	12.4	12.1	11.8	11.6	11.5	
Nm	0.96	0.98	1	1.02	1.05	1.05	1.05	1.03	1.0	0.98	0.96	0.96	
Im	7.76	8.66	9.16	9.1	8.36	7.23	6.35	6.33	6.66	6.77	7.06	7.3	
I	90.74												
a	1.99												
PET (mm)	71.1	84	92.4	93.4	85.88	70.8	59.6	58.2	60.5	60.6	62.7	65.5	864.7 (mm/yr)

4.10.1.2 Penman combination method

The physical principle of Penman combines two approaches; the mass transfer method & energy budget method. The basic equations are modified and rearranged to use metrological constants (obtained from WMO tables) and measurements of variables made regularly at climatologically stations (Shaw, 1988). The method gives good estimates of PET because it takes in to account many metrological variables, such as vapor pressure, humidity, sunshine hours, net radiation, wind speed and mean temperature.

It has a form:

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

Where PET = Potential evapotranispiration

Δ/γ = is found from weighing factor Δ/γ versus temperature from (FAO, 1967) given in (Shaw, 1994) where Δ is the slope of saturated vapor pressure versus temperature and γ is the hypsometric constant with a value of 0.4859 mm Hg ^{o}C (Rami, 1996).

E_{at} = is the energy for evapotranispiration in mm/day and it takes the formula

$E_{at} = 0.35(0.5 + u_2/100)\ (e_a - e_d) = f\ (u)\ (e_a - e_d)$

e_a = the saturated vapor pressure at air temperature, T_a

e_d = the saturated vapor pressure at the dew point = $e_a * H_R/100$

$T_d = e_a - e_d$ = the saturation deficit

u_2 = mean wind speed at 2m above the surface, miles/day

E_a = energy for evaporation based on the air humidity and air temperature

$H_T = R_I\ (1\text{-}r) - R_0 = 0.75R_I - R_0$ is the net heat

The procedures followed throughout the calculation are provided below and also in (Table 4.9). From the above equation, r is the reflective coefficient (albedo) of the area based on land use land cover type. In this work, the study area is slightly dominated by agricultural land mainly seasonal crops. This agricultural land usually become bare land after the ripened crops harvested. As a result, the barren land, crop residue together with mature forest increases the reflection capacity of the area. Considering these factors, r = 0.24 is taken for study area.

R_I = incoming radiation, R_0 = outgoing radiation, r = albedo

$R_0 = \sigma Ta^4\ (0.47 - 0.075\sqrt{e_d})\ (0.17+0.83n/N)$

Where, σTa^4 = the theoretical black body radiation at T_a

T_a = mean air temperature for a month, (^{O}C)

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

$H = 0.75R_a\ (0.18 + 0.55n/N) - 0.95\sigma Ta^4\ (0.10 + 0.9\ n/N) - (0.56 - 0.092\sqrt{e_d})$

$R_I\ (1\text{-}r) = 0.75R_a * f_a\ (n/N)$

$f_a\ (n/N) = 0.16 + 0.62n/N$ – for latitudes south of 54 and $1/2^0$ N

But this formula takes different form depending on latitude (Shaw, 1994). In this case since study area is located at latitude south of 54 and $1/2^0$ N.

R_a = solar radiation (fixed by latitude and season) = 10^0 considered for the study area, n = bright sunshine over the same period, H_T = the available heat

N = mean daily duration of maximum possible sunshine hours (North Latitudes) = 10^0considered for the study area. (After M. Shaw, 1989)

This method gives reasonable estimate of PET because it takes in to account many metrological variables which govern the rate and magnitude of evapotranispiration. The annual PET of the catchment obtained by this method is 1059.1mm and this value is used for further analysis.

Table 4.9 Mean annual PET obtained from penman combination method

Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
T (°C)	19.6	21.1	21.9	21.8	20.6	18.7	17.2	17.1	17.7	17.9	18.4	18.8	
N	11.6	11.8	12	12.3	12.6	12.7	12.6	12.4	12.1	11.8	11.6	11.5	
Ra(mm/day)	12.8	13.9	14.8	15.2	15	14.8	14.9	15	14.8	14.2	13.1	12.5	
U (mil/day)	53.7	60.7	65.5	67.6	64.4	59.1	55.8	54.76	52.08	50.47	47.24	48.32	
n/N	0.63	0.6	0.6	0.57	0.52	0.43	0.32	0.33	0.47	0.61	0.64	0.65	
H (%)	47.7	42.2	47.3	54.1	67	83.1	89.3	90.5	86.7	74.9	65	54.5	
σTa^4	14.7	15	15.2	15.2	14.9	14.6	14.2	14.2	14.4	14.4	14.5	14.6	
ea(mmHg)	17.1	18.8	19.7	19.6	18.2	16.2	14.7	14.6	15.2	15.4	16.9	16.3	
ed(mmHg)	8.16	7.94	9.32	10.6	12.2	13.5	13.1	13.2	13.2	11.5	11	8.9	
ea-ed	8.96	10.9	10.4	9	6	2.7	1.57	1.39	2	3.9	5.9	7.4	
E_{at}	3.06	3.5	3.54	3.28	2.45	1.26	0.8	0.7	0.96	1.7	2.37	2.7	
Δ/γ	2.19	2.37	2.47	2.46	2.3	2.08	1.91	1.9	1.97	1.99	2.18	2.09	
R1(1-r)	5.35	5.6	5.96	5.9	5.47	4.84	4.08	4.22	5.06	5.83	5.57	5.32	
Ro(mm/day)	2.6	2.59	2.44	2.2	1.86	1.5	1.23	1.25	1.59	2.1	2.25	2.55	
Fa(n/N)	0.55	0.53	0.53	0.51	0.48	0.43	0.36	0.37	0.45	0.54	0.56	0.56	
Ht	2.75	3.01	3.52	3.7	3.61	3.34	2.85	2.97	3.47	3.73	3.32	2.77	
PET(mm/day)	2.85	3.16	3.53	3.58	3.26	2.67	2.15	2.18	2.62	3.05	3.02	2.75	34.82
PET(mm/mon)	86.7	96.1	107	109	99.16	81.2	65.4	66.31	79.69	92.77	91.86	83.65	1059.1

From the above calculated PET by Thornthwaite and Penman combination method, the result of Penman seems to be the representative value.

This is because Penman uses many inputs of metrological parameters that affect evapotranispiration whereas; Thornthwaite depends only on temperature and usually underestimate the PET. So, the value of PET used in further analysis is the one from Penman obtained from Penman method (i.e., 1059.1 mm/yr.).

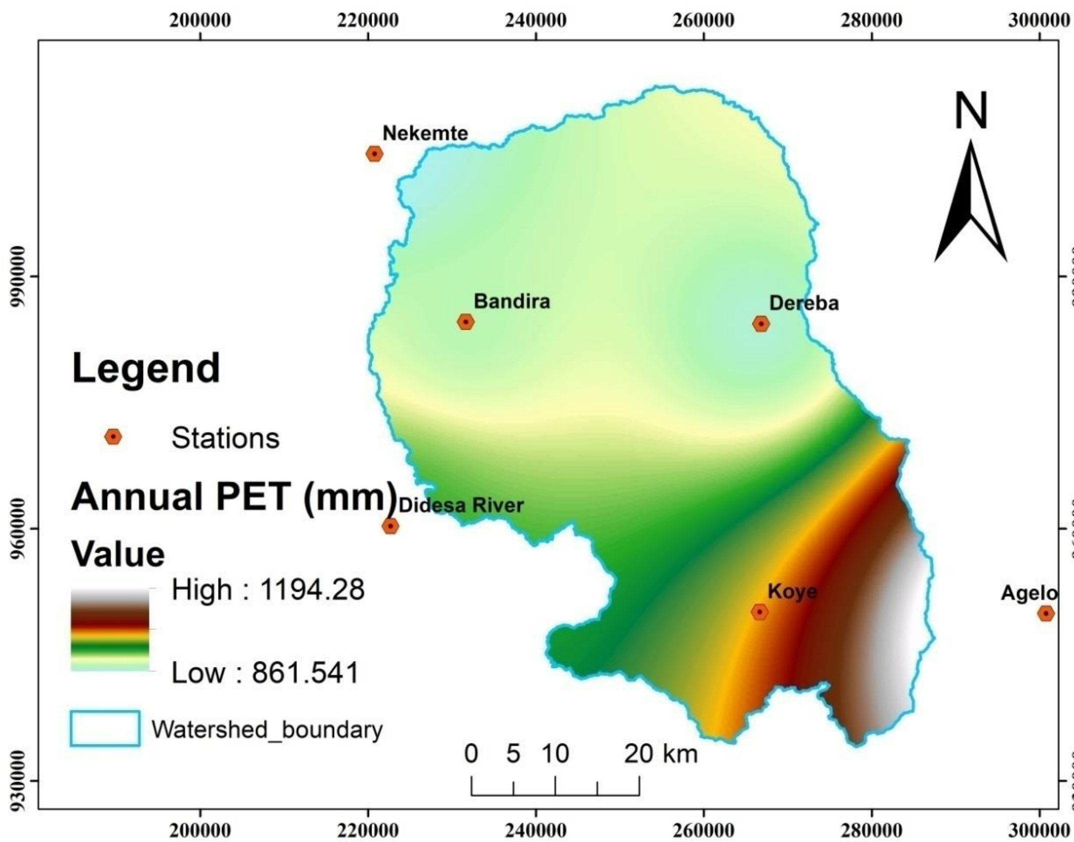


Figure 4.11 Annual PET map

4.10.2 Estimation of AET

Actual evapotranispiration is the amount of water that is actually removed from the surface by evapotranispiration under the given climatic and soil moisture condition (Fetter, 2001). It is less than or equal to potential evapotranispiration.

4.10.2.1 Empirical formula to calculate AET

One of the imperial formulas to estimate Actual Evapotranispiration is formula developed by Turc, (1954).

This is a widely used formula to estimate annual AET for catchment areas (Shaw, 1989). The formula takes into consideration mean annual precipitation and mean annual temperature of the catchment area.

$$AET=\frac{P}{\sqrt{0.9+(\frac{P}{L})^2}}$$

Where, P = mean annual precipitation (mm), which is 1715mm

$L= 300 + 25T +0.05T^3$

T = is mean annual air temperature (C^0), which is 19.23 C^0

Using this method, the estimated annual value of AET of the catchment is found to be 717mm.

4.10.2.2 Soil water balance method (Thornthwaite and Mather, 1957)

This method uses monthly values of rainfall and potential evapotranispiration as input to estimate monthly actual evapotranispiration. It has been tempted to compute soil water balance of study area with the main objective of finding actual evapotranispiration. The basic assumption of this method is that when monthly rainfall is greater than or equal to the corresponding monthly potential evapotranispiration, the actual evapotranispiration equals potential evapotranispiration, if the moisture storage in the soil zone is at maximum capacity (Thornthwaite and Mather 1957, Shaw 1994). But when the moisture content in the soil is limited and vegetation unable to abstract enough water from the soil, the actual evapotranispiration becomes less than the potential evapotranispiration.

The values of soil moisture deficit and actual evapotranispiration vary with soil type and vegetation (Shaw, 1994). Accordingly, the catchment area has been classified texturally in to two major groups of soil (loam and clay) with three types of vegetation cover with varying root depths (i.e., Deep rooted bush, scrub and grass, moderately deep rooted intensively Cultivated land which include cereals and corns, etc. and forest).

The actual evapotranispiration of the area is calculated using Thornthwaite and Mather standard soil water balance model based on the above soil and vegetation cover; precipitation and potential evapotranispiration are used as main inputs.

In the model, accumulated potential water loss, which indicates the severity of water shortage, is obtained by cumulating of the negative values of the differences between monthly precipitation and potential evapotranspiration for dry season only, and the summation begins with the first month of dry season.

In such case, the soil moisture during dry month is given by

$$SM = AWC\exp\left[-\frac{(|APWL|)}{AWC}\right]$$

Where, SM: Soil moisture during the month M (mm)

APWL: Accumulated potential water loss at month M (mm).

AWC: Available water capacity of the root zone (mm)

Actual evapotranispiration is calculated depending on the relationship between AET & PET which is affected by the soil moisture content. When the soil is saturated or when there is abundant moisture in the soil, PET = AET, that means, If $P_m > PETm$, AET = PET

Otherwise $AET_m = Pm + S_{m-1} - S_m$ where 'm' stands for month, S_{m-1} and S_m are soil moisture during month m-1 and m respectively. As soil moisture deficit increases, the AET become increasingly less than PET. Soil moisture deficit (SMD) is the difference between PET_m and AET_m.

According to the assumptions of Thornthwaite and Mather (1957) 50% of the total available runoff (TARO) in any month actually runs off, the rest 50% is detained (D) in the subsoil, groundwater as well as channels of the catchment and is available for runoff during next month. $TARO_m = S_m + D_{m-1}$ where 'S' is surplus and 'D' is detention.

On the basis of above concept, the actual evapotranispiration of the catchment is computed by taking into account different land use land cover and soil type of the catchment. For this work the soil in Wama catchment is classified into two major soil texture namely, loam and clay in which loam accounts for 86% of the area and the left one, clay is 14%. The areal coverage of each soil class in proportion to types of vegetation cover is determined. The result from each soil class then summed and the obtained value of actual evapotranispiration is 860 mm/year. The computation of actual evapotranispiration for the catchment is given below (Table 4.10) and estimation of available water in the rooting depth for the catchment area is annexed in the (Annex 7).

Table 4.10 AET for the area represented by clay and loam soil that accounted to 14% and 86% of total catchment respectively, with total available water capacity of 228 mm. All values in the tables are in millimeters.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
P	14.5	16.9	51.5	77.2	170	271.4	339.3	346.8	252	105.2	31.6	15.6	1693
PET	86.69	96.11	107.37	108.9	99.16	81.2	65.4	66.31	79.69	92.77	91.86	83.65	1059.1
P-PET	-72.19	-79.21	-55.87	-31.7	70.84	190.2	273.9	280.49	172.31	12.43	-60.26	-68.05	
APWL	-140.2	-219.5	-274.5	-306.2							-60.26	-128.3	
SM	123.3	87	68.4	59.5	228	228	228	228	228	228	175	129.8	
ΔSM	6.5	-36.3	-18.6	-8.9	168.5	0	0	0	0	0	-53	-45.2	
AET	21	53.2	70.1	86.1	99.16	81.2	65.4	66.31	79.69	92.77	84.6	60.8	860

Where P=Precipitation; PET= Potential evapotranispiration; P-PET is difference by subtraction, APWL=Accumulated potential water loss derived by accumulating negative values in row 3; SM=Soil moisture; AET=Actual evapotranispiration; ΔSM= Change in soil moisture during the month.

The result obtained from Turc method underestimates the actual values. This might be due to the case:

- ✓ Turc empirical formulae use only temperature and precipitation which do not account for the effect of the rest hydro-meteorological, pedological and botanical (land cover) effect on the rate of actual evapotranspirartion.
- ✓ Turc method is developed for specific climatic region, which may not work effectively for a different one. Therefore, the result obtained from the soil water balance thought to represent the actual evapotranspirartion of study area and will be utilized for further analysis.

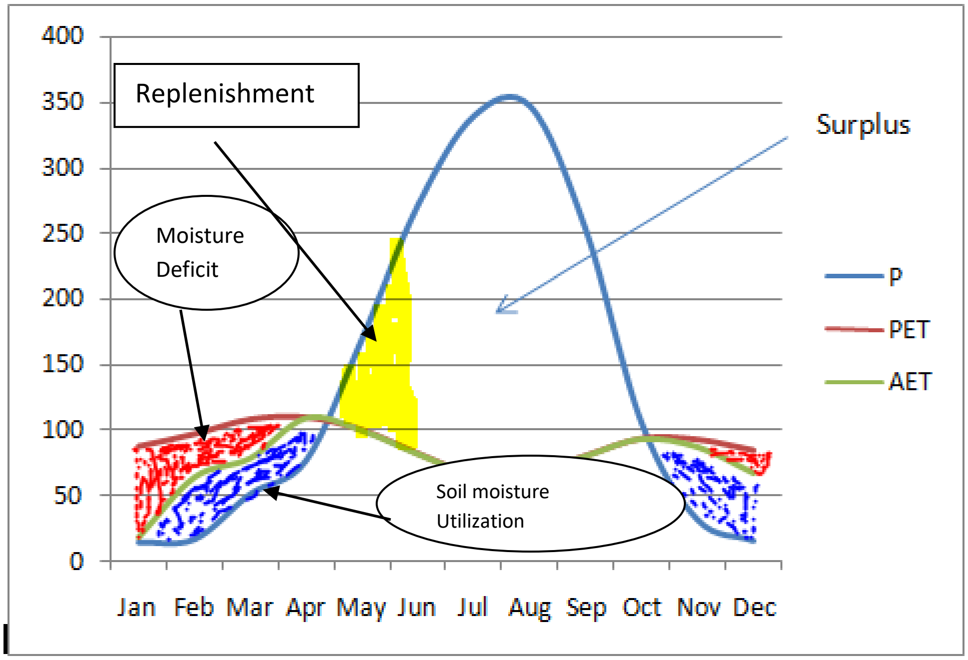


Figure 4.12 Results of monthly average water balance of the study area.

4.11. Runoff estimation

Runoff estimation using rainfall coefficient

This method estimates the runoff by multiplying the runoff coefficient to the rainfall depth of the area. The runoff coefficient is the fraction of rainfall converted into runoff (Chow, 1988)

The runoff value by rational method has its own limitations. This formula is more applicable for small catchment area (i.e., <50km^2). The researcher used this method due to the fact that the catchment area is ungauged. There is no a river flow record or river discharge gauge in the Wama River.

It is given by: R = PK.

Where, R = runoff (mm)

P = rainfall depth (mm)

K = runoff coefficient (dimensionless).

But K is obtained by,

$$K = \frac{A1K1+A2K2+A3K3\ldots+AnKn}{A1+A2+A3\ldots+A}$$

The values of runoff coefficient for different land use land cover given by Barlow (1915). Barlow is the first Chief Engineer of Hydro-electric Survey of India on the basis of his study in small catchments (~130km^2) in Uttar Pradesh) were used to estimate the runoff coefficient for the study area. Accordingly, the land use land cover as stated in chapter two is grouped under four major categories as given below (Table 4.11).

$$K=\frac{(1963.8*0.3+495*0.11+920*0.1+6*0.67)}{3385.5}=0.218$$

From the above equation, by multiplying the value of runoff coefficient (i.e., 0.218) with rain fall depth (1715mm/yr.), the annual runoff value of 374 mm/yr. was obtained for the study area. Therefore, for water balance method calculation, the catchment's annual runoff is assumed to be 374 mm/yr.

Following this approach, runoff coefficient for the entire area is estimated to be 0.218

Table 4.11 Runoff coefficient for different Land use Land cover in the study area

Nº	Classification of land use land cover	Area in (Km^2)	Runoff Coefficient
1	Cultivated (Intensively to moderately cultivated perennial crops and state farms)	1963.8	0.3
2	Pasture, bush land, grassland, open and dense wood land	495	0.11
3	Forest	920	0.1
4	Settlement	6	0.67

4.12 Recharge estimation

4.12.1 Water balance method

An important objective of most groundwater studies is to make a quantitative assessment of the groundwater resource. In order to bring these objectives in to effect, two water balance approaches, which have generally the same ground but presented in different forms, have been applied. The first approach is the one developed by (Thornthwaite and Mather, 1957), known as soil water balance, and this method helps to quantify the annual actual evapotranspiration of the area on the basis of the potential evapotranspiration already computed by using empirical and physical formulae (detail of this method was presented under soil water balance sub-topic).

The second approach is based on the general water balance equation. This equation follows basic assumptions such as:

- The surface water divides and ground water divide coincides
- The catchment is bounded by both surface and ground water divide, except at the mouth of the River where ground water escapes as base flow.
- There is no ground water inflow and outflow across the boundary
- The water balance is on annual basis and the change in storage on annual base is assumed to be zero.
- Abstraction by human is insignificant.

Based on the assumptions made the water balance equation representing the catchment is:

Inflow = Outflow + Change in storage

The inflow component of a system includes: precipitation, groundwater inflow, irrigation and artificial water transport to the system and the out-flow components include abstraction, groundwater out flow, direct runoff, evapotranspiration, recharge and water transfer to another systems. This water balance approach involves identifying which components of inflow and out flow can take place within the area of consideration and quantifying each one individually.

Based on the assumptions made the water balance equation representing the catchment is:

$$R = P - AET - Q - W$$

Where, P= mean annual precipitation in mm, AET = mean annual actual evapotranspiration in mm, Q = Mean annual surface runoff in mm, W= Withdrawal (insignificant) and R = mean annual ground water recharge in mm.

Thus, by using the above relation of the conventional water balance equation, the mean annual groundwater recharge of the Wama Catchment is estimated as follows:

AET = 860mm (From Soil water balance methods), Q = 374mm and P = 1715mm

Therefore, R= 1715mm - 860mm - 374mm = 481mm/year.

4.12.2 Chloride mass balance in evaluation of groundwater recharge

This method is used for estimation of recharge to ground water by using relatively stable environmental tracers. Chloride ion do not significantly enter in to oxidation or reduction reactions; they form no important solute complexes with other ions unless the chloride concentration is extremely high, do not form salts of low solubility, they are not significantly adsorbed on mineral surfaces, play few vital biochemical roles, and the circulation of chloride ions in the hydrologic cycle is largely through physical processes. Chloride ions moved with the water through most soils tested with less retardation or loss than any of the other tracers tested-including tritium that had actually been incorporated in to the water molecules. This conservative behavior should not be expected where movement is through compact clay or shale; however, Chloride ions may be concluded characteristically to be retained in solution through most of the processes that tend to separate out other ions (Mairs, 1967).

The method is based on the assumption of mass between the input of atmospheric chloride and the chloride flux in the sub-surface. Ignoring the direct inputs of pollution, the fluxes for a catchment can be interpreted in terms of a mass balance equation: (Drever and Clow, 1995).

Here are assumptions for this method:

- ❖ The only source of chloride in groundwater is from precipitation falling directly on the aquifer material;
- ❖ Concentration of chloride in groundwater is by evapotranspiration within the unsaturated zone, not from recycling, dissolution of minerals containing chloride, or inflow from adjacent aquifers;
- ❖ Chloride is not retarded by adsorption nor accelerated by anion exclusion

- ❖ Chloride is conservative and its mass flux has not changed over time
- ❖ Chloride application rate is constant and known
- ❖ There is no appreciable chloride run off or run on from the sampling sites and
- ❖ Steady state conditions prevail.

In this work, samples of precipitation from three stations (Wama Hagelo, Nunu Kumba, and Nekemte) were collected and tested its chloride concentration at Nekemte City Water Quality Analysis and the average value of chloride concentration for these stations was 1.88 mg/l. On the other hand, the averaged value of chloride ion concentration in the groundwater from 11 boreholes is 15.8mg/l.

The general equation for mean annual recharge estimation from chloride data and attributes is:

$GR = P* [Cl^-_p]/ [Cl^-_{GW}]$

Where GR=Mean ground water recharge in mm/year, P= Mean annual precipitation depth in mm $[Cl^-_{GW}]$ = Average concentration of chloride in ground water in mg/l, $[Cl^-_p]$=Concentration of chloride in precipitation in mg/l

In this case, P = 1715 mm/yr., Cl^-_p = 1.88 mg/l, $[Cl^-_{GW}]$ = 15.8 mg/l, GR = 204 mm/yr.

It is seen that the recharge value obtained by this method is lower than the values obtained by other methods. It has therefore the following limitations:

- Only three samples of rainfall (in mid-March) were taken; it would be better if more rainfall data were collected over a year to know the variation of Cl^- with time.
- It depends on the detecting limits of laboratory a slight error in detection can cause erroneous result.

The total amount of precipitation that carries the chloride ions is not retained with in the soil; however, part of it runs off leaving the catchment. And direct input of pollution is observed due to higher amount of concentration Cl^- in the falling Precipitation over the catchment.

4. 12.3 WetSpass model and its application

WetSpass stands for Water and Energy Transfer between Soil, Plants and Atmosphere under quasi-Steady State and is designed to predict the hydrogeological processes at annual and seasonal time steps (Batelann&De Smedth, 2001, 2007). It is designed to work with GIS environment for data preparation. Especially the new version (wetSpass 1.3) has the ability to simulate interception from vegetated surfaces, runoff from land escape, evapotranspiration, soil water balance, and recharge at monthly time step using long term mean monthly values.

The model is designed by conceptualizing the hydrogeological system of a basin based on Physical and empirical relationships, which mainly consists of plant canopy, soil zone, root zone, atmosphere and saturated groundwater zones partitioned in to grids/cells to take in to account of heterogeneity (Gebremedhin Gebremeskel, 2015). Grid maps of the same cell size of the long term mean monthly values of precipitation, temperature, potential evapotranspiration and wind speed were prepared on Arc GIS environment and parameter tables of land uses types with respect to their root depth and leaf area index and soil parameter tables with respect to their field capacity, wilting point permeability and runoff of the appropriate format are required to run the model.

4.12.3.1 Model concept

The model is a type of distributed one in which the area to be studied is discretized in to raster grid cells where by the water balance computations are performed at each individual cells/element.

Discretization of the area under consideration is performed within the GIS environment by defining the size of the cell. A calculation of individual water balance is performed by summing up independent water balance for the vegetated, bare soil, open-water, and impervious fraction of a raster cell. Therefore, the total water balance for a given watershed can be computed by summation of the water balance for each raster cell.

4.12.3.2 Water balance components

The water balance components of vegetated, bare-soil, open water, and impervious surfaces are used to calculate the total water balance of a raster cell as follows:

$ET_{raster} = a_vET_v+a_sE_s+a_oE_o+a_iE_i$………………………………........... (1)

$S_{raster} = avSv+a_sS_s+a_oS_o+a_iS_i$…………………………………........... (2)

$R_{raster} = a_v R_v + a_s R_s + a_o R_o + a_i R_i$………………………….……………………. (3)

Where:

ET_{raster}, $S_{raster,}$ and R_{raster} are the total evapotranspiration of a raster cell [LT^{-1}], surface runoff of a raster cell [LT^{-1}], and groundwater recharge of a raster cell [LT^{-1}] respectively, each having a vegetated, bare-soil, open-water and impervious area component denoted by a_v, a_s, a_o, and a_i, respectively.

4.12.3.2.1 Precipitation

Precipitation is taken as the starting point for the computation of the water balance of each of the above-mentioned components of a raster cell, the rest of the processes (interception, runoff, evapotranspiration, and recharge) follow in an orderly manner. The order is prerequisite for quantifications of processes at seasonal time scale. Water balance components performed by the model are described below.

4.12.3.2.2 Vegetated area

The water balance computations performed for vegetated area is mainly depends up on the seasonal precipitation(P), interception fraction (I), surface runoff (S_s), actual evapotranspiration (T_v) and groundwater recharge (R_v), where all the magnitude is expressed [LT^{-1}] units with the relation given as:

$P = I + S_v + T_V + R_v$…………………………………………………………………… (1)

4.12.3.2.3 Interception

An interception fraction is represented by percentage of annual precipitation value which mainly depends up the type of vegetation cover. Since the vegetation cover is taken as constant throughout the simulation period. The interception by a constant vegetation cover represents a constant percentage of annual precipitation value.

4.12.3.2.4 Surface runoff

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

$Sv - pot = Csv\ (P - I)$ ………………………………………………………………………… (2)

Where = C_{sv} is surface runoff coefficient for the vegetated areas, and is a function of vegetation, soil type and slope. In groundwater discharge zones saturated surface runoff is likely to be observed which in turn dramatically increase the surface runoff coefficient but due to the less dependency of soil and vegetation type in the surrounding area of a river, the runoff coefficient is assumed to be constant. In the second step, actual surface runoff is calculated from the S_v-pot by considering the differences in precipitation intensities in relation to soil infiltration capacities. That is:

$S_v = C_{Hor}\ S_v\text{–}pot$…………………………………………… (3)

Where CHor is a coefficient for parameterizing that forms part of a seasonal precipitation contributing to the Hortonian overland flow. C_{Hor} for groundwater discharge areas is equal to 1.0 since all intensities of precipitation contribute to surface runoff. Only high intensity storms can generate surface runoff in infiltration areas.

4.12.3.2.5 Evapotranspiration

For the calculation of seasonal evapotranspiration, a reference value of transpiration is obtained from open-water evaporation and a vegetation coefficient. It is given by:

$T_{rv} = cE_o$………………………………………………………… (4)

Where Trv is the reference transpiration of vegetated surface [LT^{-1}] Eo is potential evaporation of open water [LT^{-1}] C is vegetation coefficient [-] The vegetation coefficient can be determined from the ratio of the reference vegetation transpiration expressed by the Penman-Monteith equation to the potential open water evaporation is calculated by the following equation:

$$C = \frac{1+\gamma/\Delta}{1+\gamma/\Delta(1+\frac{rc}{ra})} \quad \ldots\ldots (5)$$

Where γ = psychrometric constant [$ML^{-1}T^{-2}C^{-1}$], Δ = Slope of the first derivative of the saturated vapor pressure curve (slope of saturation vapor pressure at the prevailing air temperature) [$ML^{-1}T^{-2}C^{-1}$], r_c = Canopy resistance [TL^{-1}], r_a = aerodynamic resistance [TL^{-1}], Again the value of the aerodynamic resistance is calculated by:

$$r_a = \frac{1}{k^2 u_a} (\ln\left(\frac{Z_{a-d}}{Z_0}\right))^2 \quad \ldots\ldots (6)$$

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

The penman coefficient (γ/Δ) varies with temperature and can be obtained from the following table:

Table 4.12 Variation of penman coefficient (γ/Δ) with temperature

T(ºC)	-20	-10	0	5	10	15	20	25	30	35	40
γ/Δ	5.86	2.83	1.46	1.07	0.76	0.59	0.45	0.35	0.27	0.25	0.17

For vegetated groundwater discharge areas, the actual transpiration (T_v) is equal to the reference transpiration as there is no soil or water availability limitation:

$T_v = T_{rv}$ if $(G_d - h_t) \leq R_d$................................ (7)

Where G_d, is groundwater depth [L], ht is the tension saturated height [L] and R_d is the rooting depth [L]. For vegetated areas where the groundwater level is below the root zone the actual transpiration is given by:

$T_v = f(\theta)T_{rv}$ if $(G_d - h_t) > R_d$..(8)

Where f(θ) is a function of the water content and for a time variant situation it is defined as

$(\theta) = (1 - a_1)^{w/T_{rv}}$ ....(9)

$w = P + (\theta_{fc} - \theta_{pwp})$.. (10)

Where a1 is a calibrated parameter related to the sand content of a soil type [-], w is the available water for transpiration [LT^{-1}] and θ_{fc} - θ_{pwp} is the plant available water content [T^{-1}] per time step, stated as the difference in water content at field capacity and at permanent wilting point.

4.12.3.2.6 Recharge

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

$R_v = P - S_v - ET_v - I$

Where ET_V is the actual evapotranspiration [LT^{-1}], which is given as the sum of T_v and E_s. Therefore, the spatially distributed recharge is estimated from the vegetated type, soil type, slope, groundwater depth, climatic variables of precipitation, potential evapotranispiration, temperature and wind speed. Like that of vegetated surface, a similar procedure is followed for the calculation of the water balance for bare-soil, open water and impervious surfaces. The only difference here is, there is no interception and transpiration term as there is no vegetation in this case. Therefore, the ET_v in this case becomes E_s.

4.12.3.4 WetSpass Input files

4.12.3.4.1 Physical and Hydro metrological grid maps

There are two types of data inputs required for the model to run. The first one is the physical characteristics of the watershed such as land use/land cover, soil, slope and elevation map and the metrological data which corresponds to precipitation, temperature, potential evapotranispiration and wind speed. The second one is parameter tables prepared for the corresponding land use/land cover and soil maps of the catchment.

Preparation of the Hydro- metrological raster map has been done using the IDW interpolation within the spatial Analyst extension tool box in the Arc Map. A 30 m resolution obtained from Ministry of Agriculture has been used in the preparation of land use/land cover and soil map of the catchment. A 200m grid cell size has been used in the preparation of the raster map. The elevation has been obtained from the shuttle Rader Topography Mission data set (see Figure 4.13 below) and the corresponding slope map has been derived from the digital elevation model using the 3D spatial Analyst extension. The groundwater depth map of the catchment has been prepared from 14 existing borehole data which consists of full record of the static water level and they have been used uniformly throughout the month. The corresponding raster map of 200m grid size has been converted to ASCII grid format using the conversion too box in Arc map environment.

For the sake of accuracy, all raster maps are clipped (produced) by rectangle which comprises of meteorological stations inside and nearby the study area. The raster format in case of rectangle consists of 445 columns and 496 rows. Whereas, the input ASCII format for the watershed boundary consists of 338 columns and 394 rows. For both watershed and rectangle, the grid cell size is 200m.

4.12.3.4.2 Parameter tables

Parameter table have been prepared for the land use/land cover and soil map of the study area, and they have been saved with the appropriate TBL format. The same type of land use/land cover and soil parameters has been used throughout the month during simulation. The parameter tables are used as lookup table which serves as a linkage for the corresponding grid map of land use/land cover and soil map for the computation to be performed.

WetSpass requires a combination of ArcView/ArcInfo grid files and tables (dbf files) as inputs, which are listed below:

Table 4.13 WetSpass model input files

Arcview/Arcinfo grid files	Soil, Topography, Slope, Land use, Temprature, Wind speed, Precipitation, PET, Groundwater depth
Tables (dbf)	Soil parameter and Land use parameter

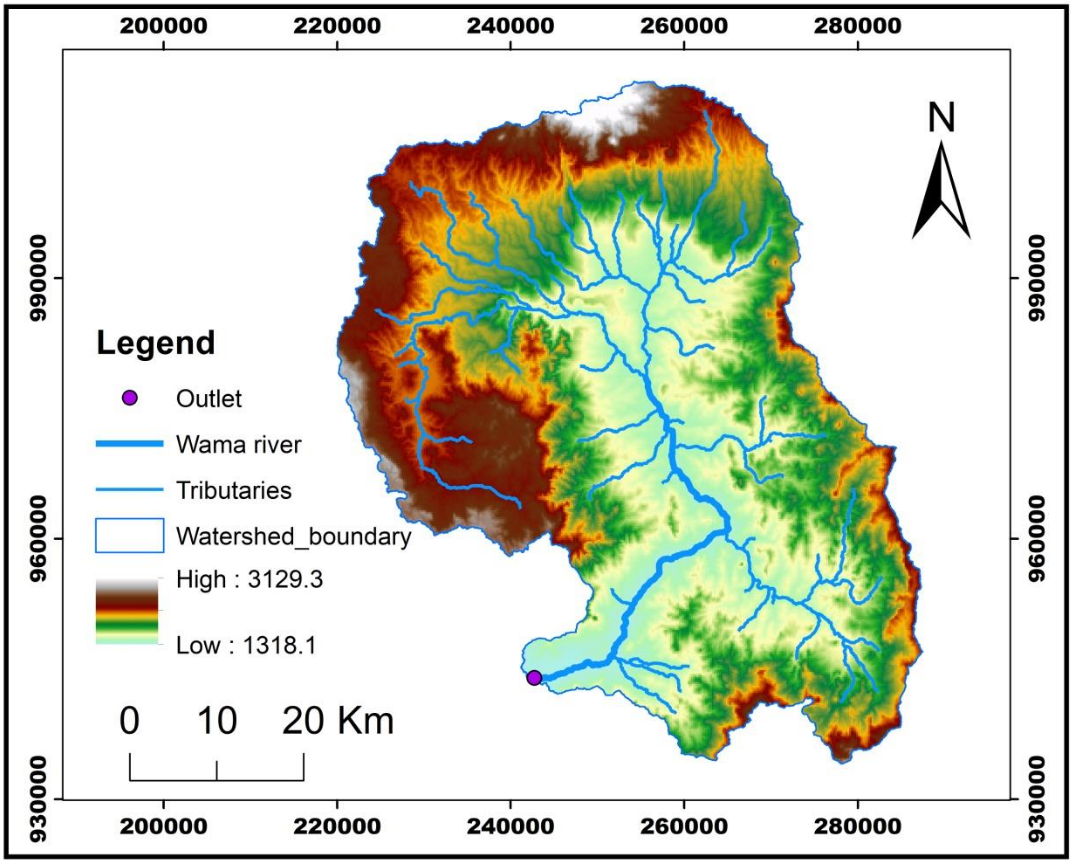


Figure 4.13 DEM of the study area

4.12.3.5 Outputs of WetSpass model

As explained earlier in the above, model inputs of precipitation, temperature, potential evapotranspiration have been prepared at monthly time-time step. The same value of groundwater depth for each month has been used for each month.

The output of the corresponding month has been converted to two seasons through map Algebra tool box in the spatial analyst extension in Arc Map. The output results are presented as raster map. The discussion of the output results is explained hereunder:

4.12.3.5.1 Actual Evapotranspiration (AET)

When rain falls to the surface, fractions of its constituents can be intercepted by vegetation which mainly depends up on wind speed, duration of rainfall, interception capacity, type and morphology of the vegetation cover, growing stage of the vegetation and form and frequency of the vegetation (Tenalem Ayenew and Tamiru Alemayhu, 2001). The residual fraction that has passed from being intercepted by vegetation and other infrastructure can eventually joins in to soil. During the day light hours evaporation can takes place from vegetation canopy, water bodies and soil surfaces (Dragoni &Sukhija, 2013).

Result of the long-term actual evapotranspiration has been simulated for each month of the year and the result has been prepared in two seasons for catchments (Figure 4.14 and Figure 4.15)

The mean long term annual actual evapotranspiration of the Wama catchment obtained from WetSpass output is found to be 908.2mm. Out of this, about 31.7% of the total actual evapotranspiration which consists of 288.3 mm occurs during winter, whereas the rest 68.3% which consists of 619.9 mm occurs during the summer season. The long term mean annual actual evapotranspiration accounts for 52.9 % of the total mean annual precipitation.

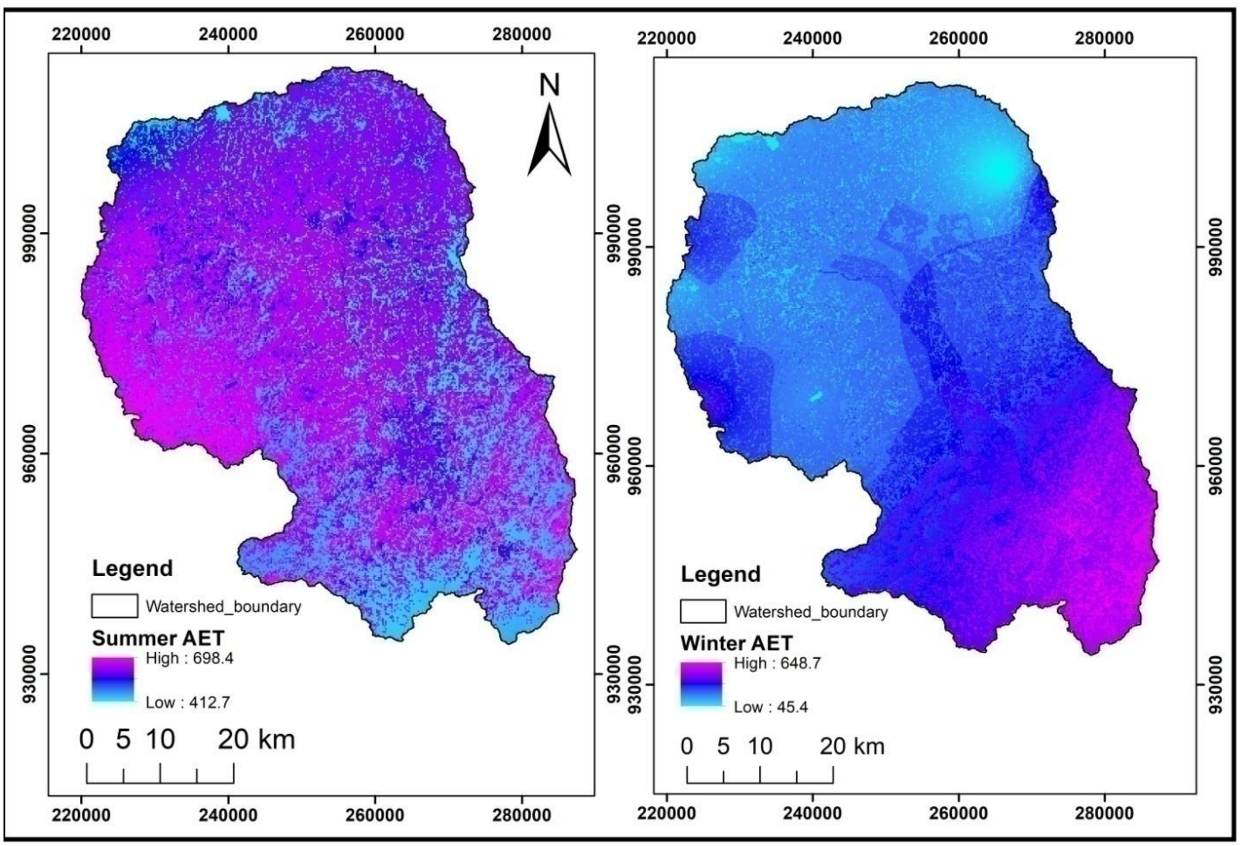


Figure 4.14 Summer and winter actual evapotranispiration of the study area.

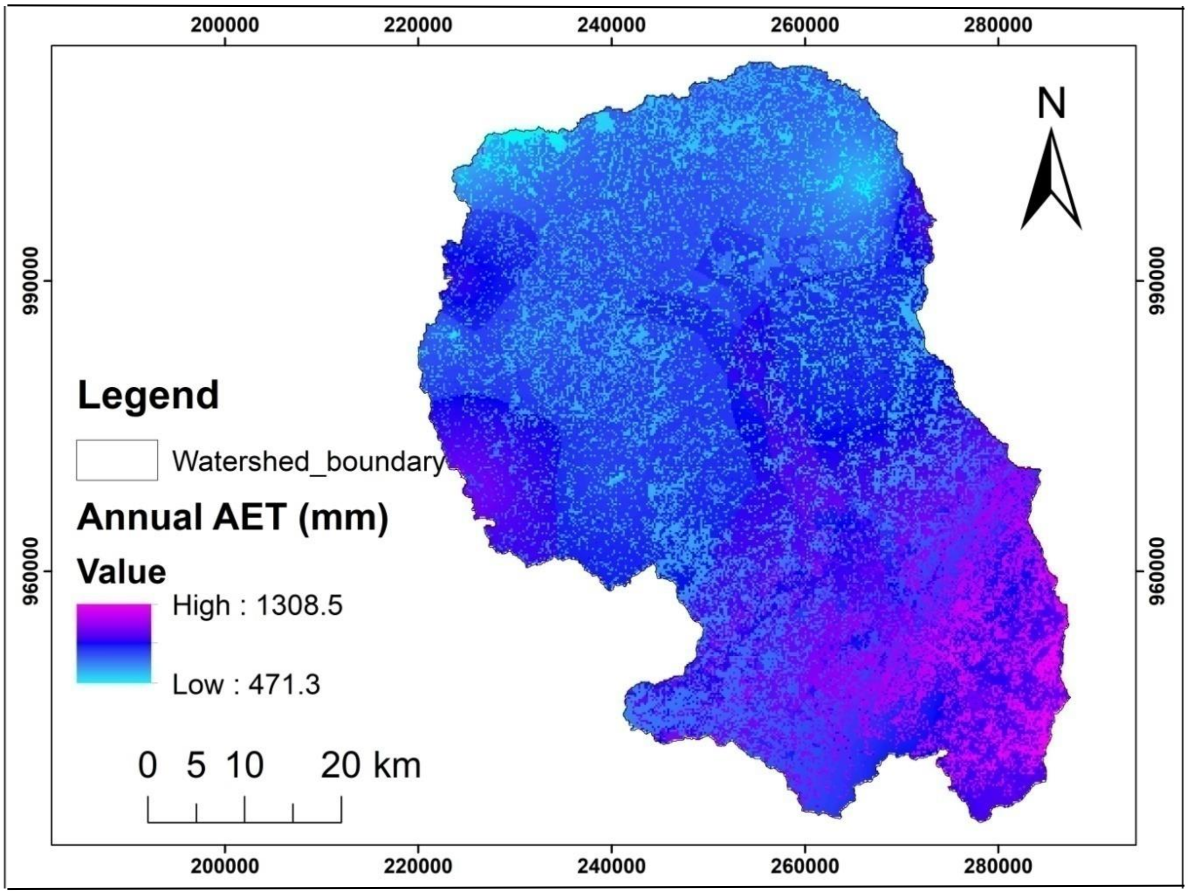


Figure 4.15 Annual Actual Evapotranispiration (mm)

4.12.3.5.2 Surface Runoff

Surface runoff over a given watershed is mainly dependent up on the intensity of rainfall, the type of land use/land cover and the soil texture. As observed from the output (Figure 4.16 and Figure 4. 17) within the catchment, the long-term annual surface runoff corresponds 473.3mm. During dry season the surface runoff is found to be 89.9 mm which is about 19% of the total annual runoff. While about 81% which is 383.4 mm of the total surface runoff is obtained during the rainy season. The surface runoff accounts about 27.6 % of the annual precipitation. Therefore, we can conclude that the amount of precipitation that is lost within the catchment area is attributed to the surface runoff.

According to Tena Bekele, G.V.R. Srinivasa and Yeramsetty Abullu (2015), Wama is the top important sub watersheds in terms of share in Didessa sub-basin's annual runoff volume (i.e., 448mm). When compared with this, the runoff estimated from wetSpass model is the representative value.

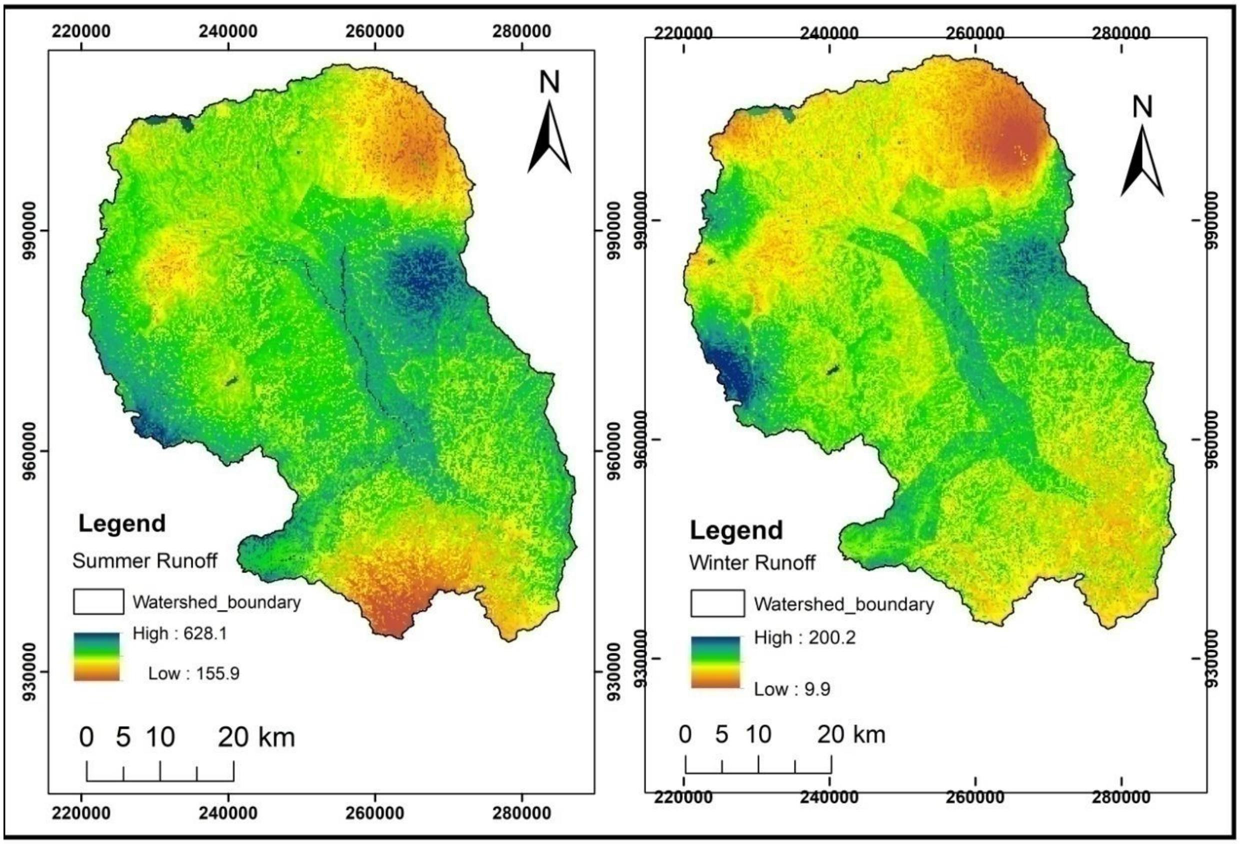


Figure 4.16 Summer and winter runoff map of the study area.

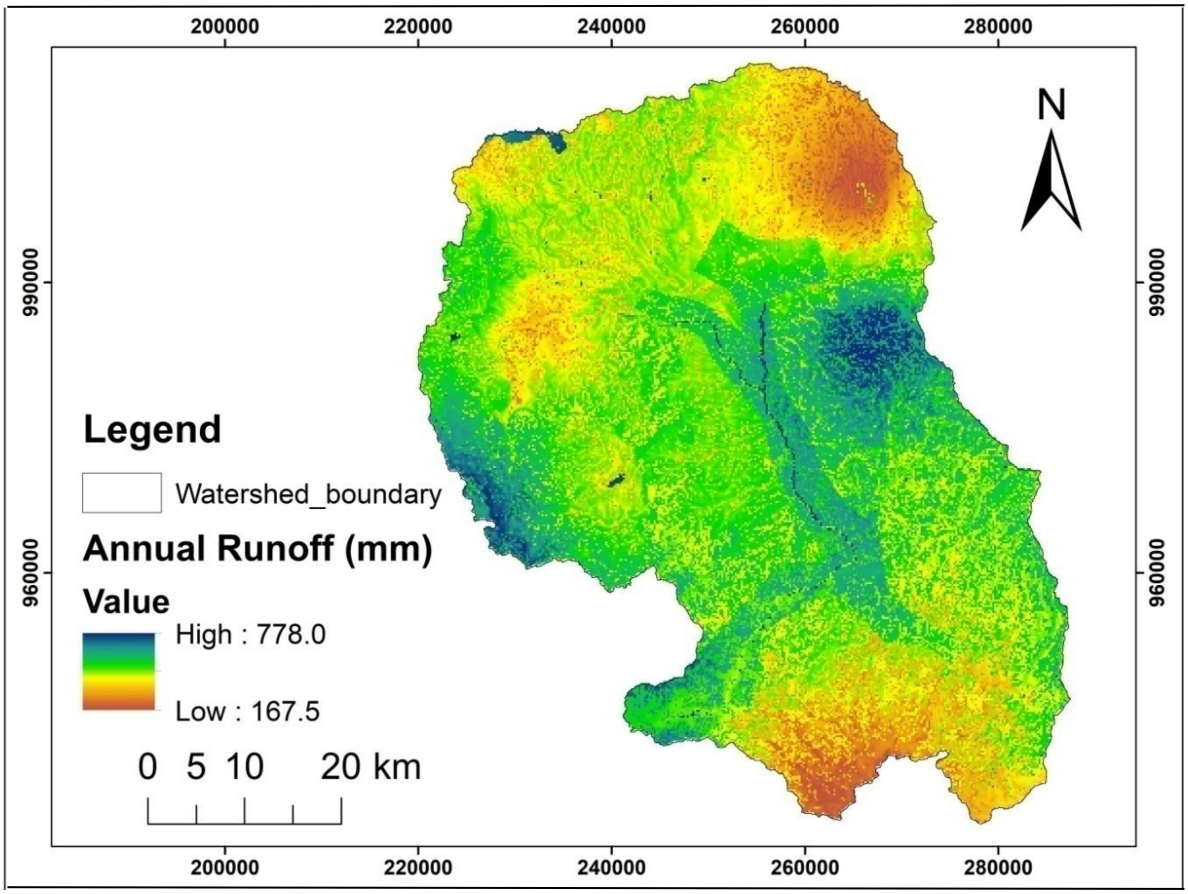


Figure 4.17 Annual runoff map of the study area

From the map above, it is clearly observed that, the highest runoff within the catchment is in an area covered with clay and settlement and also it is high where there is high rainfall intensity especially around Arjo and Dereba. There is also high surface runoff in an area which is covered with bare land.

4.12.3.5.3 Recharge (output)

The amount of water that is percolated to the sub-surface mainly depends up on the physical characteristics of the watershed. Different types of land use/land cover and soil texture have variable capacity to transmit water through them. The model has calculated the amount of recharge that is percolated to the saturated zone by subtracting the average annual and seasonal value of surface runoff and evapotranspiration from annual and season precipitation.

Within the catchment area, the long term mean annual recharge is found to be 333.5 mm which accounts for 19.5 % of the annual precipitation (i.e., 1715mm). See (Figure 4.18 and 4.19) for detail.

During the dry season the recharge is found to be 119mm, whereas in the rainy season the amount of recharge increases and is found to be 214.3mm. According to Ayenew and Alemayehu (2001), major recharge occurs in the northeastern and southwestern plateau where rainfall is high and revealed that annual recharge in highland of Keffa, Wollega and Illubabora is 250-400mm.

The catchment area is totally included in this part and the accepted recharge is in a good agreement with the foresaid value and can be representative result.

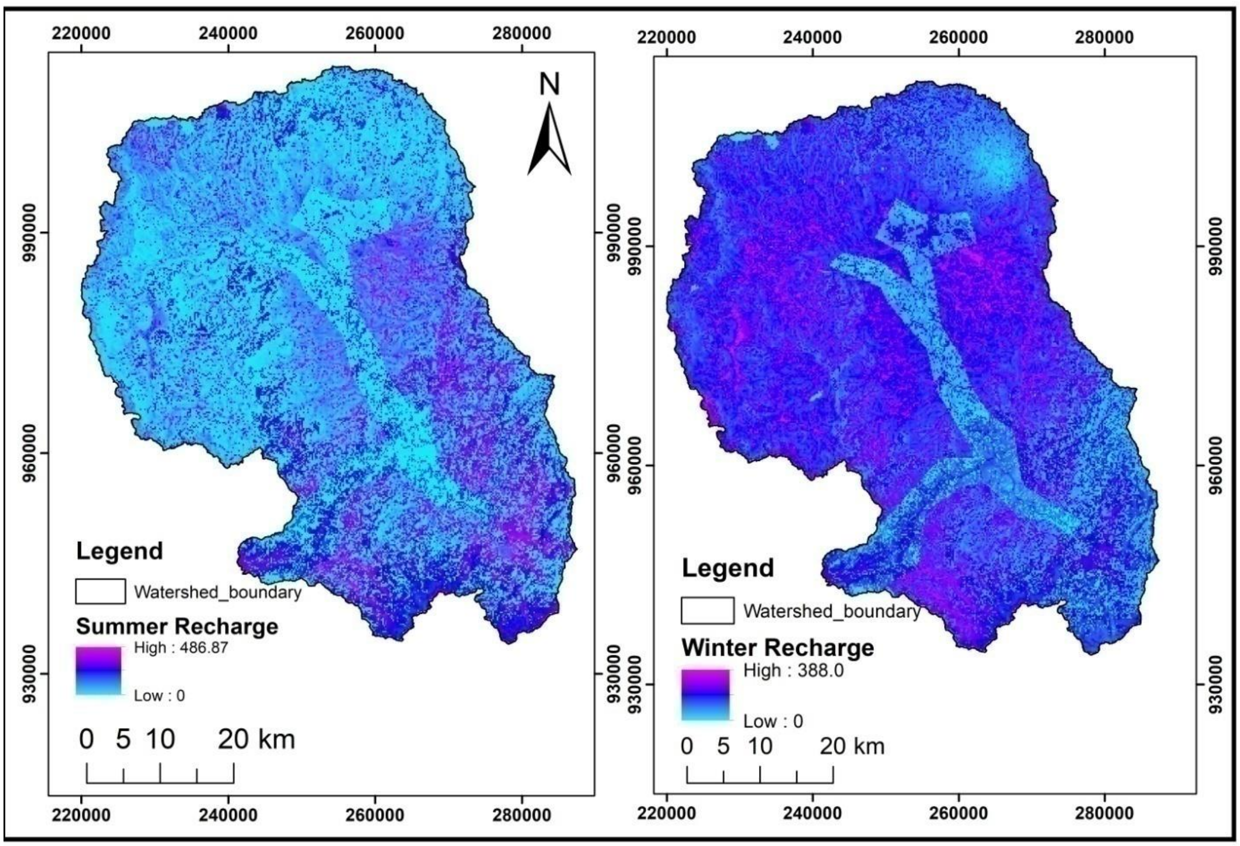


Figure 4.18 Summer and winter recharge map of the study area.

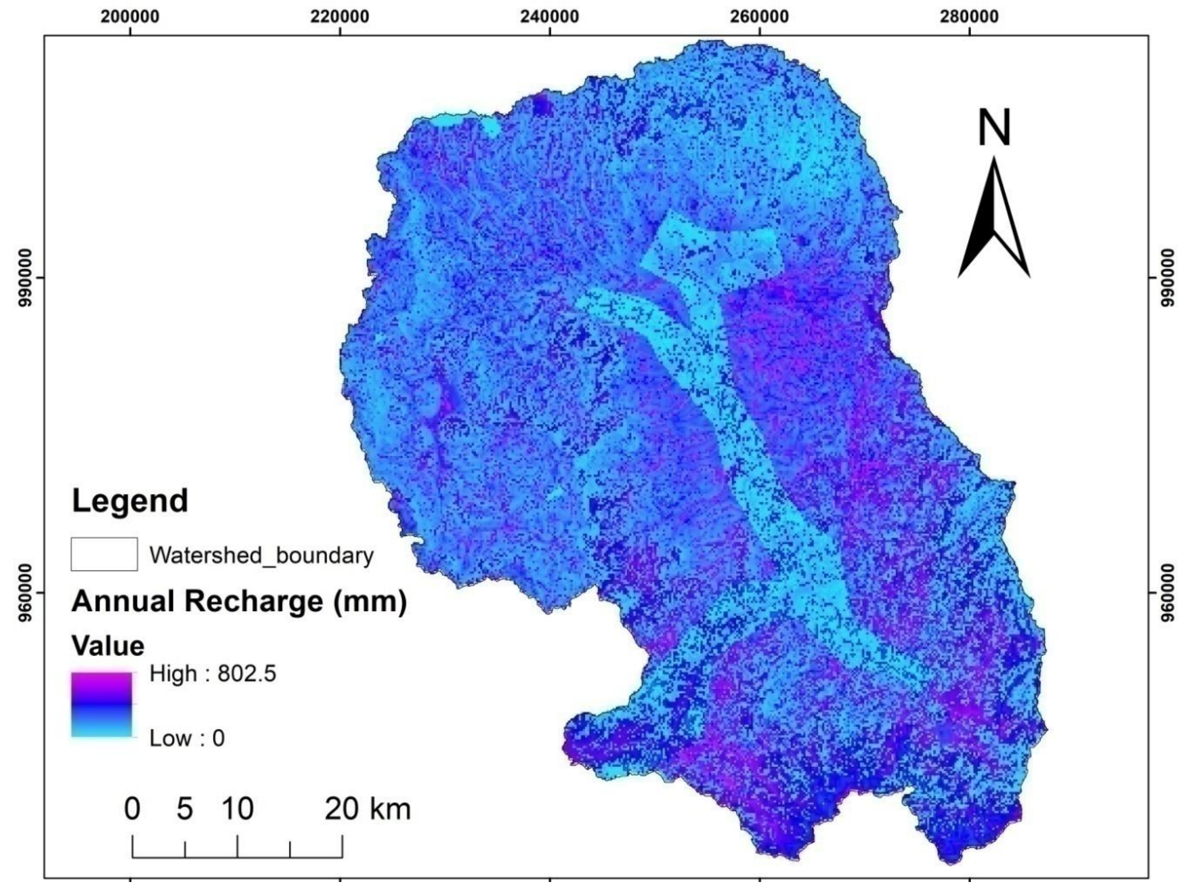


Figure 4.19 Annual recharge (mm) map of the catchment

Generally, the long-term annual precipitation (i.e., 1715mm) in Wama catchment is distributed as 19.5% recharge, 52.9% evapotranspiration and 27.6% runoff, indicating almost half of the precipitation feeding the watershed is lost due to evapotranspiration.

CHAPTER FIVE

HYDROGEOLOGY

5.1 General

Hydrogeology deals with occurrence, distribution, and movement of groundwater in the soil and rocks of the Earth's crust (commonly in aquifers). It encompasses the interrelation ship of geologic materials and processes with water (Fetter, 2001). The major hydro geologic units in the catchment area are volcanic rocks which are subjected to weathering, fracturing (and /or) local faulting processes and the hydro geologic properties of which modified by these processes.

Being situated in the Ethiopian plateau the main hydrogeological units composing Wama catchment are volcanic rock that were subjected to varying degrees of weathering and fracturing. As volcanic rocks have a wide range of chemical, mineralogical, structural, and hydraulic properties, their aquifers also range from some of the most prolific to those utilized only for limited individual supply (Kresic, 2006).

It is obvious that aquifers in volcanic rocks have a wide range of hydraulic properties. Within a few lengths of time and distance there exist significant variations in permeability and porosity. These complex spatial and temporal variations are attributed to their different stratigraphic relationships, their changeable contacts with very old and recent rocks, mode of emplacement, structural and textural variability and different level of weathering as well as variable topographic position that sophisticate the hydrogeological behavior of the volcanic rocks (Alemayehu, 2006). Owing to this fact, ability of volcanic rock to store and transmit water varies leading to a diverse aquifer type.

In the study area, there is also basement rock (granite), mainly exposed around Arjo and Adare area. These rocks are intensively weathered in the upper part and affected by local fractures. From all the lithologic logs of these wells it can be seen that, two major secondary processes enhance the permeability of this unit to be classified as aquifer.

Weathering affects the most upper part of the aquifer. The weathered column of this aquifer ranges from 48 m at Adare area. The weathering column is thicker at Adare well most likely because, the altitude is lower and temperature is higher to enhance chemical reaction there by intensifying weathering activity.

The depth of this well is 151m. Drilling at this site was easy because it has thick succession of weathered and fractured column.

5.2 Available groundwater point

Figure 5.1 Examples of water points

Spring

A spring is a concentrated discharge of groundwater appearing at the ground surface as a current of flowing water (Todd, 1959). Springs occur in many forms and can be classified by means of their origin, rock structure, discharge, temperature and variability (Todd, 1959).

It represents the out flowing of groundwater from the saturated zone as a result of hydraulic head difference between recharge zone and discharge zone under the driving force of gravity for the case of cold spring (thermal spring may be from convective upward flowing of heated ground water in the absence of gravity). Spring is a concentrated discharge of groundwater appearing at the ground surface as a current of flowing water (Todd, 1980).

The catchment is endowed with many perennial and intermittent springs. All springs in the study area are cold. People are using these cold springs for their every activity. Especially Rural inhabitants solely rely on spring for both domestic purpose and their livestock even sometimes for local small-scale irrigation (Burqa Wama) where the yield is high.

All the spring shows a fluctuation in their discharge rate with time and space. Their temporal variation may be a response of aquifer to recharge rate between dry month and rainy month recall that spring is groundwater discharge, whereas spatial variability partly depends on the extent of an area (often aquifer) contributing recharge for spring and climatic condition mainly magnitude of rainfall as it is not smooth throughout the catchment.

The springs in the catchment are a result of different geologic and geomorphic processes. Those which located on hill side and mountain foot are emerged as topographic break and some of the low land springs are originated from contact between highly weathered and less weathered lithology. But majority of them are structural spring emerged through fractured lithologies.

Hand dug well

Hand dug well is known by local people as alternative source of water supply where groundwater is very shallow. Hand–dug wells in the study area are enormous in number and distributed almost in recharge areas of the catchment, indicating that it may not indicate the regional groundwater zone, but they tap shallow circulating groundwater. Especially in highland area, hand dug might be a part of perched aquifer which eventually flows over the edges of the impermeable bed.

The seasonal fluctuation of the static water levels in most of the hand-dug wells is highly attributed to the direct recharge condition from precipitation in to the well which intern indicates the unconfined nature of the aquifers. Water of these wells are not dependable, for the reason that they commonly dry out during dry seasons and an aquifer is vulnerable to pollution.

Borehole

Deep and shallow boreholes are distributed in and around the study area. They are commonly drilled by governmental and non-governmental organizations, for the purpose of water supply to urban and rural communities. The available boreholes in the study area are used mainly for water supply purpose. It is the principal water point of hydrogeologic interest through which aquifer can be assessed.

The distribution of borehole is uneven. It is highly found in densely occupied residential area of the catchment and mainly determined by hydrogeological characteristics of the geological units. The main aquifer formations of the boreholes are volcanics which are pyroclastic deposits, weathered and fractured basalts, ignimbrites (welded tuffs), unwelded tuffs, rhyolites and trachytes. Alluvial and lacustrine formations are also recognized.

Totally, there are about 20 boreholes inside and very nearby study area including both shallow (<60m) and deep borehole (≥60m). Boreholes have different penetration depth of minimum 59.8m and maximum 180m and static water level that range from 1.38m which is located in Bilo locality that yields 7l/s to 46m around Gombo locality with yields 4.2l/s. More information about borehole data is annexed in (Annex 8).

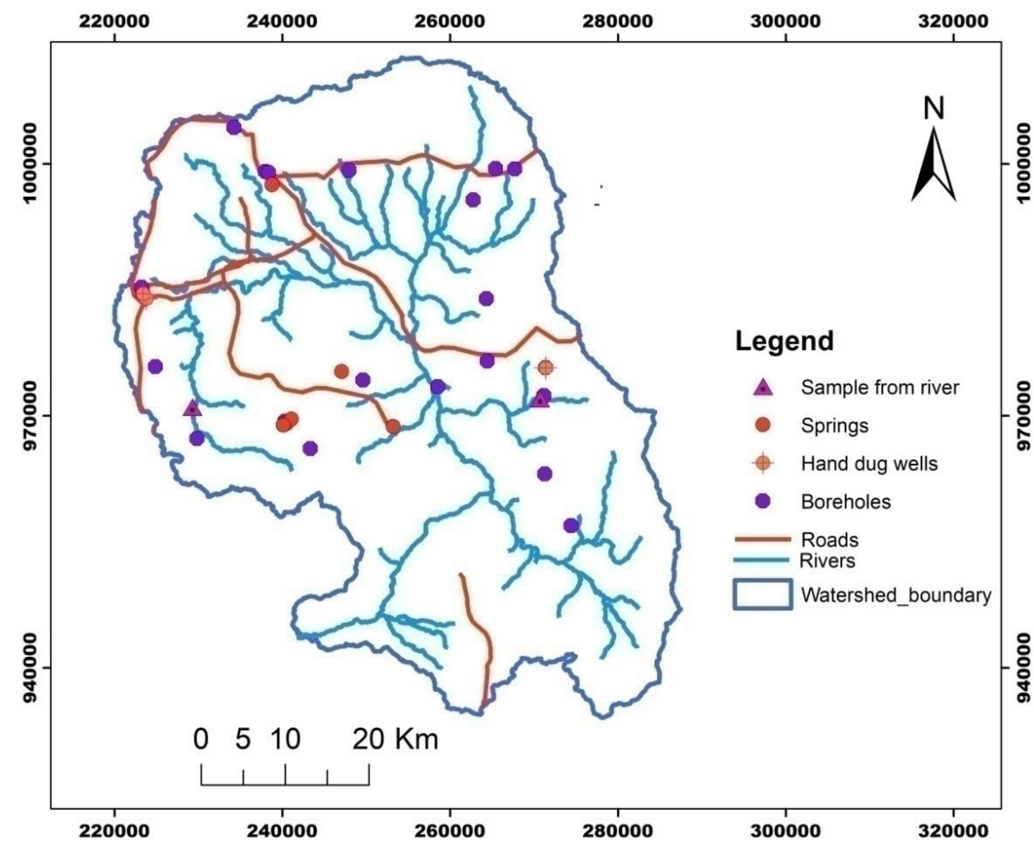


Figure 5.2 Boreholes, hand dug wells, rivers and springs where Insitu measurements were conducted in the catchment.

5.3 Types of Aquifers

An aquifer is defined as a saturated a permeable geological unit that stores and transmits economic quantities of water to wells. The excellent aquifers are unconsolidated sands and gravels of alluvial deposits, but permeable sedimentary rocks such as sandstone and limestone, and highly fractured and/or weathered volcanic and crystalline rocks can also be classified as aquifers. There are three types of aquifers: confined, unconfined and leaky (GSE, 2014).

A confined aquifer is an aquifer bounded above and below by an aquifuge; whereas an unconfined aquifer is a water table aquifer, and is bounded below by an aquifuge, but it is not restricted by any confining layer above. A leaky aquifer is also known as a semi-confined aquifer, whose upper and lower boundaries are aquitards, or one boundary is an aquitard and the other is an aquifuge.

In order to get hydraulic characteristics, it is important to know an aquifer system. Because each aquifer type (confined, unconfined) has unique model that is appropriate to compute their hydraulic parameters. This means, the hydraulic characteristics which are assumed to represent the real aquifer system relies on the model applied which in turn depends on aquifer type. Thus, aquifer type identification is a basic step in evaluating aquifer characteristic. Identification of the aquifer system of the study area has been made by considering the following technique.

The first approach is based on observation of lithologic logs of bore holes supported by well depth and general geological set up of the study area. This method utilizes aquifer location in the groundwater basin and static water level with respect to the position of water bearing formation (GSE, 2014).

As a second approach, fluctuation in discharge of springs and water level in hand dug wells are used. In the catchment area, it had been observed that discharges from springs increases during the rainy season falls with dry season. Likewise, the level of water in hand dug wells rise during rainy season and falls during dry months. These phenomena give insight that portion of the aquifer is exposed to the surface and receives recharge directly through the unsaturated zone and thus classified as unconfined aquifer. These are shallow aquifers that over lies fractured aquifers. They comprise mixture of sand, gravel and soil.

The depth goes from surface to about 25m. Spatially they are restricted to stream banks. They can easily tap by hand dug wells and shallow drilled wells.

In general, confined and unconfined aquifers are common type of aquifer in the catchment.

5.4 Hydraulic characteristics of aquifer

The main characteristics that define groundwater flow and storage are hydraulic properties (transmissivity, conductivity, yield, etc.). These properties are generally made through field measurements by means of pumping test. As it is a usual the pumping test duration is not smooth for all well and here it varies from 120 minute to 2880 minute. In almost all tests, steady sate or equilibrium is reached and data analysis is made using a suitable well-flow equations developed for such condition. Both Cooper-Jacob and Neuman analysis method were used for the interpretation of the data (GSE, 2104).

As an example, from well completion report of Bulbulo, the pumping record of well was analyzed for which the constant discharge test conducted without interruption for the total duration of 24hrs. The well discharged by a constant rate of 7l/s with a dynamic water level of 18.2m and 8.75m total drawdown. Under recovery test, water level was recovered over 71 percent within one hour. Among the important parameter to be analyzed is transmissivity, which is the measure of rate of flow under a unit hydraulic gradient through a cross-section of unit width over the whole saturated aquifer thickness. In quantitative terms, transmissivity is the product of hydraulic conductivity of the aquifer material and saturated aquifer thickness.

T = kb, where ‘k’ is hydraulic conductivity and ‘b’ is aquifer thickness.

But all the transmissivity of the studied well are derived from pump test data using aquifer test software to characterize the aquifer. Accordingly, Bulbulo well has transmissivity value of $34m^2$/day as obtained from constant test of Neuman curve fitting method for unconfined aquifer. Depending on this transmissivity value, hydraulic conductivity can be determined. Hydraulic conductivity determines the ease by which water can move through aquifers and is a function of both fluid and medium. Therefore, determines the productivity of the aquifer.

Then, hydraulic conductivity (k) =T/b where, value of saturated aquifer thickness is fairly assumed to be the length of total screened section of the well (42m).

$k = (34.2m^2/d)/ 42m = 0.81m/d$.

This value is in agreement with the one obtained from the Neuman analysis test (0.808m/d). Another parameter to define aquifer is specific capacity of a well. The data used for the calculation of specific capacity are obtained from the constant discharge rate used during pumping test and the pseudo steady state drawdown obtained at the end of constant rate test.

The specific capacity of a well depends both on the hydraulic characteristics of the aquifer and on the other features of the well like construction and pumping rate. The obtained value of specific capacity for different borehole ranges from 0.016-8.9 l/s (Annex 8).

SC = Q/S where, SC = specific capacity, Q = discharge rate (7l/s), S = drawdown

$$Sc = \frac{7l/s}{8.75m} = 0.8\ l/s/m.$$

This means 0.8 l/s can be pumped per one meter of drawdown (water level fall) in the well.

As observed from pump test analysis, the catchment aquifer shows wide range of variability in transmissivity and conductivity value. Both transmissivity and hydraulic conductivity are relatively high in the southern and extreme northern side than other side of the catchment. The conductivity and transmissivity value ranges from 0.003 – 17.28 m/d and 0.7 – 828 m^2/d respectively.

5.5 Aquifer Productivity

According to the report on hydrogeological and hydro chemical map of Arjo and Nekemte map sheet, the hydrogeological systems of the study area have been classified based on qualitative and quantitative methods. Classification and characterization of the aquifers based on qualitative approaches was based on dominant primary porosity, secondary fissured permeability and impermeable rock unit. But, to quantitatively characterize an aquifer with high degree of reliability, density of borehole data and their spatial distribution are the main requirement.

In this work, despite the fact that the classification of the hydrostratigraphic units is made on the basis of transmissivity, yields and specific capacity, the boreholes data in the catchment are limited and most of them do not have complete and continuous pumping test data.

Hence, in the area where data are not sufficiently available, field observations such as extent of weathering, fracturing, joint, distribution and magnitude of spring, topography and vegetation density were taken into consideration to accomplish the classification (GSE, 2014). On the basis of this concept, the water holding media of the catchment were grouped into different aquifer unit.

Based on the qualitative and the very limited quantitative data (the yield of springs and boreholes) and geological description, classification of the various rock units with their areal extent within the area was defined as follows:

1. Extensive (438.6 km^2) and moderately productive (T = 1.1-10 m^2/d, q = 0.011-1 l/sm, Q = 0.51 - 5 l/s for wells and/or springs) or local or discontinuous but highly productive porous aquifers in which flow is mainly intergranular. This aquifer consists of Quaternary deposits of lacustrine sediment of unconsolidated sand and silt, pyroclastic deposits and Mesozoic sediments.
2. Extensive (2008.5 km^2) and moderately productive (T = 1.1-10 m^2/d, q = 0.011-1 l/sm, Q = 0.51 - 5 l/s) or locally highly productive fissured aquifers in which flow is mainly through a regularly developed system of fissures and joints of volcanic rocks. These aquifers are shown in light green and consist of a large part of tertiary volcanics (lower, middle and upper basalt).
3. Extensive (larger than 100 km^2) and moderately productive aquifers with mixed porous and fissured permeability (T = 1.1-10 m^2/d, q = 0,011-1 l/sm, Q = 0.51 - 5 l/s for wells and/or springs). The aquifers consist of part of Jimma volcanics in the southern part of the map sheet where basalts are mixed with silicic rocks.

4) Extensive (larger than 100km^2) and low productive (T= 0.11-1m^2/d, q = 0.0011-0.01 l/sm, Q = 0.051-0.5 l/s for wells and/or springs) aquifers in which flow is mainly developed in an irregular system of fissures and the weathered mantle of crystalline rock (intrusive and metamorphic rocks) with local and limited groundwater resources.
5) Aquitards (83km^2) – minor aquifers with local and limited groundwater resources are represented by Upper trachyte flows and plugs.

5.5.1 Extensive and Moderately productive fissured aquifer

The hydrostratigraphic units of this zone are highly weathered and fractured basalt and ignimbrite/trachyte. The basalt usually possesses columnar joint and so highly susceptible to fracturing which in turn increases the potentiality of aquifer. Though fractured basalts and ignimbrites are the main constituent of this zone, scoria also encountered as water bearing formation in some borehole (Sire, Hadiya, etc.). The scoraceous nature of formations gives rise in water bearing characteristics together with high weathering and fracturing. Thus, productivity of this zone is favored by cumulative effect of high weathering and fracturing, columnar joint, paleosoil and inters lava flow between different lava successions. This basaltic unit might be a part of tertiary lower basalt exposed in part of plateau forming gentle slope and steep cliff (GSE, 2000).

Three volcanic units (Lower basalt, Middle and Upper basalt) are playing a great role as indispensable source of groundwater in the catchment. Unfortunately, Lower basalt dominate the elevated northern, southern and southwestern most extreme part of the catchment where annual rainfall is maximum.

This basalt has considerable amount of primary porosity and so it easily subjected to secondary processes. As a result, this unit has suffered weathering because of heavy rainfall and related intensive plant root that widens the joint. In some cases, it has a nature of multi-layer confined aquifer which attributed to its being affected by geologic processes at different depth. In fact, the degree of importance of the volcanic formation being an aquifer increased and gets better where it contains a secondary structure. From the borehole data an average yield of highly productive aquifer of lower basalt is 6.63 l/s, average yield of spring 0.75l/s.

The upper basalt on the other hand, dominates the northern and southeastern part of the area. Majority of this zone especially on southeastern part is characterized by thick succession of basalt and felsic rocks with basalt dominating the lower section. The felsic unit comprises ignimbrite, rhyolite, trachyte and pyroclastic material. According to Miller (1999) silicic lava such as rhyolite tend to be extruded as thick, dense flows and have low permeability except where they are fractured. Because of weathering, pyroclastic rock has formed a thick clay top soil. Even if thick topsoil enhances infiltration, this weathered material seen to reduce the opening of underlying formation as secondary filling rather than promoting recharge. Likewise, it is difficult for water to soak down through such clay mixed top soil.

As a result, more water drained and leaves the area either as runoff or evaporation lowering the total recharge. This can be revealed from Kechema borehole (Table 5.1) where formation is dominated by clay and well yields only of 1.5 l/s as estimated by compressor flushing.

But in an area where clay material is not a problem and secondary structure prevailed, upper volcanic also found to be essential aquifer with enough yield in the catchment and nearby catchment ((Hadiya and Toba (25 l/s)) respectively.

Middle basalt which occupies a higher topography and characteristically forming flat top ridges and plateau is also found in this zone. The flow attains thicker to the west, which attains a maximum thickness of 175 m around Meko area (GSE, 2014). The top part of the flow is highly weathered and fractured. The basalt is gray to grayish black and aphanitic to locally amygdaloidal.

Table 5.1 Representative lithological log of Kechema borehole

Depth (m)	Lithologic description
0 – 13.6	Cotton soil
13.6 – 27.3	Clay soil
27.3 – 31.8	Sticky clay soil
31.8 – 45.5	High sticky clay soil dominates pyroclastic
45.5 – 59.15	Slightly sticky clay soil
59.15 – 68.25	Slightly weathered clay dominated basalt
68.25 – 82	High to moderately weathered clay dominated basalt
82 – 86.43	Highly massive basalt
86.43 – 95	Highly fractured basalt

5.5.2 Extensive and moderately productive inter granular aquifer

This is aquifer associated with quaternary sediments in which the flow is intergranular. Quaternary sediments are mapped in the central part of the catchment area. It topographically situated on plain areas (topographic lows). It extensively found following the river.

Quaternary superficial deposits derived from down slope movements of weathered rock fragments and riverbank sediment occupying flat area are another distinct aquifer unit in this zone. This is the only unique formation in the catchment that behaves like intergranular unconsolidated aquifer.

Such deposit is found in limited thickness and areal extent at the foot of ridges and mainly in flat laying areas of Wama plain and its tributaries. They composed of gravel, sand, silt and clay. Generally, they are only source of groundwater in Wama valley but their productivity is determined by abundance of coarser and clay material as well as sorting. This situation results in the heterogeneity of the aquifer and hence its hydraulic conductivity is dependent on the position within the geologic formation.

No much borehole data is obtained for this unit. However, one well drilled in Daleti (Table 5.2) area close to Wama plain with depth of 150 m has aquifer thickness of 42.5 m and 1.68 m^2/d transmissivity. Maximum drawdown of 83.27 m observed with only 2.4 l/s yield. These observed values are unsatisfactory with respect to aquifer made of such formation.

The problem is that the area has low annual rainfall and high temperature that promote evapotranspiration. However, this is not only likely to be a factor. Therefore, this value probably attributed to either the error during pump test like partial penetration or the presence of intercalated clay and silt on the surface of recent alluvial deposits give rise to a limited direct recharge from rain. Generally, quaternary deposits are relatively permeable and productive. But, show great heterogeneity since their texture ranges from coarse gravel to clay and loose undifferentiated grains. According to Sen (1995), the aquifer potential of unconsolidated sediment ranges from moderate to high. In this case, depending on the result obtained from pump test the transmissivity and yield of this moderate zone range from (0.3 – 5.81) m^2/day and (0.5 – 7) l/s respectively.

Table 5.2 Representative lithologic log of Daleti borehole

Depth (m)	Lithologic description
0-13.8	Clay soil
13.8-52	Alluvial deposit
52-78.2	Highly weathered basalt
78.2-125	Scoria
125-150	Alluvial deposit

This zone is also represented by sandstone unit exposed around Wama lowland and Getema area. Sandstone is weathered at the top part while massive and fresh at the lower part. Wama sandstone shows medium to coarse grained texture and cross bedded sandstone with minor interbeds of conglomerate and conglomeratic sandstone (GSE, 2014). The sandstone has thickness up to 100m. Getema sandstone is known by its intercalation of siltstone, clay stone, shale and glacial deposits at the base of succession. The upper part is massive, thick and bedded sandstone.

Unfortunately, borehole data is not found for sandstone units. However, the sandstone formations are mostly massive and poorly sorted. The spring emerging from these units show low discharge and are seasonal, especially Getema sandstone. Few perennial springs which likely to emerge at contact between basalt and sandstone observed in Wama (Qaso spring) have good discharge. This partly associated with low topography of Wama as it is a part of discharge zone.

5.5.3 Extensive and Moderately Productive aquifers with mixed porous and fissured permeability

The aquifers consist of part of Jimma volcanics (Upper and Lower Limu Silicics) in the southern part of the area. The mixed aquifers are developed in fissured silicic basalt and porous rock in the southern part of the study area where some Tertiary sediment also intercalate volcanic rocks on the plateau.

Fresh basalt and silicic rocks are usually considered as being low permeable lithological units; however, the presence of the porous volcanic material and even sediments in between lava flows forms a body that can accumulate a large volume of groundwater by draining the surrounding fissured aquifers and contribute to the yield of wells. These fissured and mixed aquifers of the plateau represent an important hydrogeological unit in the study area.

5.5.4 Low productive fissured (weathered) Mantle of crystalline rock

This aquifer is local, discontinuous fissured in which flow is mainly developed in an irregular system of fissures and weathered mantle of crystalline rock (granite) with local and limited groundwater resources. This unit is exposed around Adere area, which is the central part of the catchment area. From the drilled well near the central periphery of the catchment (Table 5.3), for a source of water supply for Adare rural community (GPS location of 253233mE, 968716mN), it can be seen that, two major secondary processes enhance the permeability of this unit to be classified as aquifer.

Table 5.3 Representative lithologic description of Adere deep well

Deep(m)	Lithologic log
0-2	Top soil
2-32	Weathered granite
32-80	Moderately weathered granite
80-138	Slightly fractured granite
138-151	Massive granite

Weathering affects the most upper part of the aquifer. The weathered column of this aquifer ranges from 2m to 80m. The weathering column is thicker, and this is most likely because of the altitude is lower (i.e., 1522m) and temperature is higher to enhance chemical reaction there by intensifying weathering activity.

Chemical reaction enhanced the chemical weathering of this unit and the weathering product has significant porosities and specific yield, it therefore, acts as a reservoir, storing infiltrated water and releasing it to the well which has intercepted fractures.

Accordingly, from pumping test result of this well the yield and transmissivity of this aquifer are 4l/s and 4.3m^2/d respectively. Actually, these values (transmissivity and yield) are high and may group a formation as moderate productive zone.

Gaddisa et al. (2014) stated that western basement possesses the lowest hydraulic conductivities and intermediate well yields range from 0.5 – 8 l/s. To reasonably classify this formation, it needs detail investigation. Therefore, it is difficult to group beyond this zone based on a single borehole and now make a part of low productive zone.

In conclusion, the water bearing capacity and the ease to release it in this unit is highly dependent on degree of weathering and the thickness of weathered column, and the intensity of fractures. Both fractures and weathering are obviously not evenly distributed. It follows that; ground water potential in this unit is localized associated with weathering & fracturing. These phenomena made the unit to be heterogeneous & an isotropic.

5.5.5 Aquitards

Minor aquifers with local and limited groundwater resources are represented by upper trachyte flows and pyroclastic rocks (GSE, 2014). Surface exposures of this deposit are found in the northern parts of the study area covering a total area of 83km^2.

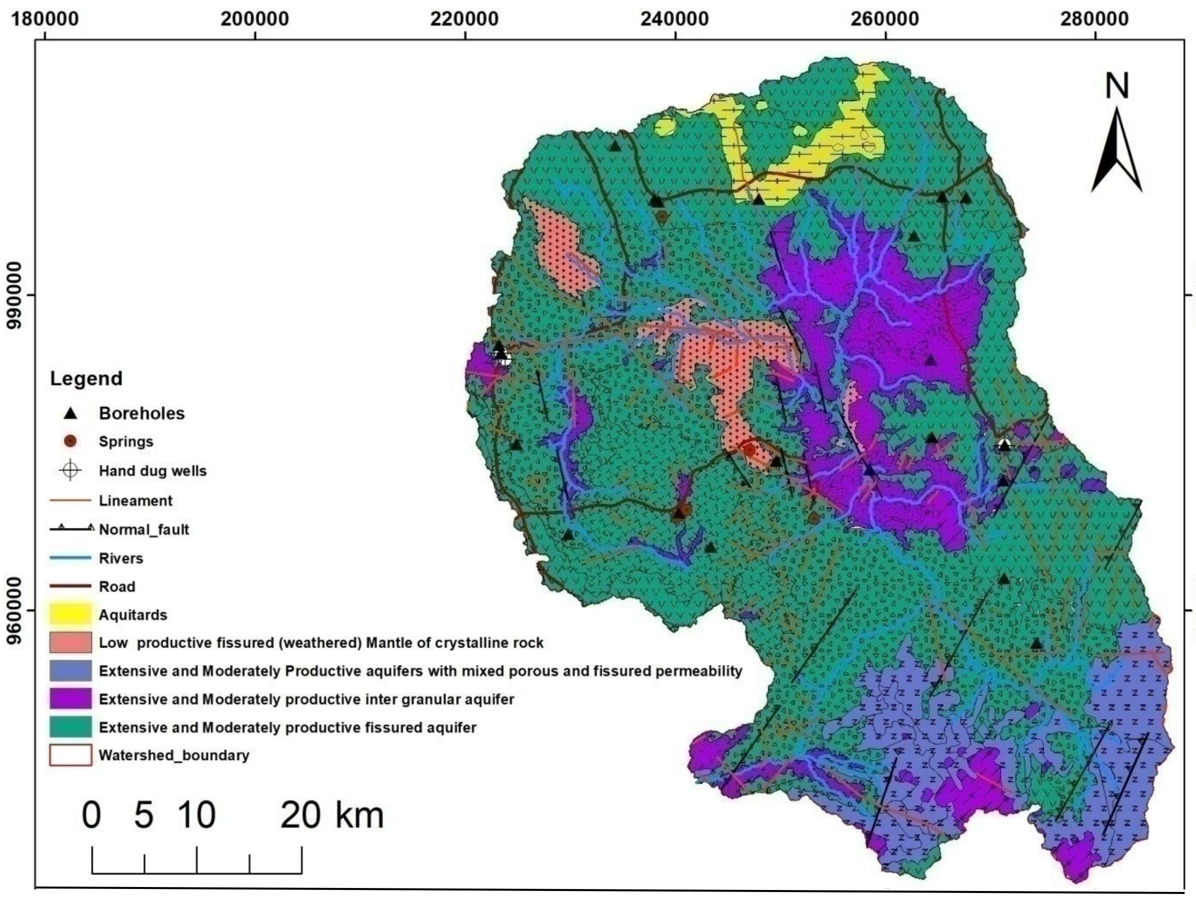


Figure 5.3 Hydrogeological map of the study area (Modified from GSE, 2014)

5.6 Groundwater flow direction and system

5.6.1 General

Groundwater flow direction is an imaginary path that particle of groundwater would flow as it flows through an aquifer. It helps in visualizing the flow nature of invisible subsurface groundwater movement. Groundwater commonly flows from regions of recharge to regions of discharge in the direction of decreasing water-level altitudes and perpendicular to the water-level altitude contours (Fetter, 2001). However, there may be local flow deviation from a regional direction due to impact of structure like sediment bedding, foliations or some hidden structures like fault. Occasionally, Variation in the hydraulic conductivity of the different rocks can even cause local deviations to the general groundwater flow direction.

In preparing groundwater flow direction, water level measurements are taken from preexisting borehole records because well have no access for water level measurement currently since they are sealed. But this may have paramount effect on the reliability of flow map. Because, water level measurements have taken at different time but temporal variation in groundwater level can also bring changes. According to John (2002) water level measurements should be measured within a few days of each other because the map represents a specific point in specific time. Another source of uncertainty is that, water level might be affected by penetration depth of well into aquifer as in some aquifer partial and in others fully penetrated. This all together with scarce distribution of borehole at important point in the catchment limited the preparation of actual map for groundwater flow direction.

5.6.2 Groundwater flow direction

Groundwater flow direction is primary controlled by topographical, geological and structural pattern of the area. However, degree of these effects on flow direction is different depending on the nature of a given catchment. In most cases, it is highly influenced by geology and topographic setup. However, in the area where geologic structure dominates groundwater flow is governed by structural alignment.

Southern part of the catchment is characterized by SW-NE running dense lineament responsible for emergence of many streams. Hence, it is likely that lineaments are acting as groundwater conduit and also partly control the local flow system.

However, groundwater flow of the catchment mainly follows gentle slope and the groundwater table is parallel to the topography. As a result, the regional trend of groundwater flow is from the surrounding ridge and highland to the northwestern direction along which there exists a general Potentiometric head decline. Spatial distribution trend of water chemistry can also justify this flow direction.

In addition to this, by means of field measurements of the water table or piezometric surface, representative contour maps can be drawn for the various types of aquifers within the hydrogeological basins (Tenalem Ayenew and Tamiru Alemayehu, 2001). However, in this work because of no enough borehole data, there is no groundwater contour produced to show groundwater flow direction. Instead of this, the groundwater depth obtained from elevation of boreholes and static water level was used to show the direction of groundwater flow (Figure 5.5).

In tracing of the cross section from any part of the catchment to the Wama plain all shows gradual elevation decline toward the outlet. This indicates that groundwater flow exhibit topographic replica. As observed from figure 5.4 below, there is a gradual elevation from Komto ridge and Koma rigde to Wama plain, and similarly from Arjo-Getema highland and from Mote rigde to Wama plain and towards the outlet. Similarly, groundwater depth (Elevation of borehole-static water level) for 14 (fourteen) boreholes decreases from the surrounding ridge and highlands to the outlet of the watershed.

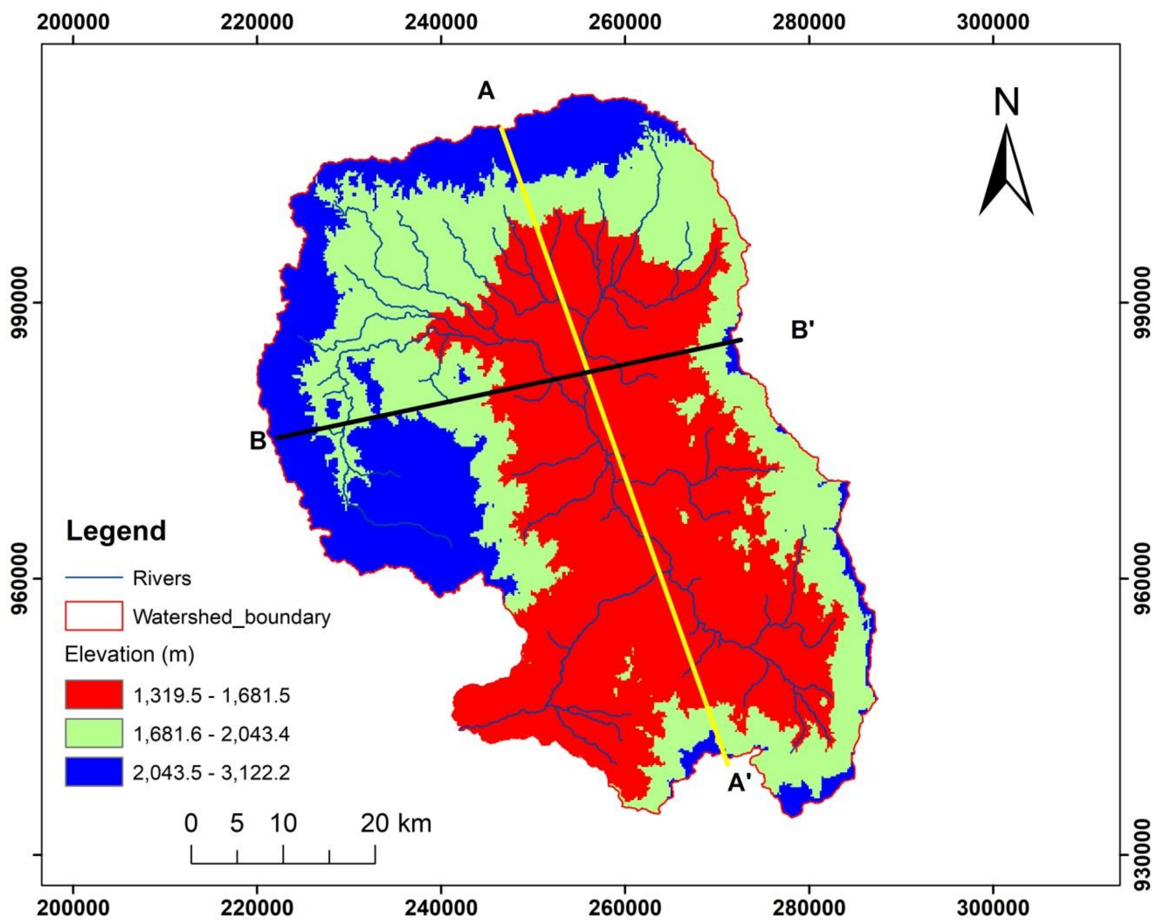
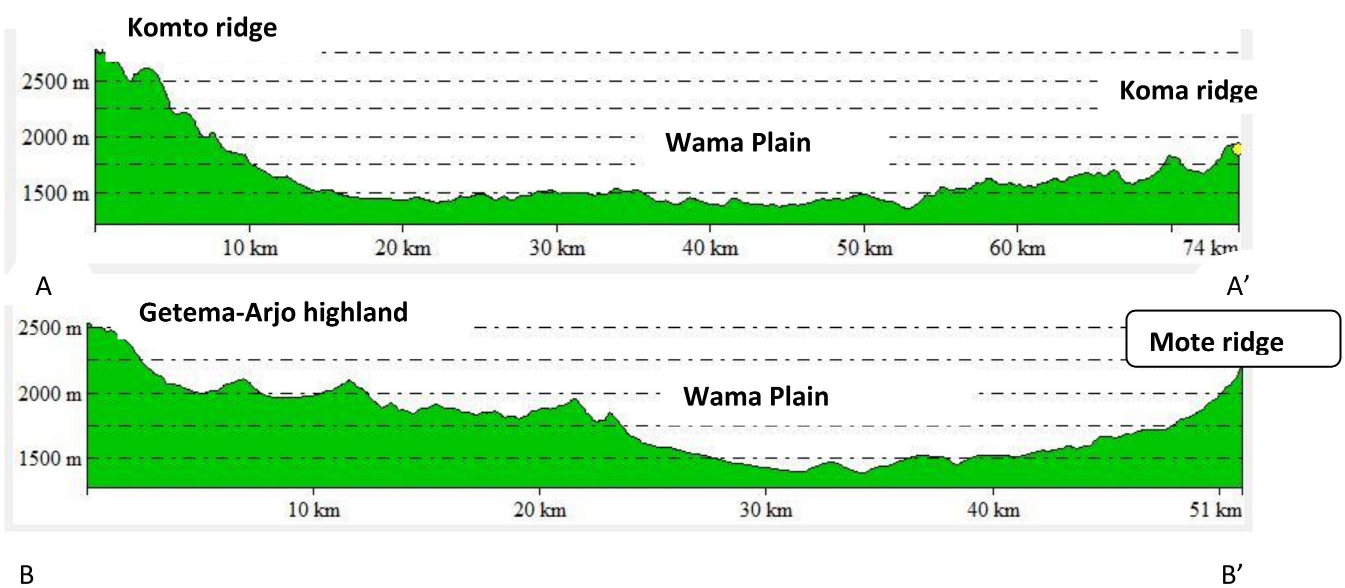


Figure 5.4 Map showing a line along which cross section AA' and BB' given below are plotted



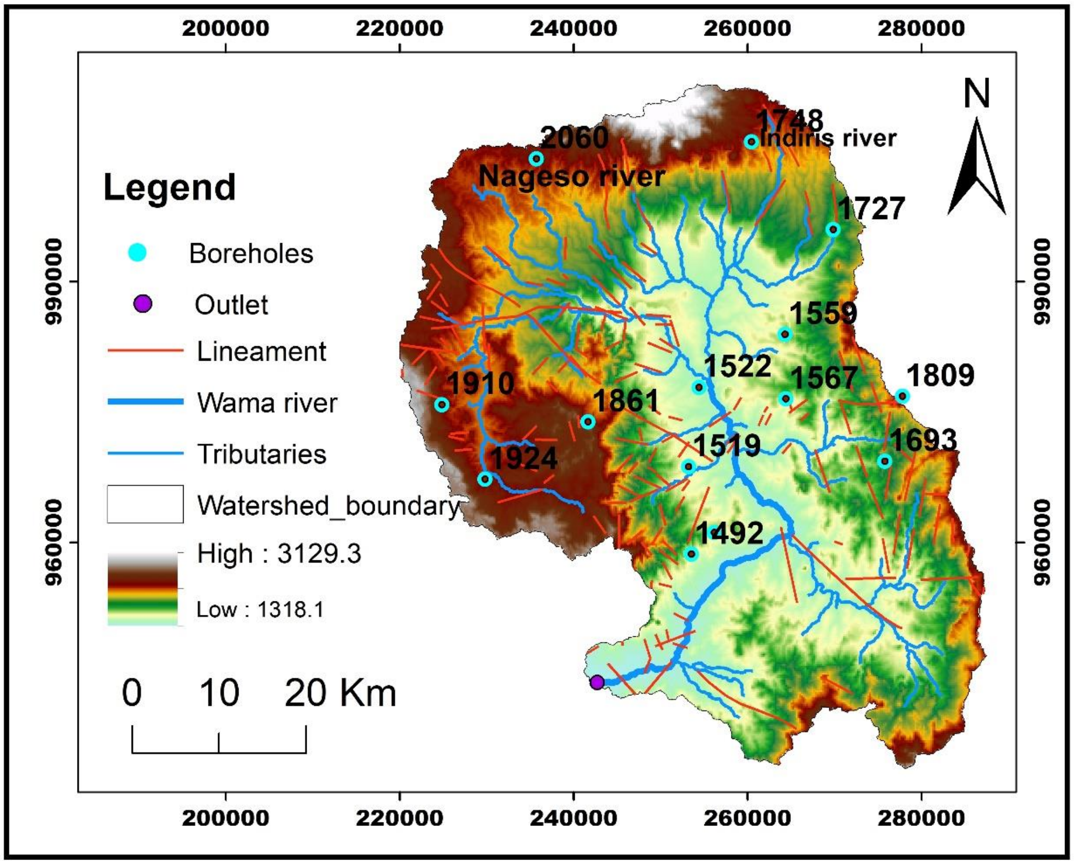


Figure 5.5 Digital elevation map with groundwater water level (in meter)

5.7 Recharge and discharge zone

Groundwater recharge is a downward flow of water reaching to the water table and forming an addition to the groundwater reservoir (i.e., an aquifer). Even though, the magnitude may differ, every catchment possesses the following identifiable three different types of groundwater recharges (Tenalem Ayenew and Tamiru Alemayehu, 2001).

- The first one is direct groundwater recharge which comes from the rainfall. It is the ultimate groundwater recharge that we worry and should worry about.
- The second is Localized groundwater recharge which is associated with very local lateral flows of infiltrated water, ultimately joining the groundwater level (table) at some distance from the point of infiltration.

- The third is indirect recharge which is obtained from surface water bodies. This type of recharge can be originated either from natural (e.g., Rivers, streams, ponds, lakes, etc.), or man-made structures (e.g., dams, irrigations, reservoirs, canals, etc).

The indirect recharge is common in arid and semi-arid areas (Tenalem Ayenew and Tamiru Alemayehu, 2001). Groundwater recharge area can be defined as that portion of the drainage basin in which the net saturated flow of ground water is directed away from the ground surface and the water table usually lies at some depth (Freeze and Cherry, 1979). In the catchment, chain of ridge and hill which act as surface water divide are the main recharge zones. High velocity surface runoff and groundwater from these mountains area rush down the slope to the discharge area.

In the catchment area, most of the northern and northwestern highlands (Komto and Getema-Arjo) and the eastern highlands (Sodu, Koma and Mote) feed the catchment from all directions (Figure 5.6). In the recharge zones, there is often deep unsaturated zone between the water table and the land surface. As the result, the opportunity to get water at surface is minimum unless at contact and intermountain depression.

On the contrary, discharge areas can be defined as the movement of the net saturated flow of groundwater directed toward the ground surface and the water table usually lies at or very close to the surface (Freeze and Cherry, 1979). By general principle, topographically high areas are usually considered as recharge zone and topographically low areas can be considered as discharge zone. In most cases, the ground water discharge areas are indicated by the appearance of springs. Here in the catchment, a lot of springs emanate at the weathered and fractured parts of high ridge and high cliff of deep gorges. Another form of groundwater discharge is the capillary rise of water from shallow groundwater tables.

The rate of capillary rise depends on the depth to groundwater table and the type of soil or rock material. This is observed forming saturated mud at surface mainly before the onset of dry month. The groundwater discharge in this form is usually a local and temporal phenomenon. Thus, it may not essentially represent the regional groundwater discharge but give rough estimate of discharge condition. In discharge area, water table is found either close or at the land surface (Fetter, 2001). This is marked by many wetlands and saturated soil.

In the catchment, communities around Wama Boneya, Nunu, and Boke are using it for agricultural activities during dry season. Unlike the recharge area, the net saturated flow of groundwater is directed towards water table and the flow vector lines converge to each other in discharge (Figure 5.6). But this convergence may not occur if the discharge zone is large. Some area but shows property of both recharge and discharge area and considered as transitional zone. Major part of Adare, Seka and Haro are few possible areas of this zone (Figure 5.7).

Toth (1963) cited in Fetter (1994) showed the possibility of mapping recharge and discharge areas on the basis of field observation using the basic indicators such as topography, piezometric patterns, hydro chemical trends, environmental isotopes, and soil and land surface feature. Among these indicators, topographic elevation is the simplest (Freeze and Cherry, 1979) and piezometric measurements are the most direct.

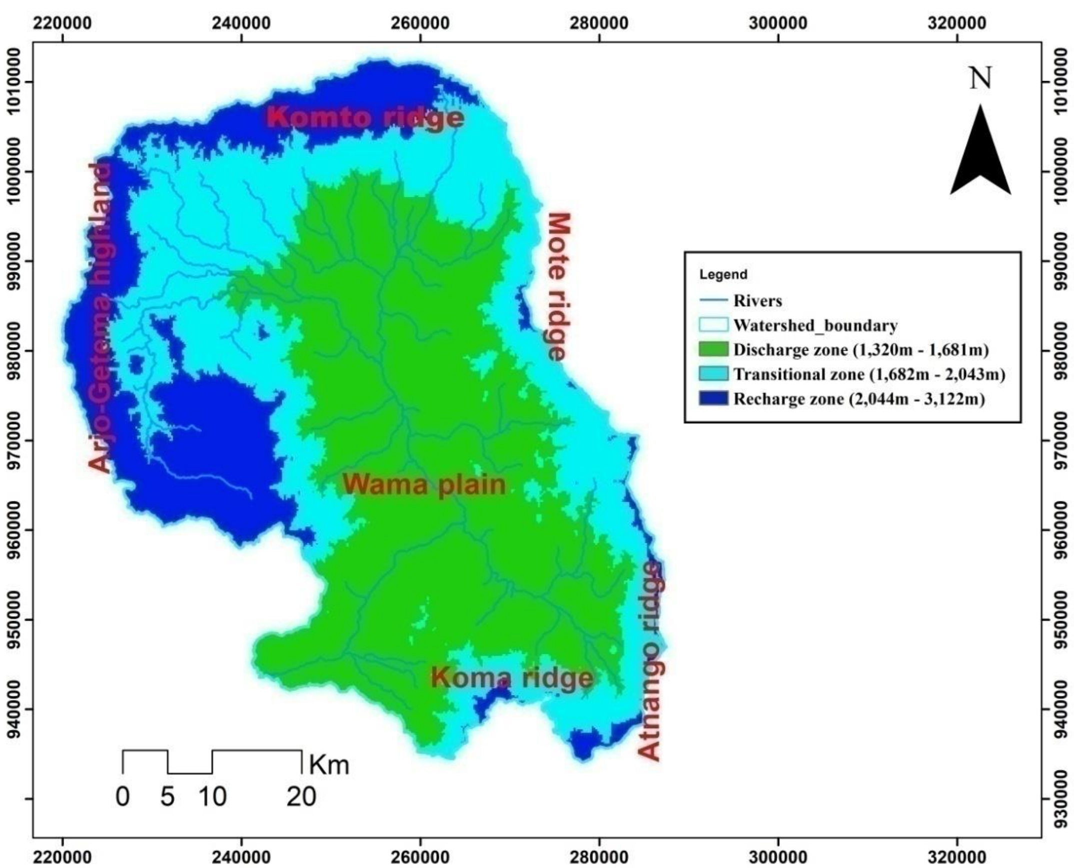


Figure 5.6 Recharge and discharge zones in inferred from elevation map

CHAPTER SIX

HYDROCHEMISRY

6.1 General

Hydrochemistry is an outstanding scientific approach in field of hydrogeological study to provide information both in space and time related to origin, quality and history of natural water. It plays crucial role in interpreting the general occurrence of various constituents in waters, controlling factors and the relation of these constituents to water use.

The water being reactive with various elements significantly affects its chemical and physical property. As water comes in contact with a given material, it inherits the property of that substance through chemical reaction or physical contact which subsequently alters its chemistry. When falls through atmosphere as precipitation, water has very small quantities of some solutes from dust and gases but acquires majority of its solute once it reaches the land surface. Its chemistry then changes due to displacement and replacement reaction between ions as a result of interaction with a rock and/soil.

The atmospheric chemical composition of rain water, the composition and chemical conditions of the soil and geological formation determine the composition of groundwater in the basin. Such that hydrochemical analysis of water composition may provide information about the environment through which the water has circulated. Thus, to determine the usefulness of the basin's water for various purposes, chemical analysis is very important for the recommendation of water quality. In this chapter it was attempted to provide the hydrogeochemical characteristics of the catchment's groundwater from the point of view of spatial natural compositional variation along with quality analysis for domestic and agricultural uses.

6.2 Field measured parameters

Some of physical parameters have to be measured Insitu in order to avoid contamination of the sensitive parameter. These include temperature, electrical conductivity and hydrogen ion activity.

Table 6.1 Statistical description of field measured parameters

Parameter	Minimum	Maximum	Mean	Standard deviation
T (°C)	21.3	28	24.65	0.4
EC (µS/cm)	62.7	452	257.25	145
TDS (mg/l)	29	365.7	298	92.8
pH	3.04	8.5	5.77	0.5

6.2.1 Electrical Conductivity (EC)

Electric conductivity is the ability of water to conduct an electric current relating to amount of dissolved solid in the water. As groundwater circulate through geological media, it enriched by different constituents through reaction and leaching property of water such that EC become high. The presence of charged ionic species in solution makes the solution conductive. As a number of ionic concentrations increase, conductance of the solution increases. Therefore, the conductance measurement provides an indication of ion concentration in the given water. The overall EC value of study area varies from 62.7µS/cm to 452µS/cm; 62.7µS/cm is the lowest EC among borehole's EC value and is recorded for Sire BH. This may relate to shallow water circulation as it is shallow well or/and because it is a recharge area which get replenished by fresh water that had short time water rock interaction.

The high EC (452 µS/cm) is recorded for Mote deep well (200m), related to high temperature around depressed area (at elevation of 1509m). High temperature raises solubility and dissolution of many minerals and provides more ionic charge (solute) that elevates electrolytic property of water. As a result, water at deep may incorporates high mineral constituents through rock dissolution triggered by high temperature coming from depth. The EC value of the area has no systematic trend in its distribution. This is attributed to rugged nature of the catchment which favors many local recharges and discharge so that groundwater replenished and exposed in any form of discharge without moving far from source area and resulted in low EC.

However, there is general increase from area of recharge to discharge as the highland of active recharge area has low EC. On the other hand, the upper north eastern side of the catchment around Wama and Limu Seka shows highest EC in the catchment. Knowingly, there is low rainfall and high temperature in the vicinity of these areas.

Therefore, this high EC may be due to high evapotranspiration which leaves behind more salt as well as low rainfall that cannot provide dilution.

6.2.2 pH (Hydrogen ion activity)

pH is a measure of water's acidity or alkalinity that has scale range from 0 (high concentration of hydrogen ions and acidic) to 14 (high concentration of hydroxide ions and strong base). In pure water, the concentration of hydrogen ions is in equilibrium with the concentration of hydroxide ions so that pH measures exactly 7. However, since pure water is hardly found in nature the PH value of natural water usually deviates from equilibrium value. This is also true for study area whose pH value range from 3.04 to 8.5. Potable water should have pH value between 6.5 and 8.5 according to WHO (2006) and Ethiopian drinking water quality standard. Any water with PH less than 6.5 is regarded as acidic and above 8.5 is basic. Most water sample fall in this range but 5 samples are below the lower limit of World Health Organization standard. Among these, two are deep well, two are hand pump well and one is spring.

pH is controlled by types of geologic formation and hydrogeochemical reactions that produce or consume hydrogen ions.

For example; $H_2O + CO_2\ (g) = H_2CO_3$

$$H_2CO_3 = HCO_3^- + H^+$$

$$HCO_3^- = CO_3^{2-} + H^+$$

Since, pH = -log [H^+], the process that contribute hydrogen ion concentration to a reaction lowers the PH of a solution. Therefore, these observed low PH may be a result of chemical and biochemical decomposition of vegetative residues and from activity of micro-organisms that release more carbon dioxide into subsurface. The above listed samples are below pH level of WHO, and are relatively shallow and most necessarily affected by near surface, biological and biochemical process that generate CO_2. Otherwise, the natural water in the area has generally a good quality in terms of pH value.

6.2.3 Total Dissolved Solid (TDS)

Total dissolved solids include all the solid material in solution and is determined from the weight of dry residue remaining after a sample of water has evaporated at a temperature of 105^0C.

As water flows through a geologic formation, it dissolves rock of different composition it encounters on the flow path. The number of dissolved materials in natural water is one of the basic measures of the water quality. It is better to see the well water and spring water in study area separately.

The TDS value varies from minimum value of relatively fresh groundwater of 45.8mg/l, for Gombo spring located at Gute (X- 0238784, Y-997496N and Z-1882m) to 365.7mg/l, for a deep well having 200m deep, which is located at Mote (X-0271200, Y-0972400 and elevation of 1509m). The lowest (45.8 mg/l) TDS value is recorded for SP-1, which is also expected value for recharge area. Even if this spring is part of discharge area, which could have high TDS value, this much value may indicate another source because dissolved solid can also added to groundwater by anthropogenic impact. On the other hand, the highest TDS (365.7mg/l) observed for BH2 (Mote), indicates that TDS value of groundwater is strongly controlled by the time of water-rock interaction along the flow path.

Generally, high land has low TDS as compared to low lands because of low water rock interaction than low land. This means, as long as the water moves from the source area through porous spaces for a long time to a long distance, the TDS became higher.

There is a direct relationship between TDS and EC value. The more total dissolved solids (TDS) in water the more it will conduct electricity. As observed from (Fig. 6.1) they are correlated with best fit of regression (R^2= 0.975).

On the basis of USGS classification of TDS, the water of study area falls under fresh water.

Table 6.2 Water class on TDS.

TDS(Mg/l)	Water class
0-1000	Fresh
1000-10000	Brackish
10000-100000	Saline
>100000	Brine

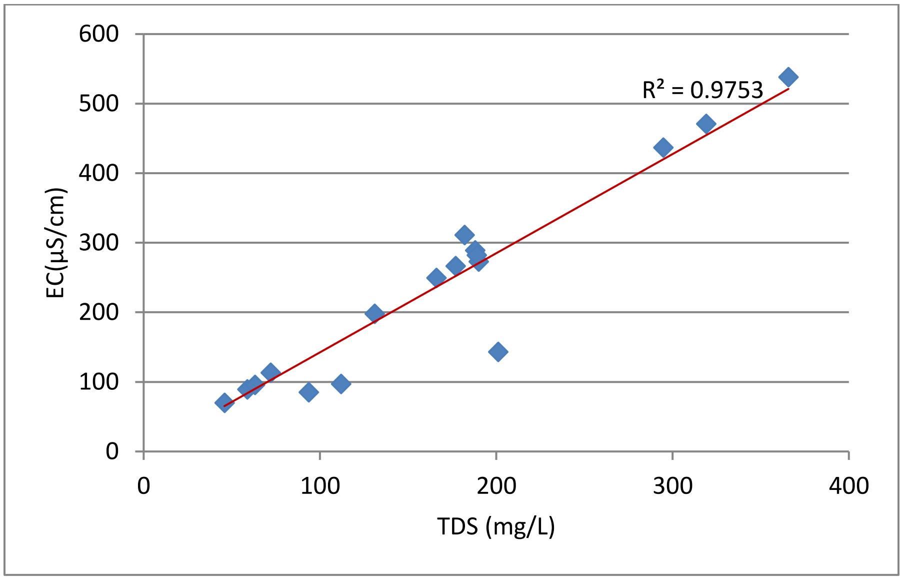


Figure 6.1 TDS-EC relationships

6.3 Major ion chemistry

More than 90% of solute in water is dominated by eight ions comprised of; Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, HCO_3^-, Cl^-, SO_4^{2-} and CO_3^- (Fetter, 1994). They are usually present in water at concentration greater than 1mg/l and water chemistry is highly controlled by this species. These solutes are naturally very variable in surface and groundwater due to local geological, climatic, and geographic conditions.

Calcium is present in all waters as Ca^{+2} and is readily dissolved from rocks rich in Calcium minerals. This cation is abundant in surface and groundwater. Acidic rain water can increase the leaching of calcium from soils and rock. From the water sample analysis results of study area, Calcium is the most dominant cation. It's concentration in groundwater sources shows variability and generally range from 15.2 mg/l to 69.6 mg/l for borehole. Surface springs have calcium concentration from 31 mg/l to 68.7mg/l. This high calcium is derived from probably the ca-rich weathering products of plagioclase feldspar and pyroxene rich basaltic rock.

Sodium is the second dominant cation next to calcium in study area. The concentration of sodium in analyzed sample is within the range of 6.72 mg/l (BH-4) to 68.5 (BH-6) for deep well and for spring water, it is from 6.4mg/l (SP-1) to 46.3 mg/l (SP-2).

The high concentration of Na is in deep well. This is insisted by deep circulation of water through subsurface fracture encountered high temperature.

Magnesium is another major cation with low concentration in study area, relative to calcium and Sodium. This may be because of its less mobility. The Mg^{+2} value ranges from 1.1mg/l to 28.4 mg/l. The concentration shows variation between highland and lowland but more dominant than K^{+}. The minimum K^{+} concentration is 1.1mg/l for (BH-4) and the maximum is 14.8mg/l for spring (SP4). Potassium is liberated hardly from silicate minerals but rather exhibits a strong tendency to be reincorporated into solid weathering products and thus found in water with low amount.

In study area HCO_3^{-} is the most dominant major anion followed by Cl^{-} and SO_4^{-2} respectively. The maximum value is (689.4 mg/l) for deep well (BH6) and the minimum is (29.28 mg/l) for (BH-1). The higher concentration of bicarbonates is due to the reaction between water and dissolved carbon dioxide that emitted from underlying heat reservoir.

Chloride is the dominant anion following bicarbonate. The maximum chloride concentration of study area is 59.6 mg/l for spring and the minimum is 2.06mg/l for boreholes. High chloride (59.6 mg/l) is from spring water and it is due to anthropogenic effect mainly from Nunu Kumba town, but in the case of BH (22.3mg/l), it could be the result of deep-water circulation.

Sulfate is another anion found in very low concentration next to chloride. Majority of analyzed sample has very insignificant amount of sulfate. It varies from 1.5 to 16.5mg/l in study area. The maximum concentration for borehole is 11.8mg/l (BH-5). The variability of the chemical ion in solution expressed by variation (standard deviation) is very important as majority of the analyzed parameter has difference in their quantity from site to site. The average and standard deviation are close to each other indicating little variation from sample to sample.

Table 6.3 Statistical description of the major ions.

Parameter (mg/l)	Minimum	Maximum	Average	Standard Deviation
Ca^{+2}	15.2	69.6	42.4	17
Mg^{+2}	1.1	28.4	14.75	7.6
Na^{+}	6.41	68.4	37.4	17.7
K+	1.1	14.8	7.95	4.1
HCO_3^-	29.28	689.4	359.34	186
Cl^-	2.06	59.6	30.83	12.7
$SO4^{-2}$	1.5	16.5	9	4.8

All water samples collected from the study area have a TDS value of less than 1000mg/l.

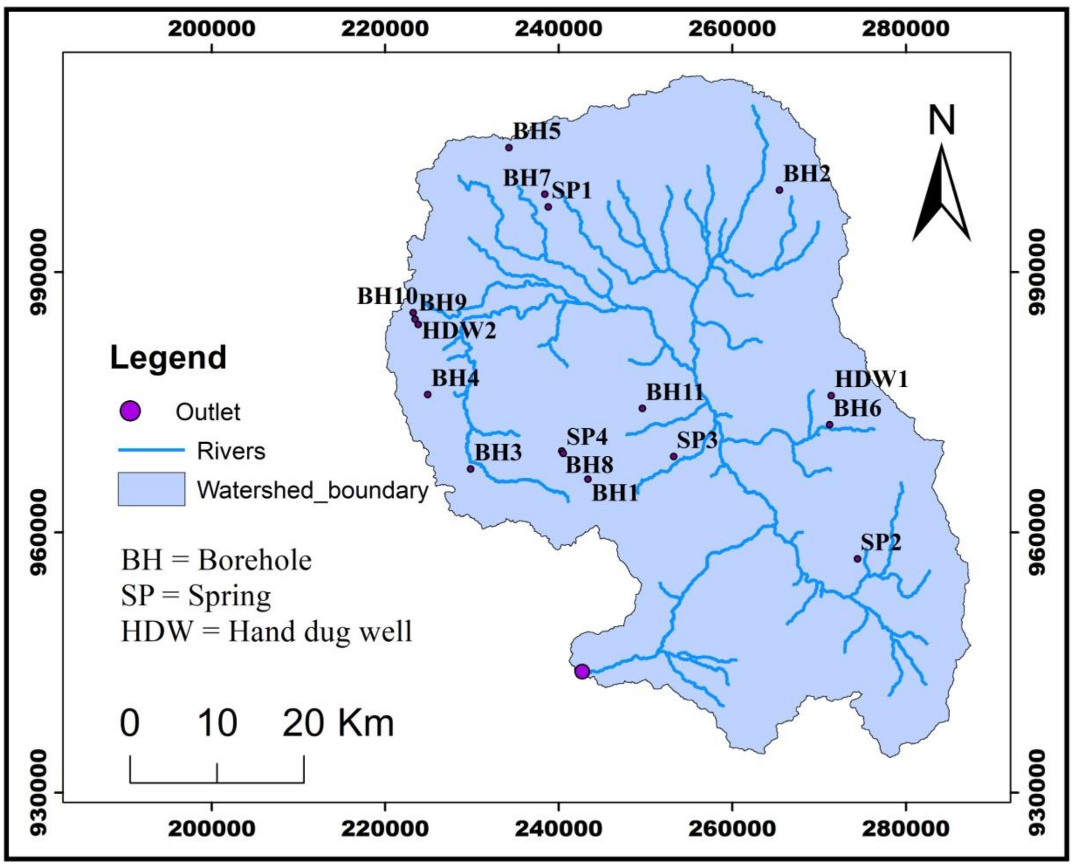


Figure 6.2 Sampling site map of the study area

Among the important task in hydrogeochemical investigation is the presentation of the chemical data in a proper manner for interpretation.

There exist different methods for hydrochemical data presentation but, it is believed that the graphical methods based on major cations (Ca^{2+}, $Mg^{2+}$and Na^{+} + K^{+}) and major anions (HCO_3^-, Cl^- and SO_4^{-2}) are thought to be best for visual observation. The classification uses a percentage of mill equivalents per liter of the anions and cations to denote number of ions on graph. For this purpose, piper plot is used to present the analysis as given below. Piper trilinear diagram is the most widely used method for interpretation and classification of water. This is due to the capacity of method in showing mixing effects between different water in addition to showing much sample at once. Here, water type is classified based on the plotting position of cations and anions.

As observed from (Fig 6.3) there is Ca-HCO_3, Ca-Na-HCO_3, Ca-Na/Na-Ca-HCO_3, and Ca-Na-Mg-HCO_3 water types. But, two water samples (one spring (Ombosha) and one borehole (Kechema)) show distinct water type, which is Ca-Na-Mg-HCO_3-Cl type. This type of water type may relate to agricultural activity like fertilizer and animal manure, or the result of anthropogenic activity. As described above in the major anion in the study area, Ombosha spring which is represented by blue color in piper plot is a water supply situated nearby town at the down side of the ridge and probably affected by domestic wastes and faeces from Nunu town.

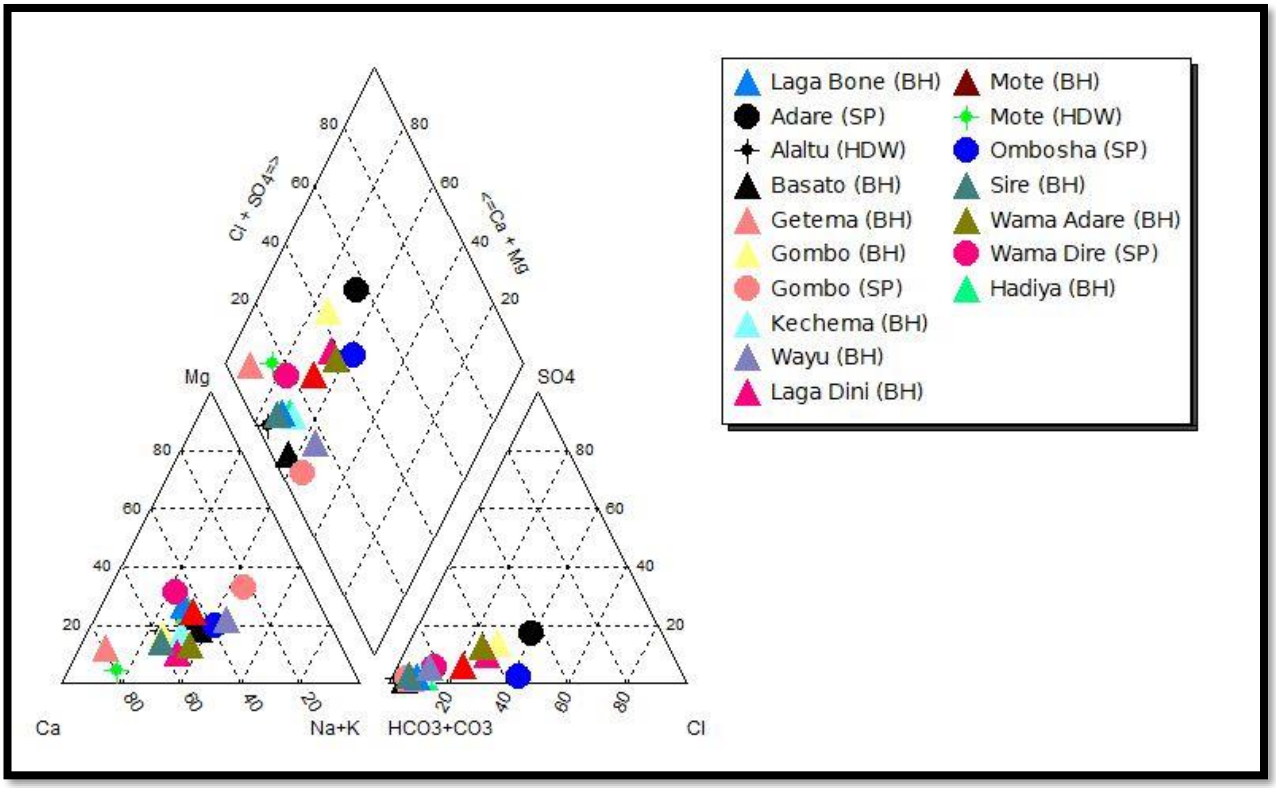


Figure 6.3 Piper plots of the water samples

6.4 Classification of water type

Accordingly, the groundwater is classified into three major water types and these groups are explained here under. However, there is also another water type like Ca-Na-Mg-HCO_3-Cl. As observed from the piper plot, Ca-HCO_3, Ca-Mg/Ca-Na-HCO_3 and Na-Ca/Na-Mg-HCO_3 are the three types of water in area. It can be observed from the piper plot, that the cations plot mainly clustering around the Ca^{2+} showing the dominant cation is Ca^{2+} with some samples aligned towards the Na^+ apex showing progressively increasing sodium enrichment. This depicts that the dominant controlling factor is rock-water interaction than mixing of distinct water types (Ca-Type, Ca-Mg type to Na-type). On the other hand, the anion plot exclusively clustered around the (HCO_3^-) manifesting all the water samples are bicarbonate- type.

Ca-Mg-HCO_3 water

This water type is commonly a typical characteristic of recharge area. It seems like that the water is fresh and not subjected to more water–rock interaction. In the general groundwater chemical evolution, Ca–Mg–HCO_3 types waters are often regarded as recharge area waters which are at their early stage of geochemical evolution (Bartolino et al., 2003).

Hence the Ca-Mg-HCO_3 type of water which is found in the recharge areas of the northern and southern highlands area dynamically circulating and evolving groundwater. The average TDS of this type water is 150mg/l which verify the water is fresh and hasn't undergone pronounced geochemical reaction.

Ca-Na/Na-Ca-HCO_3 water

Majority of the analyzed water sample belong to this water type. Such water is noticed in almost all of eastern and south eastern part of the catchment. This area is known by different lithology like Jimma volcanic (basalt, rhyolite, and pyroclastic unit) and recent volcanic of trachyte to phonolite origin as well as sandstone unit. Hence, it is likely that such water type is attributed to dissolution of the above-mentioned feldspar bearing rock that release Ca^{+2} and Na^{+} into water. On the other hand, this area can be slightly taken as recharge area on south eastern margin of the catchment.

But some area much look like a discharge zone since majority of the recharge is provided from boundary ridge like Koma and Mote. Thus, this zone also partly acts as local discharge area and has Ca-Na-HCO_3/Na-Ca-HCO_3 water which is a characteristic type of transitional zone.

Na-Ca/Mg-HCO_3 water

This water type is enriched by Na^{+}, Ca^{2+}, Mg^{2+} and HCO_3^{-} ions. The TDS value of this water type is high compared to the other groundwater samples of the area. The active discharge area of the catchment mostly the middle part belongs to this group. The Ca^{+2} ion dominance from the northern, southern, south western and south eastern part of the catchment area decreases down along the flow direction and finally replaced by Na^{+} ion evolving into this water type. There are 17 samples and the type of water for each sample is as follows.

Table 6.4 Types of water in the catchment

Nº	Water type	Number of samples
1	Ca-HCO_3	4
2	Ca-Mg-HCO_3	2
3	Ca-Na-Mg-HCO_3	3
4	Ca-Na-Mg-HCO_3-Cl	2
5	Na-Ca-HCO_3	4
6	Na-Ca/Mg-HCO_3	2

6.5 Hydrochemical evolution and major process controlling the chemistry of groundwater

6.5.1 Major cation

Knowingly, most waters of the basic and acidic volcanic province are dominated by Ca-Mg and Na ions respectively. But their amount in water is a function of many geochemical processes. Calcium which is a principal constituent of many rocks might be derived from mineral silicates of pyroxene, amphibole and the feldspar as well as carbonate rock. But, in study area carbonate dissolution is unlikely to be a case for calcium as no reported carbonate rock though it may be present as a partial filling particle between interstice of sandstone and other detrital rocks. Therefore, being a part of Ethiopian plateau the main source of Ca^{+2}/Mg^{+2} in the study area could be hydrolysis of silicate that compose the basic volcanic. Some silicate minerals undergo dissolution through a reaction to form cation and anion with solid clay mineral (Herczeg, 2001).

$CaAl_2Si_2O_8 + 3H_2O + 2CO_2 = Al_2Si_2O_5 (OH) 4 + Ca^{+2} + 2HCO_3^-$

$[CaMg0.7Al0.6Si1.7]O_6 + 4H_2O + 3.4CO_2 = 0.3Al_2Si_2O_5 (OH) 4 + Ca^{+2} + 0.7Mg^{+2} + 1.1H4SiO_4 + 3.4HCO_3^-$

This silicate hydrolysis can also represent the geochemical reaction that generate both cation (Ca^{+2}, Mg^{+2}) and anion (HCO_3^-). In general, calcic plagioclase, calcium rich pyroxene and amphibole hydrolysis suggested being main source of calcium, magnesium and bicarbonate ions in study area.

The other dominant cation is sodium. Many geochemical processes are responsible for addition of sodium ion in natural water. The common are dissolution of silicate and Halite, evaporation and cation exchange. The Halite dissolution is not likely to be a source for sodium here. If halite is the case, a linear relationship should be observed by a line with approximate slope equal to one (1:1) when concentration of Na^+ is plotted against Cl^- because both ions enter into solution in equal quantity during halite dissolution. However, if points are below or above the line the most common source for Na^+ is silicate or ionic exchange. But as observed from (Fig 6.4) there is no 1:1 relationship between them indicating Na^+ is not from halite.

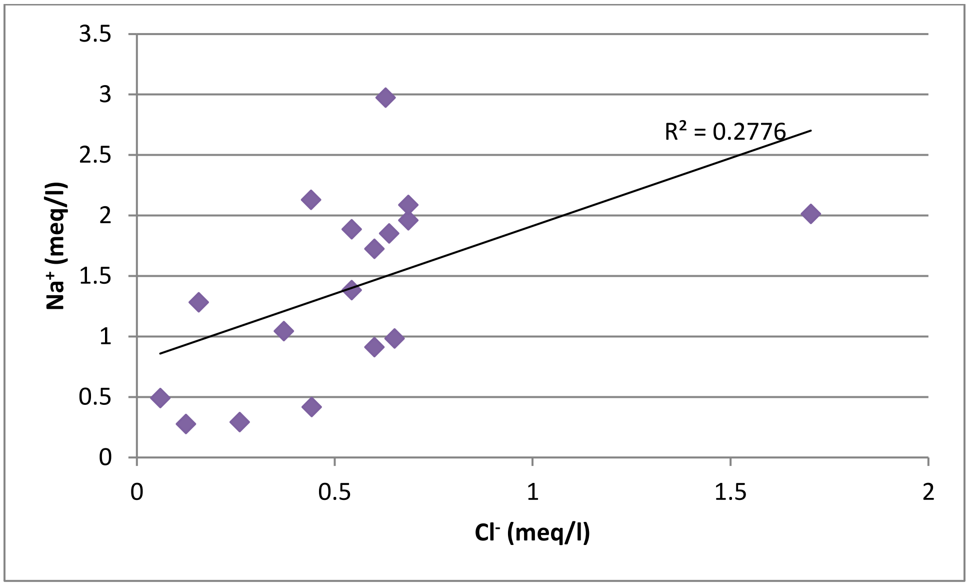


Figure 6.4 Na^+ vs. Cl^- relationship.

Thus, source of sodium in the study area could be hydrolysis of feldspar which makes up volcanic rock and sandstone. This silicate hydrolysis put Na+ into solution but also produces a new solid phase, clay minerals. These reactions are incongruent in that there is a new solid phase produced by the reaction.

$NaAlSi_3O_8 + H_2O = Na^+ + OH^- + HAlSi_3O_8$

Another source of sodium may be from cation exchange of magnesium and calcium for sodium retained by adsorption on mineral surface deposits having high cation exchange capacities such as clay.

$Na_2X + Ca^{2+} \Leftrightarrow CaX + 2Na^+$

$Na_2X + Mg^{2+} \Leftrightarrow MgX + 2Na^+$ where X is aquifer solid phase, usually clay

This reaction can be verified from lithologic log. For instance, from the secondary data collected, borehole located in Bilo, Bidaru, is Na-HCO_3 type water and it has a maximum concentration of sodium. It has a thick clay soil as observed from lithologic log (Table 6.5) below.

Table 6.5 Representative lithologic log of Bidaru

Depth (m)	Lithologic log
0-7	Brownish colored clay soil
7-16	Reddish colored clay soil
16-24	Darkish colored clay soil
24-34	Slightly fractured basalt (aquifer)
34-40	Slightly fractured basalt with some clay
40-47	Fresh basalt (massive)

From this one, it can be observed that there is involvement of cation exchange. Generally, silicate dissolution and cation exchange are the main geochemical processes that are responsible for the dominance of sodium in study area.

6.5.2 Major anion

The major anion of interest in study area is bicarbonate. Bicarbonate ion is derived from the atmospheric and soil CO_2 as well as dissolution of carbonates rocks such as calcium carbonate. Bicarbonate usually the primary anion in groundwater is derived from CO_2 released by organic decomposition in the soil (Todd, 2005). Similarly, the major source of HCO_3 in study area is supposed to be from biological process in the soil. The decayed organic matter in soil produces dissolved carbon dioxide which react with H_2O to form carbonic acid in the soil zone that later dissociate to form HCO_3- as represented below.

$$CO_2 + H_2O = H_2CO_3$$

$$H_2CO_3 = H^+ + HCO_3^-$$

And the other source of HCO_3- is silicate hydrolysis

$$CaAl_2Si_2O_8 + 2CO_2 + 3H_2O = Al_2Si_2O_5(OH)_4 + Ca^{+2} + 2HCO_3^-$$

These two reactions are the primary source of HCO_3^- concentration in study area. The other anion (Cl^-, SO_4^{-2}) are minimum in concentration. Chloride enters surface waters with the atmospheric deposition, dissociation of some sedimentary rocks, evaporation, industrial and sewage effluents, and agricultural practices.

Minerals in which chloride is an essential component are not very common, and chloride is more likely to be present as an impurity (Hem, 1985). Chloride is frequently associated with sewage and often incorporated into assessments as an indication of possible faeces contamination. Likewise, evaporation and anthropogenic activity is expected to be a source for chloride in study area as so. Sulfate may come from leaching of sulfur containing mineral in contact with aerated water, polluted rainfall and anthropogenic source. It also emanated from subsurface heat zone as a volcanic gas.

6.6 Water quality

The primary purpose of water analysis is to determine the suitability of water for intended use. Therefore, in the assessment of water quality, it needs to identify the purpose for which the quality is referred to. Such that determination of quality of natural water for certain use is according to certain standards set by different organization (e.g., World Health Organization (WHO) for specific water uses (drinking, agricultural, Industrial).

Since groundwater often occurs in association with geological materials containing soluble minerals, higher concentrations of dissolved salts are normally expected in groundwater relative to surface water. The type and concentration of salts depends on the geological environment and the source and movement of the water. Two principal features of ground water bodies distinguish them from surface water bodies. Firstly, the relatively slow movement of water through the ground means that the residence times in ground waters are generally longer than for the surface water, therefore, once polluted; a ground water body could remain so for decades or even more (UNESCO guide, 1992).

Secondly, there is a considerable degree of physico- chemical and chemical interdependence between the water and the aquifer. And there is considerable scope of water quality modification by the interaction of the two.

For comparison purpose the World Health Organization, WHO guidelines for drinking water and the ranges of concentration of major ions are supplied in the following table.

6.6.1 Groundwater quality for domestic purpose

Groundwater forms an important source of water for drinking and other domestic purposes. Groundwater is safe for use than surface water especially from point of view of bacterial pollution and its enrichment in important mineral. The prescribed standards for drinking-water vary from country to country, depending upon climate condition, food habits and geographic location and etc. Ethiopia has its own standard guideline values, but recognizes the WHO standards as a target for drinking water. For this work, the chemical analysis results from the water samples in the study area have been evaluated and compared with WHO guideline values for water quality standard. As seen from water quality data, almost all of the sampled water falls within the range of WHO standard.

Table 6.6 Comparison of water samples with WHO (2011) drinking water quality standard.

Parameter	WHO (2011) standard	% Samples exceeding WHO (2011) standard
PH	6.5-8.5	23
TDS (mg/l)	1000	0
Na (mg/l	200	0
Ca (mg/l)	200	0
Mg (mg/l)	150	0
Cl (mg/l)	250	0
SO_4 (mg/l)	400	0

The overall abundance of sulfate and chloride is very low. This indicates that deterioration of groundwater due to human impact is not a serious problem in study area.

6.6.2 Water quality for irrigation purpose

Water quality along with soil type and cropping practice play a vital role in successful agricultural activity. Water of good quality permits maximum yield consistent with proper soil and water management. However, suitability of water varies spatially and temporarily depending on the geologic environment, climatic condition and source of groundwater.

The quality of water for irrigation can be measured using electrical conductivity (EC), Sodium adsorption ratio (SAR), Sodium percentage (Na %), Residual sodium carbonate (RSC) and others.

Electrical conductivity (Salinity hazard)

The most influential water quality guideline on crop productivity is the water salinity hazard as measured by electrical conductivity. The primary effect of high EC water on crop productivity is the inability of the plant to compete with ions in the soil solution for water. When the EC is higher, less water is available to plants even though the soil may appear wet because plants can only transpire pure water. This means, usable plant water in the soil solution decreases with increasing EC amount. Thus, salinity of the water governs its suitability.

Evapotranisipiration tends to concentrate salinity in soil water and usually used as good assessment technique in arid environment.

Table 6.7 Irrigation water quality compared with EC.

Parameter	Sample (n=27)			Range	Water class	% Sample
	Min	Max	Mean			
	62.2	452	288.2	≤250	Excellent	44.5
				250-750	Good	55.5
				750-2000	Medium	0
				2000-3000	Bad	0
				≥3000	Very bad	0

Based on above salinity hazard criteria, about 44.5 % of the water samples are in the range of excellent class and the rest one 55.5% are in fall in the range of good class. This depicts that catchment is suitable in general and no quality objection is rise in terms of salinity (EC). Figure 6.5 also shows less salinity hazard.

Sodium Adsorption Ratio (SAR)

The sodium hazard expressed as the sodium adsorption ratio (SAR) has great effect on soil physical properties. It is a ratio of sodium to calcium and magnesium in water. Sodium reduces permeability and hardens the soil. This happens when Na^{+} in soil water replaced for Ca^{+2} and Mg^{+2}.

The United States Salinity Laboratory (1954) as cited in Hem (1985), proposed that the Sodium Adsorption Ratio (SAR) using the following relation could calculate the sodium effect.

$$SAR = \frac{Na}{\sqrt{\frac{Ca+Mg}{2}}}$$

Table 6.8 Water quality for irrigation based on Sodium Adsorption Ratio (SAR).

SAR	Water class	% Sample	Remark
<10	Low	100	Use of sodium sensitive crop should be cautioned
10-18	Medium	0	Good for course-grain permeable soil. Unsuitable for clay soil. Amendment such as gypsum and leaching needed
18-26	High	0	Generally unsuitable for continuous use and needs more addition of organic matter and high drainage
>26	Very high	0	Generally unsuitable

In the catchment the SAR value for analyzed water point ranges from 0.87mg/l to 9.4 mg/l with an average value of 4.34 mg/l (Annex 8). As observed above and from (Figure 6.5) water has little amount of SAR, indicating that the area has good quality for irrigational purpose.

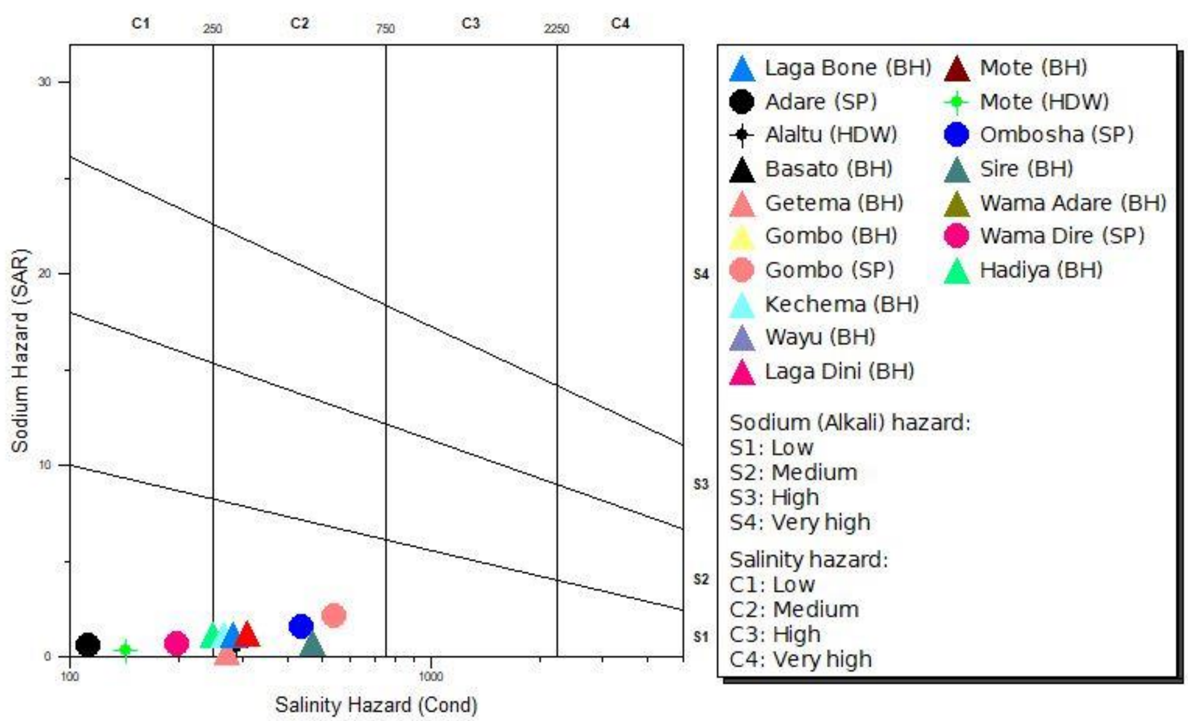


Figure 6.5 Wilcox Salinity and SAR hazard

Sodium percentage (Na %)

The relative proportion of sodium to other cations in irrigation water usually has been expressed simply as the percentage of sodium among the principal cations. Accordingly, it is also possible to classify water for irrigation considering sodium hazard using following formula and result for all samples is provided in (Annex 8).

$$\%Na = [(Na + K) / (Ca + Mg + Na + K)] \times 100$$

Table 6.9 Irrigation water quality based on Na% criteria.

Na%	Water class	% Sample
<20	Excellent	12
20-40	Good	70
40-60	Permissible	18
60-80	Doubtful	0
>80	Unsuitable	0

From this table, we can understand that the percentage of sodium (%Na) is low relative to the other cations, which indicates the suitability of water for irrigation.

CHAPTER SEVEN

CONCLUSION AND RECOMMENDATION

7.1 Conclusion

The overall objective of this work was to assess the groundwater resource of Wama catchment. Estimation of quantitative values of water cycle components (Precipitation, surface runoff, PET, AET, ground water recharge) are tried to be performed using different approaches. From the three methods for calculation of aerial depth of precipitation, the value obtained by averaging the results of rainfall depth from the three methods (i.e., 1715mm/yr.) was used for successive analysis because these results have no significant differences.

Potential evapotranspiration (PET) is estimated by using two approaches namely, Thornthwaite and Penman combination methods. Those methods gave 864.7 mm/yr. and 1059.1mm/yr. respectively. Thornthwaite method underestimates the value most probably because it relies on mean monthly temperature and sunshine hour. The Penman combination method on the other hand takes many parameters as input. It considers parameters like temperature, vapour deficit, sunshine hours, solar radiation and heat, and the value obtained by the method is reliable and used in the consequent analysis. Therefore, the PET obtained from Penman combination method was used in this work.

Actual evapotranispiration (AET) is obtained by adopting empirical formula of Turc, soil- water balance developed by Thornthwaite and Mather, 1957 and WetSpass model. By these methods the calculated AET were 717mm /yr., 860mm/yr., and 908.2mm/yr. respectively.

Because the Turc method underestimates the value, the AET obtained from soil water balance method is used in the calculation of recharge by water balance method. However, the result obtained from soil water balance method is not representative value. This is because, in estimating available water in the rooting depth, the reality of the soil texture used is under question.

The Wama River has no gauging station at the catchment mouth. This is cause for possessing the problem on obtaining the reliable runoff value, which is used in Water balance calculation. Chloride Mass Balance methods has its own limitations in calculating groundwater recharge.

Only three rainfall samples were taken once (in mid-March) and analysed for Cl^- concentration. These and other factors introduce errors and unique value of recharge could not found. Compared to the previous work, groundwater recharge value obtained from WetSpass model (i.e., 333.5 mm/year) is assumed to be the catchment's annual groundwater recharge.

The main aquifers in the basin are identified to be volcanic rock of fractured and weathered basalt. The hydrogeologic characteristics of the catchment's aquifer materials vary widely because of the differing extent of weathering and fracturing distribution of the volcanic rocks. Generally depending on transmissivity, specific capacity and yielding capacity observed from pumping test data in conjunction with geological and hydrometrological consideration, catchment is grouped into five potential zones (moderately productive porous aquifers, moderately productive fissured aquifers, moderately productive mixed porous and fissured permeability aquifers, low productive fissured crystalline rock and aquitards).

Fracture traces as manifested lineaments in land sat images are abundant in the catchment area. They have significant controls on drainage pattern, drainage density and ground water flow systems. Water flows from surrounding highland to the discharge areas following low hydraulic gradient and regional groundwater flow is generally toward the southwestern direction.

Hydro chemical data has been used in order to understand the hydro chemical variability of the region. Topography and hydrochemical trends are found to be good indicators of recharge and discharge areas.

Chemical analysis of water shows that the catchment has a characteristic chemistry of fresh water. This is attributed to short residence time of infiltrated rain water to reach discharge area due to undulated topographic nature of the watershed.

The predominant water type in the study area is a bicarbonate type. Ca-Mg-HCO3 and Ca-Na/Na-Ca-HCO3 water type dominates the area. As indication of anthropogenic impact, chloride and sulfate are low in concentration as there is no huge industry that can pollute ground water in the catchment so far except few contaminations from feces and agricultural activities.

7.2 Recommendations

- Wama catchment is a catchment of data scarce area. Though it is the major tributary of Didessa Sub-basin (the most important basin in the Blue Nile basin), there is no river discharge gauge that records the flow of river for the watershed. It is therefore, highly recommended for Ministry of Water, Irrigation and Energy of Ethiopia for installation of river gauging station.
- The existing borehole data are not well organized. Zonal water offices are strongly recommended to compile well completion reports and pump test reports and organize data base for water wells and springs.
- It is also recommended to conduct integrated scientific investigation to assess the groundwater resource potential of the catchment.
- Oromia Water Works Design and Supervision Enterprise (OWWDSE) are recommended to conduct appropriate scientific investigation to study the soil texture of the area.

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ANNEXES

Annex 1 Available metrological stations, variables, and data span.

Station	Data span	Rainfall	Temperature	Wind speed	Sunshine	Humidity
Nekemte	1986-2014	√	√		√	√
Nunu	1970-2006	√	√			
Didessa River	1979-2013	√	√	√	√	√
Arjo	1989-2015	√	√	√	√	√
Sire	1970-2006	√	√			
Bandira	1979-2013	√	√	√	√	√
Dereba	1979-2013	√	√	√	√	√
Seka	1970-2006	√	√			
Agelo	1979-2013	√	√	√	√	√
Koye	1979-2013	√	√	√	√	√
Getema	1988-2016	√				
Muleta Diga	1989-2016	√				
Bilboshe	1988-2016	√				
Gunjo Mariam	1989-2016	√				

Annex 2 Mean monthly Sun shine hour for available stations in the study area.

Station	Jan	Feb	mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Arjo	7.27	7	6.78	6.65	5.87	5.1	3.11	3.17	4.48	6.81	7.83	8.03
Nekemte	8.47	8.29	7.7	7.12	6.35	4.45	3.25	3.22	4.67	6.61	7.72	8.22
Bandira	6.93	6.59	7.14	7.1	7.12	6.12	4.87	5.1	6.73	7.72	7.03	6.88
Dereba	6.83	6.45	7	6.93	7.06	6.03	4.66	4.88	6.7	7.81	7.03	6.81
Didesa River	7.52	8.7	7.75	8.03	7.54	7.02	5.35	5.7	7.81	8.23	8.18	7.57
Koye	7.67	8.9	8.05	8.3	7.8	7.3	5.73	6.06	8	8.36	8.23	7.62
Agelo	7.7	9.04	8.1	8.3	7.85	7.4	5.89	6.15	8.05	8.4	7.86	7.6
Mean	7.34	7.08	7.2	6.95	6.6	5.43	3.97	4.09	5.65	7.24	7.4	7.5

Annex 3 Mean monthly Wind speed for available stations in the study area.

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Arjo	1.38	1.57	1.67	1.79	1.72	1.59	1.59	1.49	1.26	1.15	1.1	1.15
Didessa Riv	1.44	1.56	1.65	1.74	1.63	1.3	1.15	1.1	1.17	1.4	1.43	1.42
Bandira	1.38	1.48	1.56	1.67	1.6	1.3	1.2	1.1	1.16	1.4	1.45	1.4
Dereba	1.53	1.59	1.62	1.61	1.55	1.35	1.2	1.13	1.2	1.5	1.6	1.57
Koye	1.32	1.42	1.5	1.5	1.4	1.2	1.07	1.02	1.08	1.26	1.3	1.29
Agelo	1.67	1.76	1.77	1.68	1.53	1.3	1.16	1.12	1.21	1.49	1.6	1.64
Mean	1	1.13	1.22	1.26	1.2	1.1	1.04	1.02	0.97	0.94	0.88	0.9

Annex 4 Mean monthly temperatures for available stations in the study area

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Arjo	16.7	17.6	17.8	17.4	16.8	16	15	15	15.6	16.5	16.7	17
Nekemte	19.2	20.3	20.7	20.4	19.3	17.5	16.7	16.8	17.4	18	18.4	18.5
Didessa Riv.	20.25	22.15	23.15	22.7	21.45	19.1	17	16.75	17.2	17.1	18.05	18.85
Nunu	19	20.16	21.16	21.3	20	19	18.35	18.4	18.7	18.74	18.35	18.3
Sire	19.44	20.7	21.58	21.95	20.39	18.75	18	18.25	18.53	19.19	19	18.94
Dereba	21.2	22.65	23.35	23.25	21.65	18.75	16.6	16.55	17.4	17.8	18.95	19.55
Bandira	22.2	24.15	25.05	24.4	22.9	19.85	17.5	17.35	18.15	18.45	19.8	20.85
Seka	17.73	19	19.94	20.23	19	18.73	17.9	18	18.23	18	17.33	17
Koye	20.6	22.55	23.85	23.82	22.35	19.85	17.4	17.05	17.75	17.75	18.8	19.5
Agelo	20	21.8	22.9	23.2	21.7	19.5	17	16.7	17.6	18	18.9	19.3
Mean	19.6	21.1	21.9	21.8	20.6	18.7	17.15	17.1	17.7	17.9	18.4	18.8

Annex 5 Mean monthly Relative humidity for available stations in the study area.

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Nekemte	55	49.3	53	59.3	71	84.7	88	89	86.2	76	68.8	61
Arjo	59.8	57	59.2	63	73.2	84.2	88.7	90.7	85.5	72.7	68.7	64.2
Bandira	42.1	35.8	42.3	50.1	66.1	83.8	90.4	91.4	88.2	77.3	65.2	50.9
Dereba	42.5	37.3	43.9	51	65.3	84.8	91.8	92.7	88.9	75.3	62.2	49.4
Didesa Riv.	46.9	39.8	46.2	54.7	68.7	84.5	90.7	91.4	88.3	79	68.7	56.1
Koye	44.9	38.5	44.02	51.5	64.3	81	88.3	89.5	85.6	75	63.9	52.1
Agelo	42.6	37.4	42.7	49.4	60.4	79	86.9	88.5	84.5	69.5	57.4	47.4
Mean	47.7	42.2	47.3	54.1	67	83.1	89.3	90.5	86.7	74.9	65	54.5

Annex 6 Mean monthly rainfalls for available stations in the study area.

Stations	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Nekemte	9.94	14.7	51.6	83.6	256.3	395	400.2	381.6	283.7	147.9	46.5	18.1	2089
Arjo	14.9	17.9	96.3	120.1	238.3	318.9	327.7	347.2	280.4	130.3	60.7	29.2	1982
Nunu	16.3	28.6	41.2	58.6	138.1	229.2	294.7	286	175.9	75.2	40.4	18.4	1409
Gunjo Mariam	9.4	12.1	51.5	77.6	136.1	233.5	275.5	259.5	145.8	96.5	36.1	20.6	1354.2
Sibusire	70.4	23.5	21.3	65.3	228.9	268.1	395.3	363.9	466.3	127.2	28.2	16.3	2074.6
Bandira	6.8	11.6	40.1	67	159.3	323.6	483.1	511.5	351.7	98.4	22.2	8.8	2084
Didessa River	7.02	12	39.05	69.8	139.6	261.4	355.5	368.1	256.2	83.6	14.9	8.4	1615
Getema	12	16.4	54.2	93.8	198.7	250.6	249.5	290.7	223.9	132.6	45.1	30	1597.5
Dereba	9.26	15.1	51.8	73.4	167.5	383.3	610.8	633.3	383.1	118.6	24.2	10.6	2481
Diga	9.2	12.5	53.3	86.8	219.6	312.9	308.1	316.8	234.9	137	48.3	20.1	1759.5
Koye	2.9	7.44	25	46.9	89.1	203.5	311.5	324.5	197.1	58.4	6.6	3.3	1276
Bilboshe	13.5	16	57.3	73.8	162.5	279	310	304.4	200.9	96.1	21.2	12.3	1547
Agelo	2.2	5.4	19.9	36	68.4	160.5	261	271.3	161.2	45.3	6.8	2.6	1040.6
Seka	19.2	28.4	92.4	102.7	137	196.3	221.2	232.6	198	106	41.8	17.4	1392
Mean	14.5	15.8	49.6	75.4	167.1	272.6	343.1	349.4	254.2	103.8	31.6	15.4	1693

Annex 7 Estimation of available water in the rooting depth for the catchment area

Soil type	Areal proportion of the soil (%)	Available water in the soil in 1m column (mm/m)	Land use land cover		Rooting depth (m)	Available water at rooting depth (mm)	Available water w.r.t. land use (mm)	Available water in the root zone for the soil (mm)	Available water for the soil w.r.t. areal proportion	Total available water at rooting depth for the catchment (mm)
			Type	Percentage						
1	2	3	4	5	6	7 = 3*6	8 = 5*7	9 = ∑8	10 = 9*2	11 = ∑10
Clay	14	200	Deep rooted crops(Woodland plants, pasture, grass, shrubs,)	60	0.67	134	80.4	170	23.8	228
			MDR (corn, cereals, tobacco, sugar cane)	15	1	200	30			
			Forest	25	1.17	234	58.5			
Loam	86	200	Moderately DR (Sorghum, corn, cereals, cotton, barley, coffee, Teff, wheat, etc.)	70	1	200	140	237.5	204.25	
			Deep rooted crops(pasture bush, grass, Shrubs)	15	1.25	250	37.5			
			Forest	15	2	400	60			

Note: LULC= Land use/Land cover, W=Available water capacity, mm=millimeter, m=meter, and w.r.t. = with respect to

Annex 8 SAR and %Na value

Site	Na(mg/l)	Mg (mg/l)	K(mg/l)	Ca (mg/l)	SAR	%Na
Kechema(BH)	9.6	4.5	3.8	15.2	2.3	40
Sire town(BH)	11.3	4.8	2	24.8	2.2	31
Wayu (BH)	29.5	8.12	1.6	32	4.9	43.7
Gombo(BH)	6.72	5.2	1.1	56	0.87	11.3
Hadiya(BH)	31.8	11.6	3.4	65.4	3.37	31.4
Mote(BH)	68.4	28.4	7.3	31.2	9.4	55.9
Basato(BH)	42.6	22	11.2	63.5	4.9	38.6
Laga Bone(BH)	39.7	12.7	10.1	64.1	4.73	39.3
Getema(BH)	43.4	24.8	8.7	69.6	4.8	35.56
Gombo(SP)	45.1	8	3.9	68.7	5.3	39
Wama Dire(SP)	24	11.8	7.8	34	3.8	40.97
Adare(SP)	6.4	1.1	1.6	31	1.1	19.9
Ombosha(SP)	46.3	13.8	14.8	43.6	6.5	51
Mote(HDW)	21	7.9	10.4	53.3	2.77	33.9
Alaltu(HDW)	48	9.6	4.4	60.4	6	42.8
Laga Dini(BH)	22.6	19.6	7.3	47	2.9	31
Wama Adare(BH)	49	14.6	11	37	7.36	53.7

Note: BH = borehole, SP = spring, HDW = Hand dug well and SAR = Sodium Adsorption Ratio

Annex 9 Insitu measurements of physical parameters

S. Nº	Well site	X	Y	Z (m)	T(°C)	pH	EC(µS/cm)
1	Hadiya	0234266	1004312	2147	22.4	8.5	103
2	Madalu river	0270713	0972047	1485	28	7.7	270
3	Mote (BH)	0271200	0972400	1509	26.6	3.08	452
4	Mote (HDW)	0271388	0975732	1725	25	3.04	400
5	Minya Kura (BH)	247973	999228	1541	26.5	5.7	275
6	Wara Sayo (BH)	237988	999089	1744	24.2	6.1	213
7	Gombo Spring	0238784	997496	1882	23.4	6.7	112
8	Basato(BH)	0238380	0998945	1959	24	8.0	249
9	Ombosha (SP))	0240513	0969084	2290	24.3	7.36	403
10	Laga Deressa(SP)	0241082	0969609	2300	22.2	5.03	291
11	Laga Bone (BH)	0240339	0969353	2345	26..6	4.85	250
12	Laga Busha(SP)	0240117	0968885	2282	21.3	7.68	302
13	Negeso river	0229300	0971041	1993	23.2	7.6	320
14	Laga Alalt (HDW))	0223808	0983951	2168	21.6	7.77	120
15	Getema(BH)	0223421	0948544	2187	24.1	7.48	261
16	Laga Dini (BH)	0223233	0985308	2152	24.2	7.56	203
17	Adare (SP(	253233	0968716	1522	25.3	5.67	84.7
18	Bikila (BH)	267717	999389	1784	22.5	5.4	62.7
19	Sire town (BH)	265427	999423	1828	24.8	6.7	289
20	Jarso Wama(BH)	262754	995707	1697	23	6.1	174
21	Bota Wangaro(BH)	264329	983930	1577	26.3	5.34	257
22	Gonda(BH)	264429	976522	1585	23	5.9	301
23	Kechema (BH)	243362	966101	2205	24.3	6.63	113
24	Wama DirrE (SP)	247095	975279	1746	22	7.3	393
25	Wama Adere (BH)	0249623	0974259	1565	23.8	5.9	202
26	Gombo (BH)	224889	975856	1698	24.1	7.32	273
27	Wayu Warke (BH)	229828	967296	1784	25.1	6.6	311
28	Kofali (BH)	274417	956925	1555	24.8	7.3	180
29	Bilo (BH)	271303	963087	1582	24.2	6.9	263
30	Yube (BH)	258535	973465	1361	25.1	7.8	173

Annex 10 Laboratory measured water chemistry parameters

Site	Sample ID	Mg (mg/l)	Na (mg/l)	K (mg/l)	Ca (mg/l)	Cl (mg/l)	HCO3 (mg/l)	SO4 (mg/l)	pH	Temp (°C)	EC (µS/cm)	TDS (mg/L)
Kechema	BH1	4.5	9.6	3.8	15.2	15.47	29.28	8.9	6.63	23.2	113	72
Sire town	BH2	4.8	11.3	2	24.8	2.06	163.97	2.1	6.7	22.5	289	188
Wayu	BH3	8.12	29.5	1.6	32	5.46	192.76	1.5	6.6	21.8	311	182
Gombo	BH4	5.2	6.72	1.1	56	9.1	219.6	3	7.12	23.2	273	190
Hadiya	BH5	11.6	31.8	3.4	65.4	19	62.22	11.8	6.48	23	89.3	58.8
Mote	BH6	28.4	68.4	7.3	31.2	22	689.4	10.8	7.05	22.7	538	365.7
Basato	BH7	22	42.6	11.2	63.5	22.3	301.14	5.7	6.46	22.7	249.7	166
Laga Bone	BH8	12.7	39.7	10.1	64.1	21	318.57	10.8	6.41	22.5	266.3	177
Getema	BH9	24.8	43.4	8.7	69.6	19	350.92	6.8	7.13	22.8	282	189
Gombo	SP1	8	45.1	3.9	68.7	24	92	11.7	5.51	23	69.9	45.8
Wama Dire	SP2	11.8	24	7.8	34	13	74	4.8	6.12	23.4	84.9	93.7
Adare	SP3	1.1	6.4	1.6	31	4.35	51	1.7	7.03	23.1	143	201
Ombosha	SP4	13.8	46.3	14.8	43.6	59.6	134.4	3.9	5.84	22.8	436.7	294.7
Mote	HDW1	7.9	21	10.4	53.3	21	602.3	14.7	6.67	22.9	471	319
Alaltu	HDW2	9.6	48	4.4	60.4	24	102	16.5	5.83	23	95.9	63.1
Laga Dini	BH10	19.6	22.6	7.3	47	22.8	256.35	14.1	6.3	22.9	197.9	131
Wama Adare	BH11	14.6	49	11	37	15.4	198	10	5.9	22.2	96.9	112

Note: BH = Borehole, SP = Spring and HDW = Hand dug well

Annex 11 Hydraulic characteristics of boreholes obtained from well completion reports100228

Well site	X	Y	Z (m)	D(m)	SWL(m)	T(m^2/d)	K(m/d)	Y(l/s)	Sc(l/s/m)	DD(m)
Wayu	229828	967296	1930	115	6	0.7	0.02	1	0.016	75.18
Sire	260463	1006050	1752	155	3.7	31.8	0.6	25	0.8	31.1
Gombo	224889	975856	1956	150	46	5.81	0.137	4.2	0.1	40.7
Bulbulo	231823	881977	1635	114	9.45	34	0.8	7	0.8	8.75
Nunu	241683	973882	1891	180	30	33	0.51	8	0.5	13.72
Daleti	253549	958662	1498	150	5.83	1.18	0.003	2.4	0.03	83.27
Bilo	269887	995982	1728	94	1.38	13.8	0.38	7	0.27	25.61
Hadiya	235740	1004116	2062	147	2.33	82.8	17.28	25	8.9	2.8
Halelu	275822	969350	1700	70	9			1.4		
Daba	277823	976829	1815	92	6			1.5		
yaya	254442	977847	1404	60	8			1.5		
Wama Dire	249827	975933	1541	130				6.17		
Fododo	993042	219195	2217	126				4.5		
Birniqas	256199	961147	1559	126	12			2		
Adare	253233	0968716	1522	151	3	4.32	0.09	4		
Bata Wangaro	264329	983930	1577	59.8	18			0.5		
Gonda	264429	976522	1585	60	18			2		
Kofali	274417	956925	1555	60		29.6	0.9940	5.5		

Note D=well depth, Z= surface elevation, SWL=static water level, T=transmissivity, Y=yield, Sc=Specific capacity, DD=Draw Down, K=Conductivity

Annex 12 Available meteorological stations in and nearby the study area along with their location

Stations	Lat	Long	Elevation (m)
Agelo	8.58629	37.1875	1597
Arjo	8.75	36.5	2565
Bandira	8.89852	36.5625	1945
Bilboshe	8.889167	36.988	1726
Dereba	8.89852	36.875	1648
Didessa River	8.683333	36.48	1333
Getema	8.9	36.46667	2110
Gunjo Mariam	9.017667	36.93717	1844
Koye	8.58629	36.875	1509
Muleta Diga	8.95	36.48333	2130
Nekemte	9.08333	36.46333	2080
Nunu	8.763	36.6375	2346
Sibu Sire	9.045	36.87183	1826
Seka	8.458	36.868	1992