ADDIS ABABA UNIVERSITY

SCHOOL OF EARTH SCIENCES

GROUNDWATER FLOW DYNAMICS IN THE EASTERN UPPER JEMMA RIVER CATCHMENT, BLUE NILE BASIN, ETHIOPIA

MELKAMU ADIMAW MELESSE

A Thesis Submitted to the School of Graduate Studies of Addis Ababa University in Partial Fulfilment of the Requirements for the Degree of Master of Science in Hydrogeology

Addis Ababa, Ethiopia

June, 2019

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DECLARATION

I, undersigned declare and confirm that this thesis is my original work, and has not been presented for a degree in any other University. I have followed all the ethical and technical principles of research in the data collection, data analysis and compilation of this thesis. All sources of material used for this thesis have been duly acknowledged.

Melkamu Adimaw Melesse

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Date_________________

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

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Date_______________

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This is to certify that the thesis prepared by Melkamu Adimaw Melesse, entitled: Groundwater flow dynamics in the Eastern upper Jemma River catchment, Blue Nile Basin, Ethiopia, submitted in partial fulfillment of the requirements for the Degree of Master of Science in Hydrogeology complies with the regulations of the University and meets the accepted standards with respect to originality and quality.

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ABSTRACT

Groundwater Flow Dynamics in the Eastern Upper Jemma River Catchment, Blue Nile Basin, Ethiopia

Melkamu Adimaw Melesse

Addis Ababa University, 2019

The present study was conducted in the Eastern Upper Jemma River catchment, which is found in the Northwestern Ethiopian plateau, Blue Nile Basin and has an area of 1255 Km^2. The main objective of the study was to characterize the groundwater flow dynamics and the major aquifer systems of the area. By analyzing the available meteorological data, potential evapotranspiration was calculated using penman combined method and the result is 1376.64mm/year respectively. The actual evapotranspiration of the catchment is calculated using Thornthwait and Mather soil water balance model. Thus; annual AET is 799.76 mm/year. The groundwater recharge of the catchment was evaluated by using Water Balance Method (WBM), Baseflow Separation (BFS) method and Chloride Mass Balance (CMB) methods and the results are 100.47 mm/year, 211.84 mm/year, and 559.1mm/year respectively. The area is dominantly covered by fractured, weathered and faulted volcanic rocks with some Mesozoic sandstone and quaternary deposits. Depending on the analysis of pumping test data and qualitative descriptions made, the area is classified into aquifer types of; fissured aquifer developed on basalts on the plateau (moderate to low groundwater potential), mixed aquifer (high permeability and very high productivity), fissured aquifer developed on basalts in deep valleys (high permeability and low to moderate storage), Porous and fissured Sandstone aquifer in deep valleys, and localized aquifer with intergranular porosity and permeability(High permeability and high productivity). From the analysis of water level measurements of 40 boreholes, 26 hand-dug wells, 111 springs, and Physicochemical measurements' (pH, TDS, EC & T), the groundwater flow dynamics is controlled by surface morphology and structures and flows from the southeastern, southern and south-southwestern corner towards north and northwestern corner of the catchment.

Keywords; Aquifer, Baseflow Separation, Chloride Mass Balance, Groundwater Flow Dynamics, Upper Jemma, Water Balance.

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LIST OF ABBREVIATIONS

AET	**Actual Evapotranspiration**
BFS	**Baseflow Separation**
BE	**Beressa**
BH	**Boreholes**
BFI	**Baseflow Index**
CMB	**Chloride Mass Balance**
DA	**Dalecha**
DEM	**Digital Elevation Model**
E-W	**East- West**
EC	**Electrical Conductivity**
ECDSWC	**Ethiopian Construction Design and Supervision Works Corporation**
EMA	**Ethiopian Mapping Agency**
GSE	**Geological Survey of Ethiopia**
GIS	**Geographic Information System**
GPS	**Global Positioning System**
HDW	**Hand Dug Well**
ITCZ	**Inter-Tropical Convergence Zone**
MAOE	**Meteorological Agency Of Ethiopia**
m.a.s.l	**meters above sea level**
MCM	**Million Cubic Meter**
MWIAE	**Ministry of Water, Irrigation, And Electricity**
NE-SW	**NorthEast-SouthWest**
PET	**Potential Evapotranspiration**
Rap	**river analysis package**
SRO	**Surface Runoff**
SWL	**Static Water Level**
SRI	**Surface Flow Index**
TDS	**Total Dissolved Solids**
UTM	**Universal Transverse Mercator**
WBM	**Water Balance Method**
WHO	**World Health Organization**

CHAPTER ONE

1.0 Introduction

1.1 Background

Groundwater is the safest and most reliable water source used in domestic, agriculture, and industries. Groundwater is a very significant part of the natural water resources system. The occurrence, origin, movement and chemical constituents of groundwater are dependent on geology, Geomorphology, drainage density, rainfall, Geological structures/lineaments, Land use/Land cover and soil of groundwater regime (Tesfaye Tessema., 2015)

Most of the Ethiopian land mass is covered with volcanic rocks forming spectacular interconnected highlands and rift basins. Although the Ethiopia relief is complex and challenging, it is easier to classify it into five discernible topographic features. These are the western highlands, western lowlands, eastern highlands, eastern lowlands, and the rift valley (Tenalem Ayenew et al., 2008). Thus; the eastern upper Jemma river catchment is found in the western highlands of Ethiopia.

The Eastern upper Jemma river catchment is the aquifer system providing water supply to different cities like; Debre Birhan town, Tarmaber town, Gudoberet town, Seladingay, Dinbaro/Keyit town and other smaller towns found in the catchment. Besides; it also provides water supply for different industries around Debre Birhan Town and for rural communities found in the catchment. Therefore, the groundwater of the catchment is extracted for different purposes; hence it is very important to know its flow dynamics, characterizing the aquifer, and estimating available resource quantitatively. Understanding groundwater dynamics, characterizing the aquifer and evaluation of recharge in the catchment is very crucial which in turn helps to manage the available water resource for domestic, industrial, and agricultural purpose.

Therefore, this study aims to deal with mainly groundwater dynamics; aquifer characterization and evaluating groundwater recharge based on obtained meteorological, hydrological, hydrogeological, and pumping test data. The other parameter i.e. recharge will be evaluated by using base flow separation, water balance methods and chloride mass balance methods for effective and sustainable use of the groundwater resource of the Eastern upper Jemma river catchment.

1.2 Literature Review, Previous Works, and Research Gaps

In the Blue Nile and the adjacent areas; different geological and hydrogeological studies were performed. The different studies that are carried out in and around the Eastern upper Jemma river catchment are summarized as follows:

Abel Abebe (2017), has carried out M.Sc. thesis entitled" Evaluation of Recharge and Shallow Groundwater Dynamics in the Upper Awash Basin, Central Ethiopia". The research was done with the objective of evaluating the groundwater recharge using different techniques and recognizes the dynamics of shallow groundwater for sustainable management and exploitation of the groundwater resource.

Tilahun Azagegn et al. (2015), explained the litho-structural control of interbasin groundwater transfer in central Ethiopia. The article shows the litho-structural control on the interbasin groundwater transfer between the two adjacent basins and also shows the factors that control the groundwater dynamics. The amount which fluxes from the Blue Nile to Awash basin was calculated numerically.

Tilahun Azagegn (2014), Ph.D. thesis entitled "Groundwater Dynamics in the Left Bank Catchments of the Middle Blue Nile and the Upper Awash River Basins, Central Ethiopia". The dissertation was carried out with the objective to characterize the scarcely known hydrogeological system of the area with emphasis given to amount of recharge, aquifer distribution, groundwater flow pattern, hydraulic connection and flux between aquifer systems of the adjacent basins (middle blue Nile and upper awash basin) and the factors that control the groundwater dynamics. This study addresses; recharge boundary, aquifer distribution, and groundwater flux between adjacent river basins and the factors that control them.

Seifu Kebede (2013), Groundwater in Ethiopia. This study shows the occurrence of groundwater in regions and basin.

Tadesse Shewakena (2013), has carried out MSc thesis on "Numerical groundwater flow modeling of Beressa and Gado river catchment, Debre Birhan area, North Shoa zone, Amhara regional state". The thesis was conducted with the objective of the numerical simulation of groundwater flow system of the area to evaluate the response of the hydrogeologic system to different stress so that the resulting consequence on the system can be estimated.

Mekdes Nigatie (2012), M.Sc. thesis on "Characterization of Aquifers and Hydrochemistry in Volcanic Terrain of Central Ethiopia". The research was done with the objective of systematically characterizing the aquifer systems and their chemistry. The result shows the different aquifer systems of the area by classifying both qualitatively and quantitatively. The water types are also identified as dominantly bi-carbonate type.

"Andarge Yitbarek (2009) Hydrogeological and hydrochemical framework of complex volcanic system in the Upper Awash River basin, Central Ethiopia: with special emphasis on inter-basins groundwater transfer between the Blue Nile and Awash rivers". The dissertation was done with the objective to characterize the hydrogeological system of the upper awash basin by giving special emphasis on the inter-basin water transfer across the Blue Nile and Awash River basins watershed boundary. To achieve this objective converging evidences from the conventional hydrogeological investigation, exploratory drilling, litho-hydrostratigraphic relationships, water quality monitoring, water chemistry, isotope hydrology, and numerical modeling were used to set up the hydrogeological framework of the study area.

Aster Denekew and Seleshi Bekele (2009), Characterization and Atlas of the Blue Nile Basin and its Sub-basins, International Water Management Institute. The paper focuses on the characterization of the Blue Nile Basin and its sub-basins about the topography, climatic conditions, hydrology and land use/ land cover, soil and other related properties of the basin and its sub-basins.

Ahmed Wolela, (2008), Sedimentation of the Triassic–Jurassic Adigrat Sandstone Formation, Blue Nile (Abay) Basin, Ethiopia. According to the paper, the Northwestern Ethiopian Highlands are the main source for the sedimentation of the Adigrat Sandstone Formation and the course to medium-grained sandstone in the Adigrat Sandstones Formation has porosity and permeability up to 20.4% and 710 m/d, respectively.

Tenalem Ayenew et al. (2008), Hydrogeological framework and occurrence of groundwater in the Ethiopian aquifers. The occurrence and distribution of groundwater are systematically analyzed in relation to the geomorphological and geological setting. The study starts from regional conceptualization to a more focused analysis of selected areas with distinct hydrogeological features.

Tilahun Azagegn (2008), M.Sc. thesis on "hydrogeochemical characterization of aquifer systems in upper awash and adjacent Abay plateau using geochemical modeling and isotope hydrology". The research was carried out with the objective to provide a preliminary geochemical conceptual model on the hydrogeochemical behavior, the evolution of relatively shallow and deep aquifer systems and nature of inter-basin groundwater flow between the upper Awash River basin and adjacent Abay Plateau.

Nigussie Kebede (2005), has carried out his study on "water resources potential evaluation of Beressa river catchment, in North Showa, Amhara region". He has carried out the research with the objective to study the hydrogeology of Beressa river catchments with particular emphasis on groundwater resource evaluation and aquifer characterization. The research shows the hydrogeology of the area and evaluates the recharge of the catchment. He also characterizes the aquifer and trays to show the hydrochemistry of the catchment and indicates the possible sources of pollution.

Seifu Kebede et al. (2005), Groundwater recharge circulation and geochemical evolution in the source region of the Blue Nile River, Ethiopia. Geochemical and environmental isotope data were used to advance the first regional interpretation of groundwater recharge, circulation, and its hydrochemical evolution in the target area.

Kieffer et al. (2004) Flood and Shield Basalts from Ethiopia: Magmas from the African Superswell. According to this paper, The Ethiopian volcanic plateau is not a thick, monotonous, rapidly erupted pile of undeformed, flat-lying tholeiitic basalts. Instead, it consists of a number of volcanic centers with different magmatic character and with a large range of ages. The shield volcanoes are magmatically similar to the underlying flood basalts. The tholeiitic Simien shield overlies tholeiitic flood basalts, and the alkaline Choke and Guguftu shields overlie alkaline flood basalts. According to this paper, the change in volcanic style is driven not by a change in the compositions of the magmas but probably by the tectonic setting and a decrease in magma flux.

Generally, the increasing demand for groundwater resources and the complex nature of volcanic aquifers requires accurate and reliable characterization and evaluation of groundwater dynamics and its recharge for sustainable groundwater management.

The country Ethiopia is even now not made detailed studies of groundwater dynamics and the recharge of groundwater at large scale in spatial distribution. Most of the researches are regional. The study area which is found in the northwestern plateau (north-western flanks of the rift) is well studied by a number of researchers about its hydrogeology, geology, structural controls, geomorphological setup regionally, however, understanding groundwater dynamics at a catchment level (large scale investigation) is very limited. Therefore characterizing and understanding the dynamics of groundwater at a larger scale is very crucial to know the flow direction of groundwater and to characterize the aquifer for sustainable utilization of the groundwater.

Since the area is not far from the capital city of Ethiopia, Addis Ababa, different fabrics and industries are built within the catchment. As the population increases the need for water also increases, thus characterizing and evaluating the resource dynamics and amount is very important. Therefore this work was carried out in the eastern upper Jemma river catchment (Jemma sub-basin) in the Blue Nile basin at a larger scale to characterize groundwater dynamics of the catchment in detail.

1.3 Objective

1.3.1 General objective

The general objective of this research was to characterize the groundwater flow dynamics of the Eastern upper Jemma River catchment and to characterize the major aquifer system.

1.3.2 Specific objectives

The specific objectives of this research were to;

- ✓ Evaluate the recharge of the catchment by using different methods
- ✓ Characterize the major aquifer systems from existing pumping test data
- ✓ Characterize the groundwater flow by producing groundwater contour map from water level measurements in boreholes and dug wells.
- ✓ Characterize in situ Water quality measurements (physicochemical properties i.e. EC, PH, T, TDS)

1.4 Approach and Methodology

For the achievement of the objective, the research activities were done in three phases; this is pre-field activities (data collection), fieldwork, and post-field activities (data processing and interpretation).

Pre-field activities are those activities which were done before going to the field. The major activities that were done at home are review of previous works in the area or elsewhere related to the area (literature review), preparation of the field equipment like, GPS, topographic map, geological maps, pH-meter, EC-meter and other materials that are helpful during fieldwork, Collection of hydrometeorological data, well completion reports, pumping test data and hydrogeological loges were collected from different institutions and organizations.

Fieldwork is the second phase which is mainly done in the field. The major field activities are; Phsico-chemical parameters like (PH, Temperature, Electrical conductivity, and TDS), water sampling, geological descriptions and study the geomorphological setting of the area, taking photos of the representative geological exposures and geological structures, taking the GPS location of the sample points.

The third phase to achieve the objective of this research was **post field activities** (data analysis and interpretation). The main activities are: groundwater flow characterization from water level measurements of boreholes, dug wells, springs and in situ, water quality measurements. To characterize the major aquifer systems: pumping test results of boreholes, hydrogeological logs, and field geological and structural interpretations were used. Hydrogeological and groundwater contour maps were produced from existing water level measurements of boreholes and dug wells by using different software. The recharge and discharge zones of the catchment can be clearly observed from the map, generated from the contour maps, which is processed from water level measurements of some boreholes and hand dug wells. The software's used to process the data are Aquifer test, arc map 10.2. Global Mapper, Exelis ENVI, Geomatics, rock works, and others which was helpful during data processing. Landsat-8 image and DEM were used for the Extraction and interpretation of the lineaments in the study area. The land use land cover of the area was classified from Landsat_8 by supervised classification and the soil types are taken from FAO 1998.

To evaluate the groundwater recharge of the catchment; the first activity was collecting hydrometeorological data from the Meteorological Agency of Ethiopia and River discharge data from the Ministry of Water, Irrigation, and Electricity. Water balance methods, chloride mass balance and baseflow separation methods were used for recharge estimation.

Finally; after successful completion of the three phases, valuable conclusions and recommendations were given for future uses of the water resources in the catchment in its flow dynamics, amount, and management aspects.

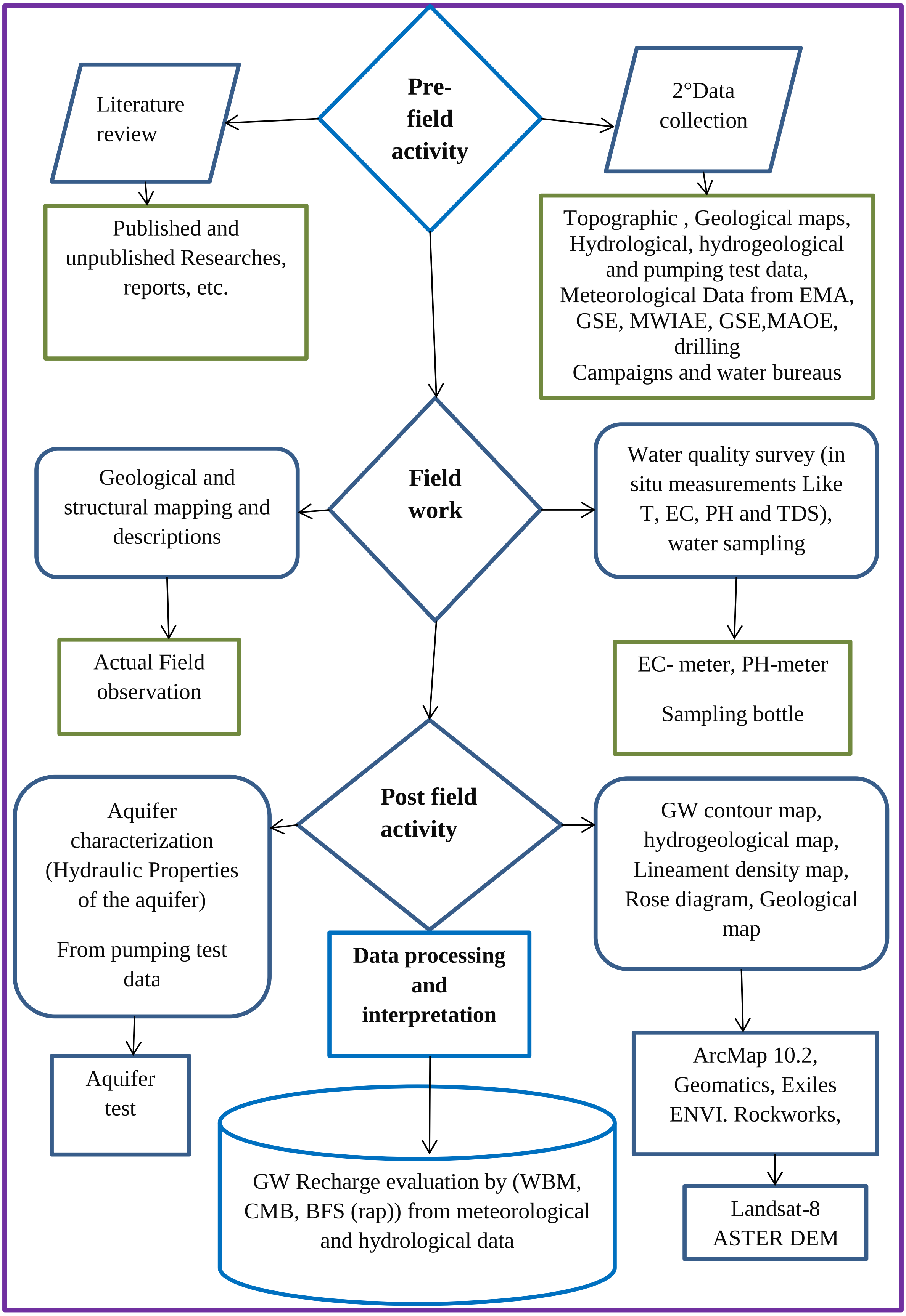


Figure 1.0 Flowchart to show the general methodology

1.5 Expected Outputs of the Research

The expected outputs of the research are:

- Groundwater flow directions from groundwater contour maps produced from water point measurements.
- Groundwater recharge of the catchment estimated by the three methods,
- Aquifer distribution and their hydraulic properties.
- Hydrogeological maps

1.6 Significance of the Research

This research will be significant for sustainable groundwater management, Used to propose the maximum benefit from the aquifer(s) found in the study area without affecting the aquifers, base for groundwater exploration, reference for further investigation and development, the newly generated data during the research work will be used as a basic input for related studies that will be done in the future.

CHAPTER TWO

2.0 Study Area Description

2.1 Location

The study area is located in central Ethiopia, in Amhara regional state, North Shoa administrative zone around Debre Birhan town. The area is approximately bounded between 9°30’0” N to 10°6’0” N latitude and 39°25’0” E to 39°45’0” E longitude. The total area of the catchment is 1255 square kilometers and the elevation of the area is between 1554m - 3679 meters above sea level.

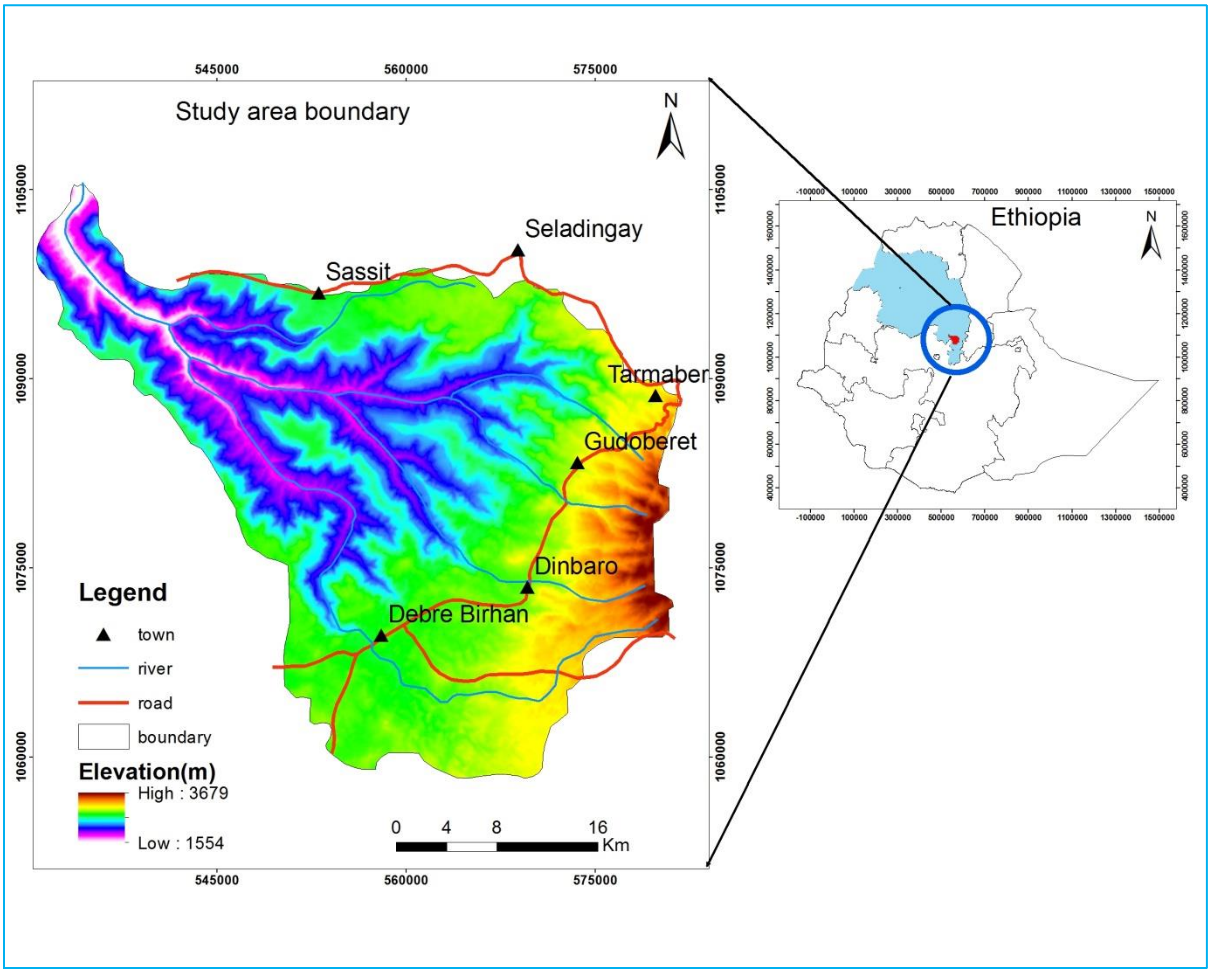


Figure 2.0 location map of the study area

2.2 Climate

The area is mainly characterized by a wet climate in which the main rainy season passes from July to September. Based on long term observations made by the Debre Birhan, Gudoberet, and Enewari stations (1988-2018), the mean maximum annual temperature and the mean minimum annual temperature of the area is 19.61 °C, 7.8 °C respectively and the mean annual temperature is 15.33°C. From long term observation of the eight stations at Debreberhan, Chacha, Enewari, Gudoberet, Ankober, Jihur, Seladingay, and Debresina, the mean annual rainfall of the area is 1240.29mm.

According to Tamiru Alemayeu (2006) classification of climate based on altitude and temperature, the climate of the area ranges from cool/kur/ to temperate/Weina Dega/climatic zones.

2.3 Physiography

The Eastern Upper Jemma River catchment is found in the central parts of northwestern Ethiopian plateau and westernmost part of the rift margin. Surface elevations in the study area range between 1554 – 3679 m.a.s.l. On the basis morphology and drainage type the area is divided into two physiographic divisions i.e. Plateau, and Escarpment.

The plateau covers the central part of the study area that includes Debre Birhan, Dinbaro and Seladingay localities. The plateau part of the area is largely characterized by flat-lying topography with some undulating ridge chains and deeply dissected valleys in the downstream of the plateau. The deeply dissected valleys located at the northwestern parts of the area are represented by Beressa, Gado, Gedemsa, Ayserawum, and Mehal Amba Rivers and its tributaries.

The escarpment is located in the Eastern and Southeastern parts of the area which is the rift margin and it starts from the Tarmaber and passes through the southeast of Dinbaro and Debere Birhan towns.

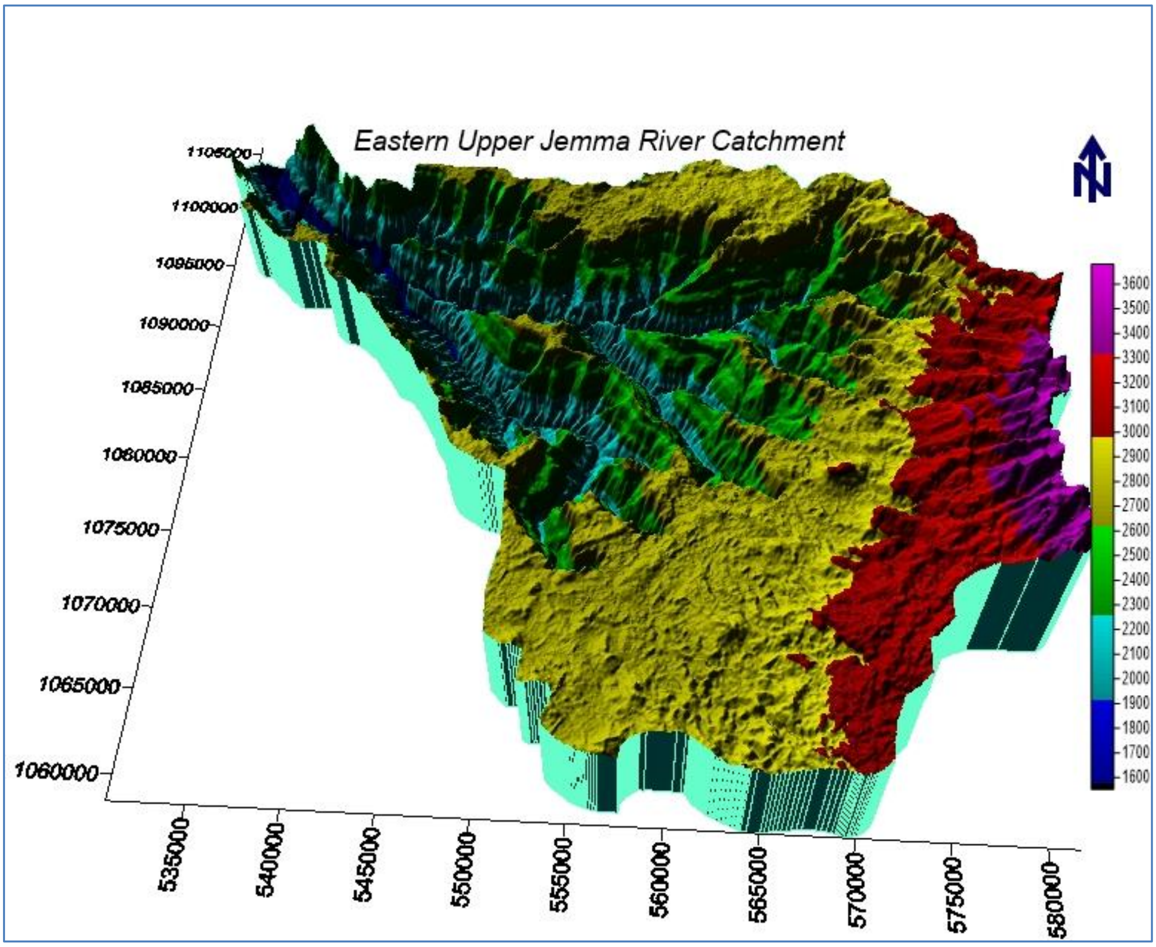


Figure 2.1 3_D view to show the physiography of the area

2.4 Drainage

The study area which is found in the northwestern Ethiopian plateau is highly drained and dissected by well-developed rivers and matured streams which form the Jemma drainage basin. Jemma River is one of the major tributaries of the Blue Nile Basin in Ethiopia. Streams and rivers in the area start from the eastern part of the plateau and escarpment drained from east to west towards Jemma River. The stream includes intermittent (Derk Wenz, Dalecha) and perennial (Gado, Gedemsa, Legeyida, and Beressa) rivers. The drainage pattern of the area looks like sub-parallel to dendritic drainage patterns.

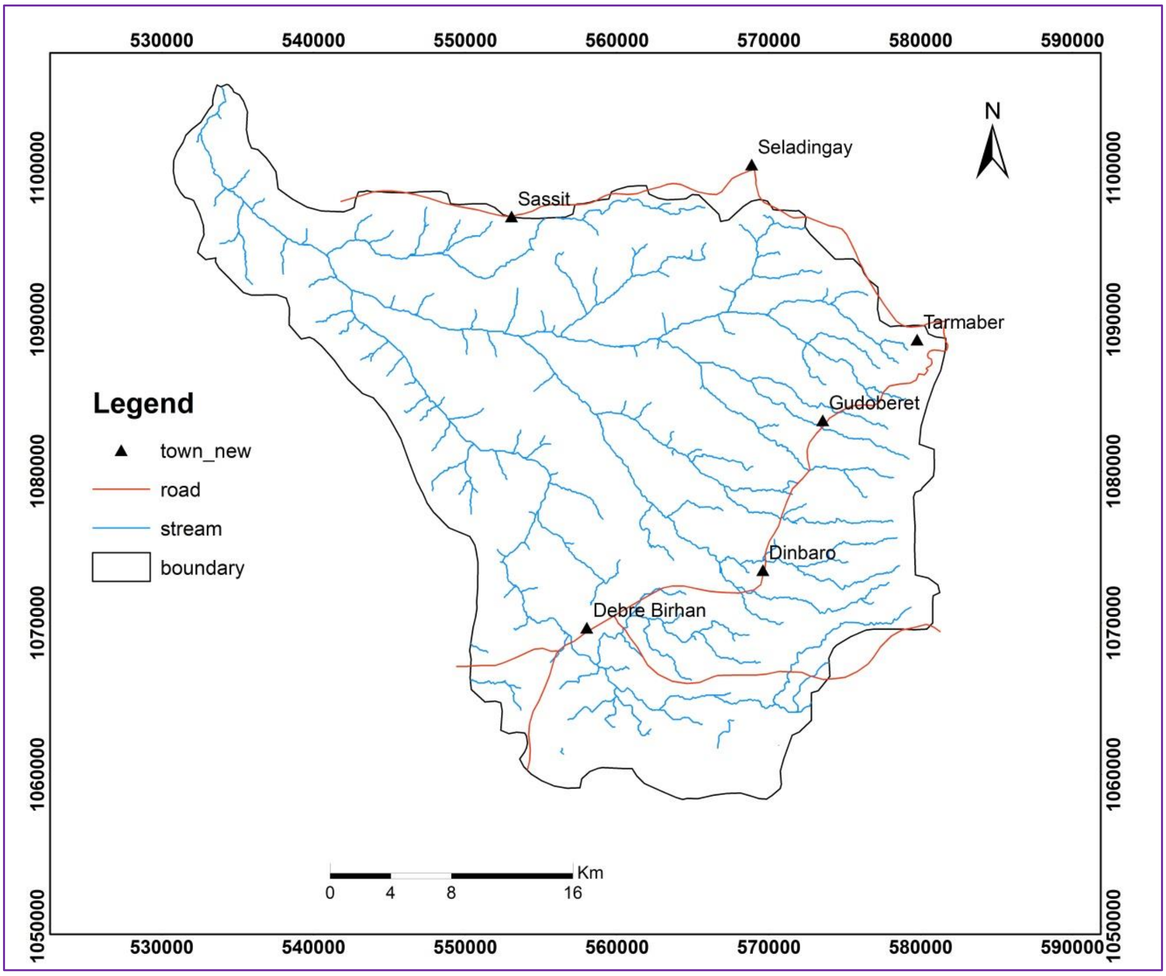


Figure 2.2 Drainage map of the study area

2.5 Soil

Soil characteristics of an area depend on the landscape, geology (parent material), the type of land use practice and agricultural activities (Nigussie Kebede., 2005). According to the soil map obtained from FAO, (1998) the study area is covered by five soil types. These are Eutric Cambisols, Eutric Leptosols, Eutric Vertisols, Lithic Leptosols, and Vertic Cambisols. The study area is dominantly covered by Eutric leptosols and Lithic Leptosols. The texture of the soil ranges from clay to sandy loam.

Eutric Cambisols: Cambisols represent soils in which soil formation is characterized by a certain development of structure, or by colors indicating moderately pronounced alteration and development (Development studies associates and showel consult international, 2005). This soil type is found in the North_East corner of the study area with a small extent.

Lithic Leptosols: according to the Development studies associates and showel consult international (2005) Leptosols are very shallow soils limited in depth by continuous hard rock. They occurs mainly steep side slopes. The soils are generally young and are limited by their topsoil horizon or directly over altered parent rocks from which they have developed. These soils have little or no agricultural potential except little grazing. Therefore leptosols are more susceptible to erosion due to it does not support sufficient vegetative growth.

Eutric Leptosols: This soil type covers most of the western and central parts of the plateau with a wide extent. This soil is common in eroding areas and they are very weakly developed found on hard rock.

Leptosols are the most widely spread soils in the study area and are shallow. According to the Development studies associates and showel consult international, (2005) (2-60 cm), excessively drained, sandy loam to clay. They are common with rockiness and stoniness.

Eutric Vertisols: This soil type is found in the northern parts of the study area**.** The soils of this category are deep to very deep, imperfectly drained soils formed on flat to almost flat topography. They are very hard to extremely hard when dry and very sticky and plastic when wet, which is reflected in their poor workability (Development studies associates and showel consult international, 2005).

Vertic Cambisols: This soil covers the southern parts of the study area. The Cambisols are Shallow to very deep, excessively drained to well-drained, clay loam to sandy loam and formed from variable volcanic and sedimentary rocks on plains and rolling plateaus (Development studies associates and Showel consult international, 2005; UNFAO, 1998).

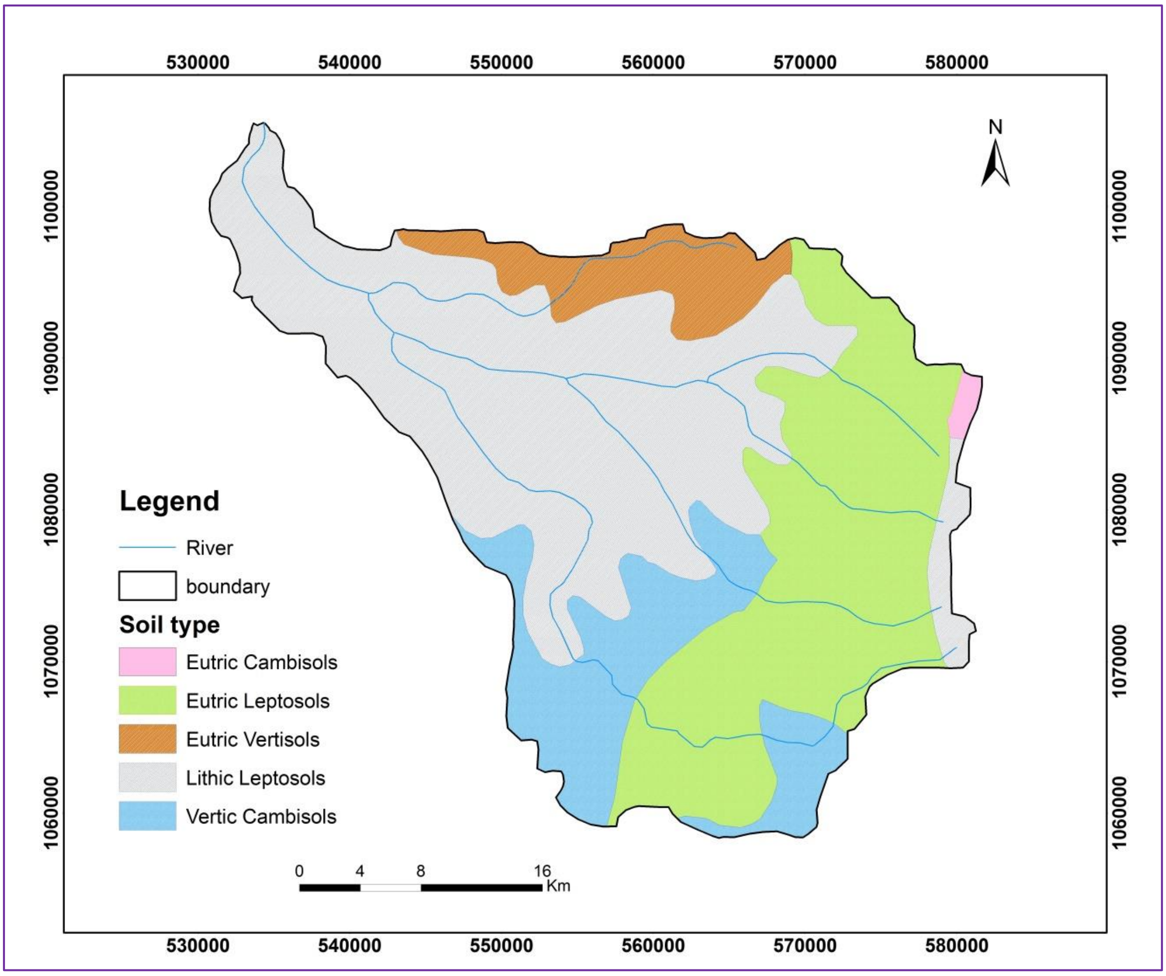


Figure 2.3 Soil map of the study area (Source UNFAO, 1998)

2.6 Land Use and Land Cover

The land use and land cover of an area depend on landscape, climatic condition, and agricultural activities. The study area eastern upper Jemma river catchment is covered by the sparsely vegetated, grasslands, forests, settlements/urban/, and small water bodies and largely by agricultural areas with some bare lands. The elevated and mountainous areas are covered by eucalyptus trees, shrubs, and undifferentiated vegetation. The eastern part of the study area which has high elevation is covered by dense eucalyptus trees.

Table 2.0 Landover type and areal coverage

No	Land cover	Areal coverage (Km²)
1	Agricultural area	757.4
2	Bare land	3.8
3	Forest	76.8
4	Grassland	24.0
5	Sparsely vegetated	382.1
6	Urban	10.6
7	Waterbody	0.2

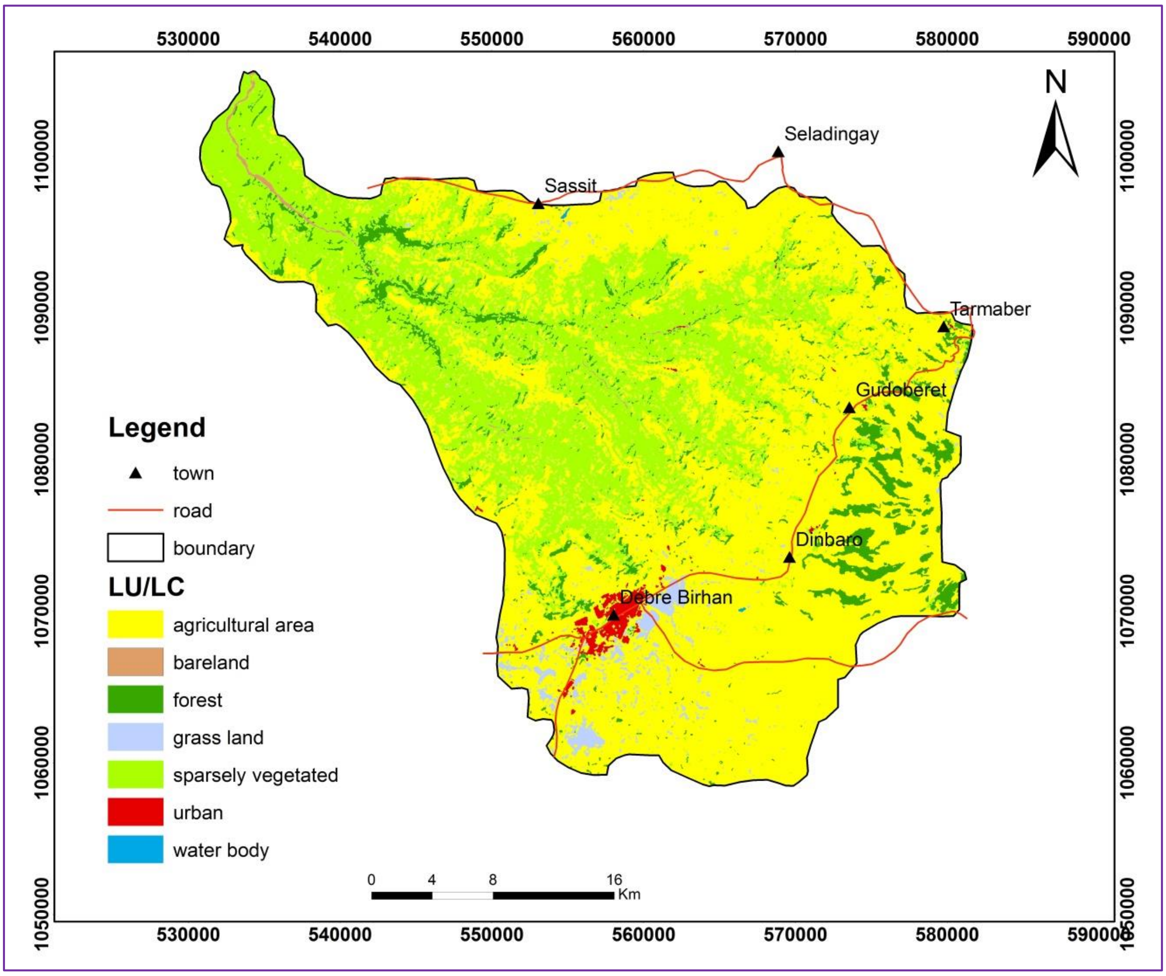


Figure 2.4 Land use/land cover map of the study area (supervised classification of Landsat_8)

CHAPTER THREE

3.0 Geology

3.1 Regional Geological Setting

According to Daniel Meshesha et al., (2010) the study area consists of two lithostratigraphic units. These are; Mesozoic sediments, Cenozoic volcanic rocks and Quaternary superficial deposits (table 3.1). The study area is dominantly covered by Cenozoic volcanic rocks.

Table 3.1 Classification of lithologies and stratigraphy of the study area

Age		Lithostratigraphic units	Lithologies
Cenozoic	Quaternary	Superficial deposits	**Eluvium (Qel)**
	Tertiary	Volcanic rocks	**Tarmaber-Megezez basalt (Ttb)** plagioclase phyric and olivine plagioclase phyric basalts with minor olivine-phyric, pyroxene phyric, plagioclase-pyroxene-olivine phyric and aphanitic basalts. **SelaDengay-Debre Birhan-Gorgo ignimbrite (Tdig)** ignimbrite, tuff, rhyolite, aphanitic basalt, tuffaceous sediments, ash, agglomerate **Kesem basalt (Tkb)** aphanitic basalt intercalated with plagioclase phyric basalts and thin beds of ignimbrite
Mesozoic	Sediments		**Sandstone (Msst)**

3.1.1 Mesozoic Sediments

The Mesozoic sediments are exposed in the highly dissected plateau area at the northwestern tip of the study area. Stratified Sandstone is the typical Mesozoic sedimentary rock which is found in the study area, situated within the gorge and forms steep cliffs.

3.1.1.1 Sandstone (Msst)

The sandstone is mainly exposed in the lower valleys of Jema and its tributaries (Derek Wenz, Bersena, Chira, Chacha, Beressa, Adabay and Mofer Wuha) in the northwestern tip of the study area. It forms very steep cliffs along with stream cuts with maximum thickness about 433m at Jema-Yewelo and its exposed thickness decreases towards the northeastern (209m at Jema-Lem Washa), southern (200m at Bersena-Molt Amba) and central (35m at Bersena-Sya Debre) part of the area. The other section of the sandstone in the area is at the downstream of Chacha, having a maximum 30-meter vertical thickness. The rock (Msst) is medium-grained, light red (fresh color) to reddish/yellowish/pinkish brown (weathering color), sub-rounded grains, poorly to well sorted, compacted and thickly bedded to laminated, including the dominant crossbedding structure. In most cases, the unit shows cyclic fining upward sequence except in the Dilamo area (upstream of Chacha), where the topmost part of the sequence shows coarsening upward. Each sequence is separated by conglomeratic beds and the unit as a whole continues to the north without significant lateral variations. The sandstone unit is unconformably overlain by the Tertiary volcanic rocks (Daniel Meshesha et al., 2010).

3.1.2 Cenozoic Volcanic Rocks

Founded on their manner of occurrences and previous works in the field, the Cenozoic volcanic rocks are grouped into Tertiary and Quaternary volcanic rocks. The Tertiary volcanic rocks are mainly exposed along the plateau (e.g., high lands of Tarmaber, Debre Berhan, Saya Debir, Weberi, Wenoda, Sheno, and Sendefa) and the NE-SW trending rift margin (Debre Sina, Ankober, Aliyu Amba, Gorgo, Megezez and Meteh Bila). The rocks mainly consist of a thick succession of basalts and ignimbrites with sporadically distributed trachyte, rhyolite and scoria cones. The Quaternary volcanic rocks occupy the MER and the volcanic comprise fissural to central and vesicular to scoriaceous basaltic rock, ignimbrite and some trachyte. Texture, mode of occurrence and stratigraphic sequence are the main measures applied to subdivide the major age groups into different subunits (Table 3.1). In addition to compositional and textural criteria of each subunit, mostly known localities where the unit is predominantly exposed and attains its maximum thicknesses, is used here for nomenclature purpose and the name of few formations are also adopted from (Zanetiine et al.,1974; Kazmin, 1979; Kazmin et al.,1980; Tefera et al., 1996 as cited in Daniel Meshesha et al., 2010; Tadesse Shewakena., 2013).

According to Daniel Meshesha et al., (2010) the Tertiary volcanic rocks are the earliest volcanic rocks in the study area that happen along the plateau surrounding the rift, which was erupted from fissures due to extensional tectonic activity. The rocks consist of a thick succession of aphanitic basalts and ignimbrites which are overlain by a central volcano (plagioclase phyric basalts). Within the Tertiary volcanic rocks, thin beds of volcanoclastic sediments (Tertiary sediments) are likewise found. According to Geological Survey of Ethiopia, (2010), these tertiary volcanic rocks are classified as Kesem Basalt, Sela Dengay-Debre Birhan-Gorgo ignimbrite and Tarmaber-Megezez basalt. The detailed descriptions of each lithology are described as follows;

3.1.2.1 Kesem Basalt (Tkb)

The Kesem basalt is found at the lower stratigraphic sections of Kesem and Jema (Bersina, Derk Wenz, Chira, Chacha, Mofer Wuha and Beressa) drainage basins. The Kesem basalt is strongly fractured, irregularly to columnar jointed, spheroidally weathered, aphanitic to porphyritic in texture and forms very steep cliffs. In the Jema drainage basin, the contact with the underlying Mesozoic sandstone is sharp and marked by the presence of baked and dark brown soil horizon (palaeosols). The Kesem basalt consists of dominantly aphanitic basalt intercalated with plagioclase phyric basalts and thin beds of ignimbrite. The aphanitic basalt is the most abundant, fine-grained, dark gray to black (fresh color) to bluish gray (weathering color), columnar jointed and it contains petrified wood at Wintaf River (north of Inewari town). It is characterized by different phases of basaltic flows separated by randomly exposed reddish palaeosols (0.6 meters thick) and Sediments (1-4 meter, west of Lizib Dingay Gebreal area). Aphanitic basalt, its groundmass is dominated with plagioclase microliths and exhibit trachytic to seriated texture. The plagioclase phyric basalt is exposed mostly at the topmost part of the aphanitic basalt and forming a steep cliff. It is coarse to very coarse-grained, dark gray and phyric. The ignimbrite is very limited in its vertical extent as compared to the aphanitic basalt. It is found at the middle and sometimes on top of the aphanitic basalt with varying thickness at different localities. It is fine to medium grained, bluish gray to gray, friable and composed of small rock fragments (Daniel Meshesha et al., 2010; Tadesse Shewakena., 2013).

3.1.2.2 Sela Dengay-Debre Birhan-Gorgo Ignimbrite (Tdig)

According to Daniel Meshesha et al., (2010) Sela Dengay-Debre Birhan-Gorgo ignimbrite is exposed mainly at Sela Dengay, Sefi Beret, Debre Birhan, Ankober, Aliyu Amba, Gorgo, Shembeko Ber, Alem Gebaya and Sendafa localities. It has sharp contacts with the overlying (Tarmaber- Megezez) and underlying (Kesem) basalts. It comprises ignimbrite, rhyolite, Tertiary sediment, tuffaceous sediment, aphanitic basalt, agglomerate, and ash.

The ignimbrite forms gentle to steep cliffs, elongated ridges and sporadically distributed isolated hills (e.g., Kotu Gebya and Cheki). It is medium to coarse-grained, light/bluish/brownish gray to gray to dull/dark gray (weathering color), highly consolidated to welded tuff and bedded with columnar joint, vertical joints, and fractures. It contains rock fragments of rhyolite and basalt ranging up to 2cm in diameter and elongated fibrous glass shards (fiamme), whereas the amount of rock fragments significantly varies from place to place. At Awajo Gebrial (2km north of Mezezo town), there are two distinct layers of ignimbrite. The upper layer is white to light yellow while the lower one is dark and contain basaltic rock fragments.

The rhyolite is found around Deneba, northeast of Debre Birhan (Beriyo Baleweld), Shola Gebya and Gina Ager. It is fine to medium grained, bluish/light/greenish gray (fresh color) to dull gray, light/dark brown (weathering color). It is highly fractured and vertically jointed at the northeast of Debre Birhan (Beriyo Baleweld).

Tertiary sediment mainly exposed in and around Jema (Mofer Wuha, Aboya Jema, Chacha and Ayserawem river sections), Kesem (e.g., Argu, Uroa Wiha and Meti Sheet sections), Awash(Mote and Mensa) tributaries and Nito Debri locality (north of Debre Birhan), consisting of an alternating bed of tuffaceous sediments and sandstones. There are two different layers of Tertiary sediment, the upper and lower layers. The upper layer is only exposed in the upper part of Chacha, Bersena river valleys and Nito-Wydeme section (Nito Debri locality) and has a maximum thickness of 65m and pinches out at Metkoria and Amora Gedel localities. The sediment in general forms gentle slope and the lower sediment attains its maximum exposed thickness (~120m) around Mafud locality. The tuffaceous sediment is light gray to pinkish gray, coarse-grained with basaltic rock fragments and laminated (at MoyaMariam and Goshe Bedo sections).

Plagioclase is altered to sericite. It shows angular to subrounded and in equant grains of feldspar and quartz within clay (ash) matrix. The sandstone layer is sandwiched within the tuffaceous sediment and has different exposure thickness and characters. In the Mofer Wuha river section, the sediment (80m thick) is characterized by alternating layers of sandstone and tuffaceous sediments, whereas at Aboya Jema section, there is only 60m thick sandstone with 10cm thick grayish green and fissile shale. South of Lizib Dingay Gabriel (southeast of Aleltu) and around Sar Amba Silase (east of Gina Ager) the sandstone has 2-5m thickness. The sandstone is medium grained, reddish brown, brownish gray to light yellow, sorted, crossbedded (only around Menyet village and Metekoria area) and conglomeratic. There are also coal-bearing sediments confined within the tuffaceous sediments at Mush valley (3m thick, 30km north of Debre Birhan town) and Shirer Libanos (1-2m thick; west of Koremash town) but the lateral extents of the two coal-bearing sediments are obscured.

The aphanitic basalt is fine-grained, black/dark/gray, irregularly fractured, slightly jointed, columnar jointed and rarely shows a massive appearance that forms a steep morphology. It is strongly deformed at the south of Abo Danse locality.

The Agglomerate contains fragments of ignimbrite and vesicular variety of dark gray porphyritic to aphanitic basalts cemented by white ash. It is loose and highly weathered with angular rock fragments from cobble to pebble size and forming low slope angle than other rocks.

The ash is forming mostly gentle slope and flat topography. It is white, light yellow, pink and light brown (fresh color) to red, yellowish gray and black (weathering color). It contains small fragments of basalts and pumice.

3.1.2.3 Tarmaber-Megezez Basalt (Ttb)

Tarmaber-Megezez basalt is dominantly exposed on the western (Wenoda, Sendafa, and Megezez) and north central (Debre Sina, Termaber and Ankober) part of the plateau. It forms a series of linear ridges Andhigh Mountains (Mt. Megezez, 3595m a.s.l.) and Mt. Yekur (3400m a.s.l.). It has sharp contact with the underlying Sela Dingay-Debre Birhan-Gorgo ignimbrite.

Termaber-Megezez basalt includes fine, medium to coarse-grained, dark gray (fresh color) to Light/reddish/dark/yellowish brown (weathering color) and aphanitic to porphyritic basalts. It is characterized by different phases of basaltic flows separated by randomly exposed reddish palaeosols and reddish brown scoriaceous basalts (0.5-8m thick). It is dominantly represented by plagioclase phyric varieties (plagioclase phyric and olivine-plagioclase phyric basalts) together with minor olivine-phyric, pyroxene phyric, plagioclase-pyroxene-olivine phyric and aphanitic basalts.

Plagioclase phyric basalt is the most abundant rock type and mostly occupies the highlands of Debre Sina, Tarmaber, Ankober, and Wenoda including Mt. Megezez and Mt. Yekur where it attains its maximum thickness. It is medium to coarse-grained and dark gray, containing plagioclase phenocrysts up to 5cm in length. The plagioclase phyric basalt shows randomly distributed and faint columnar jointing (at the north of Debre Birhan and south of Mezezo town). The rock exhibits trachytic, porphritic, ophitic to seriated textures.

Olivine-plagioclase phyric basalt is mostly exposed around Berek-Chancho ridges (north of Sendafa), between Beke and Aleltu, and around Gina Ager localities. It is medium to coarse-grained, dark gray (fresh color) to dull gray (weathering color), phyric with dominant plagioclase and few olivine phenocrysts. It is massive and blocky in appearance, exhibiting spheroidal weathering. The rock exhibits porphyritic to seriated textures.

Olivine-phyric basalt is exposed northeast of Shola Gebeya (Gorfo village) and southeast of Mt.Yekur. At Gorfo village, the olivine-phyric basalt forms a ridge with blocky appearance. The rock is coarse-grained, greenish gray (fresh color) to gray (weathering color).

In general, the dominant Tarmaber-Megezez basalt (plagioclase phyric basalt) gradually ranges to aphanitic basalt with no or few phenocrysts from the center to the periphery along Mt. Megezez, Mt. Yekur, Chancho-Berek, and Tarmaber ridges. There are also randomly distributed patchy outcrops of such aphanitic basalt throughout Tarmaber-Megezez basalt (Sembo, Chacha, Mendida, and Deneba). The aphanitic basalt is fine-grained, black and dark/light gray (fresh color) to gray and dull gray (weathering color), columnar jointed. North of Sheno and along the road of Kotu Gebya-Hageremariam, there are scoria deposits associated with the aphanitic basalt.

3.1.2.4 Quaternary Superficial deposits/Eluvium Soil/ (Qel)

As it is explained by Daniel Meshesha et al.,(2010) the eluvium soil is mostly found on the plateau and escarpment of the area, occupying flat lying and gentle topography. It is formed by the gradual weathering of the basalt, ignimbrite, and rhyolite. There are rock fragments of basalt, ignimbrite, and rhyolite within the eluvium soil. It is silt to clay sized, light/dark gray to the reddish-brown fertile soil. It is highly plowed by the local people.

3.2 Local Geology

The Eastern upper Jemma River catchment is dominantly covered by volcanic rocks with some Mesozoic sediment. The study area was mapped by the Institute of geological surveys (2010) at the scale of 1: 250,000 and this scale of geological mapping are not enough to talk about the detail geological nature. Therefore, from image interpretation and geological field mapping of the eastern upper Jemma river catchment, five lithologic units were identified. These are:

1. Sandstone unit
2. Lower basalt
3. Ignimbrite
4. Upper basalt
5. Superficial deposits

3.2.1 Sandstone unit

The lowermost part of the study area is covered by Mesozoic sediments (sandstone). This unit mainly exposed in the downstream of the catchment in the northwestern tip of the study area in the river gorges. This unit forms very steep cliffs and is difficult for traverses. The rock unit is medium-grained, the color of the fresh sample is light red and weathering color is pinkish brown. The grains are sub-rounded, poorly to well sorted, compacted and thinly bedded.

3.2.2 Lower basalt

The next lithologic unit overlying the sandstone unit is the lower basalt. This unit is mainly exposed in the Beressa, Dalecha and in the upstream of Gado river gorges forming steep cliffs. The lower basalt unit is highly jointed and fractured. It has a dark grey color and texturally it is aphanitic. The successive flow of lower basalt is deeply eroded by rivers resulting in steep cliffs alternating with shoulder shaped gentle slope. This rock is very similar to Kesem basalt described in regional geology.

Plate 3.0 Fractured Basalt in the Beressa River section

3.2.3 Ignimbrite, Rhyolite

Ignimbrite and rhyolite are exposed in most of the study area on top of the lower basaltic unit, the silicic volcanic unit. This unit covers most of the area with a wide extent. The ignimbrite and rhyolite are jointed, weathered and fractured. The color of the fresh rock is light grey, light greenish and white color. The coarser grain ignimbrite rock contains phenocrysts of quartz and feldspars. These rock units are similar with Sela Dengay-Debre Birhan-Gorgo ignimbrite unit described in above in the regional geology.

Plate 3.1 Weathered, Fractured and Columnar Jointed Rhyolitic Ignimbrite at Gadilo River Section

Plate 3.2 A and B Weathered and fractured Ignimbrite around Sassit/Filagenet locality (A) and light color Ignimbrite at a quarry site near to Debre Birhan University (B)

3.2.4 Upper Basalt

On top of the silicic volcanic rocks, the overlying formation is basalt. This unit mainly exposed in the eastern and southeastern (around Tarmaber and Minilik Window/Gemasa Gedel), and in the western tip of the study area. The upper basalt is columnar jointed, fractured and weathered. Its texture ranges from aphanitic to porphyritic with major phenocryst of plagioclase feldspar. The grains are fine to medium, dark gray color. Paleosols are found between different flows with different thickness. This unit is very similar to the Tarmaber Megezez basalt described in the regional geology section.

Plate 3.3 highly weathered basalt around Tarmaber at the Minilik Window (A) and fractured, weathered and fine-grained basalt at Arat Dildiy River section (B)

3.2.5 Superficial Deposits

On the gentle slope of the study area, there is a wide area of cultivated land having brown clay and silt residual soil overlaying on the ignimbrite, rhyolite, and basaltic bedrocks. This type of soil results from the weathering and disintegration of the basalts, ignimbrite, and rhyolite. The color is mostly dark gray to the reddish brown fertile soil. It is highly plowed by the local people.

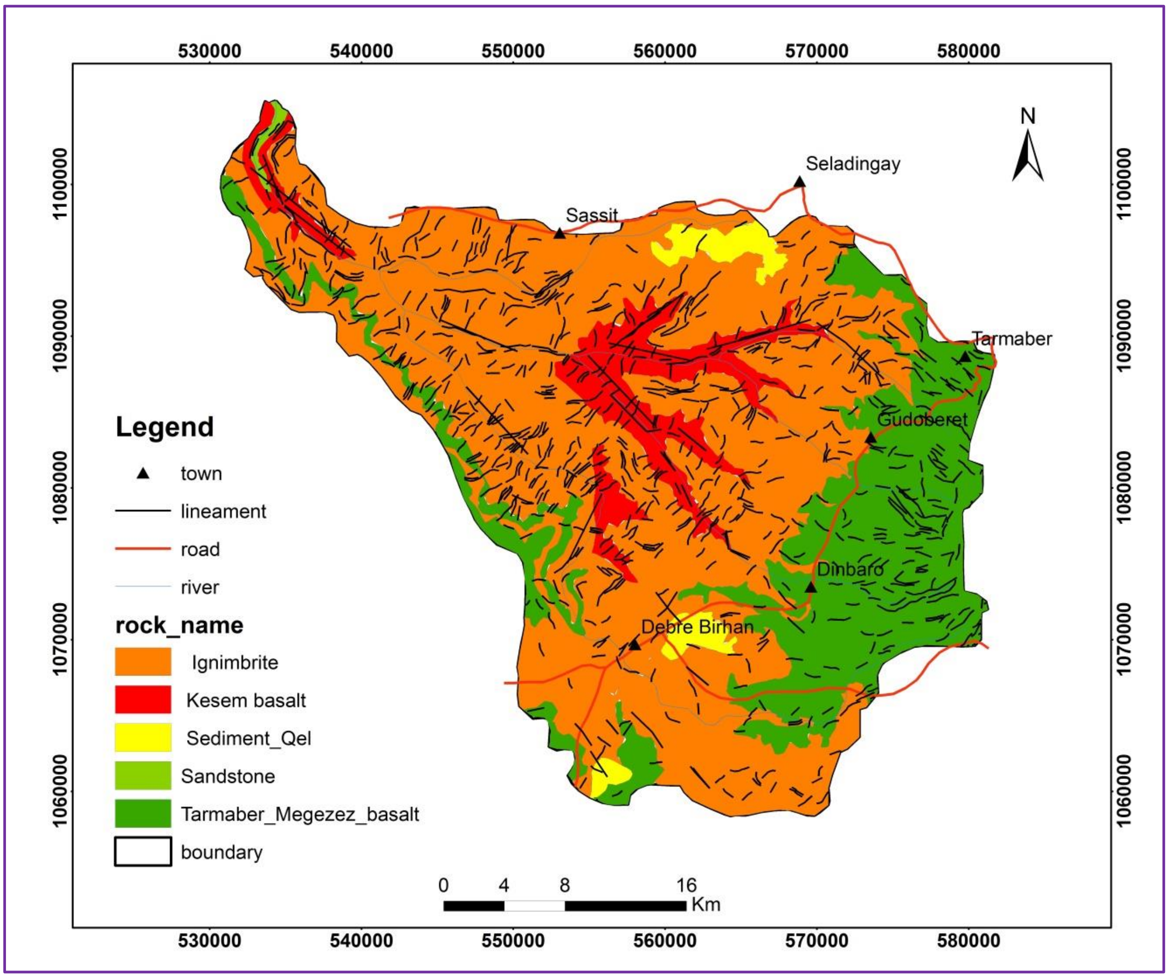


Figure 3.0 Geological map of the study area (modified from Daniel Meshesha et al., 2010)

3.3 Structural Setting

The lineaments were automatically extracted from Landsat_8 by using GEOMATICA version 2018 and the Landsat image is enhanced for the principal component analysis by using Exelis ENVI version 3.5. The lineament density map was produced from the extracted lineaments by using ArcGIS version 10.2. The rose diagram of the lineaments is obtained from the software called Rockworks 17. From Landsat image interpretations and field observations, there are different structures including different sets of joints, minor faults, and fractures that are observed in the study area. As it is observed from the lineament density map most of the study area following the river gorges are affected by structures which are marked by red color.

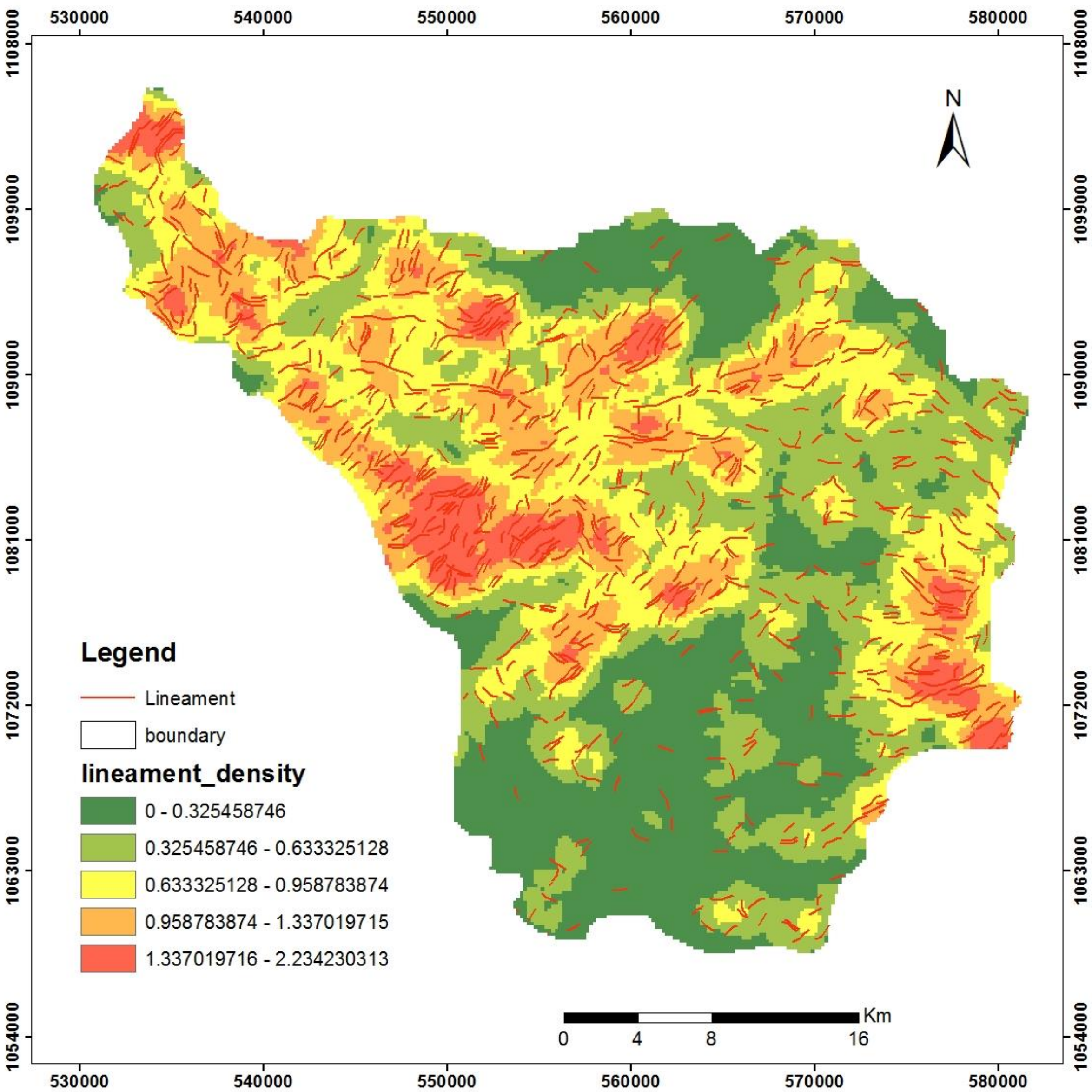


Figure 3.1 Lineament density map of Eastern upper Jemma River catchment

The preferred orientations of the lineaments are dominantly NE_SW as it is observed from the rose diagram. East-West orientations of minor faults are also observed. The NE_SW trend of the structures clearly shows that the study area was affected by the tensile forces during the opening of the main Ethiopian Rift. According to Gani et al., (2008) the quaternary NE_SW tensile stress is related to the separation of the Arabian plate to African plate.

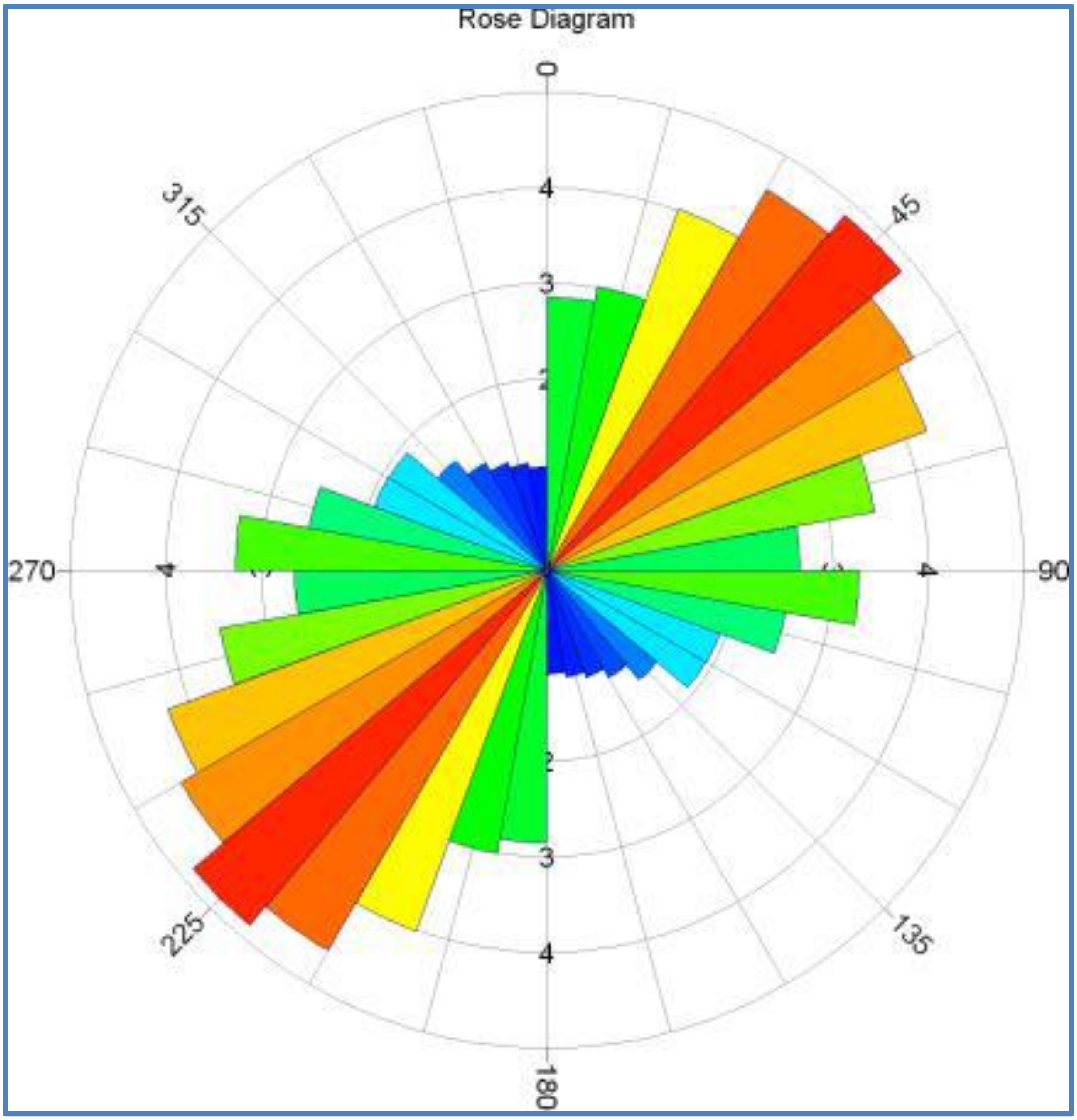


Figure 3.2 Rose diagrams of the lineaments in the study area extracted from LandSat_8.

CHAPTER FOUR

4.0 Hydrometeorology

4.1 Introduction

Hydrometeorology is the science which deals with the movement of water and water vapor in the atmosphere (Raghunath, 2006). According to Shaw, (1988) Hydrometeorology is the branch of science which links both hydrology and meteorology. Hydrology is important in the assessment, development, utilization, and management of the water resources, of any region is being increasingly realized at all levels (Raghunath, 2006). Hydrometeorological data are required to determine the water balance of a basin for developing and managing its water resources. The most useful hydrometeorological elements are precipitation, evaporation, evapotranspiration, solar radiation (sunshine hours), air temperature, relative humidity, soil moisture, water levels (surface and underground), stream discharge, water quality data of surface streams and groundwater (Raghunath, 1987 as cited in Nigussie Kebede., 2005).

There are eight meteorological stations within and around the study area and monthly data of the meteorological parameters are obtained from the meteorological agency of Ethiopia (MAOE). The stations are selected based on data availability and their position with respect to the study area. Therefore the nearest station which has long term continues data is very crucial to estimate the hydrometeorology of a catchment or a basin at large

The basic purpose of collecting and analyzing meteorological data is to calculate the water budget of the catchment area by first determining the potential evapotranspiration (PET), actual evapotranspiration (AET) soil moisture and runoff. The locations of the meteorological stations within and around the study area are summarized in the table below.

Table 4.0 Meteorological stations within and around upper Jemma River catchment

No	Station	Location (UTM)		Elevation(m)	Annual rainfall (mm)	Recording periods (years)
		Easting	Northing			
1	Debre Berhan	556250	1068300	2780	930.0	1988-2018 1*
2	Gudoberet	574500	1083300	3100	1280.4	1988-2018 2*
3	Jihur	527396	1109007	2700	879.2	1988-2015 3*
4	Seladingay	570450	1092920	2850	1276.1	2006-2018 3*
5	Chacha	549500	1053650	2770	880.9	1998-2018 3*
6	Enewari	516448	1086521	2561	1150.9	2000-2018 1*
7	Debresina	586139	1086890	2680	1902.5	1988-2018 3*
8	Ankober	580400	1060400	2601	1622.4	1998-2018 3*

1* records of precipitation, Temperature, Sunshine hours, relative humidity, and wind speed
2* records of precipitation and temperature, 3* records of precipitation only

4.2 Precipitation

4.2.1 General Occurrence in Ethiopia

Rainfall in Ethiopia is controlled by the position where the opposing north-east and south-east trade winds converge, so-called the inter-tropical convergent zone (ITCZ). The ITCZ is a zone of high atmospheric pressure where the rising air triggers heavy rainfall and high air temperature (Valadon, 1992; Angel, 2006 as cited in Wakgari Furi., 2010; Abel Abebe., 2017). In its oscillation to the north and south of the equator, the ITCZ passes over Ethiopia twice a year and this migration causes a variation in the wind flow patterns over the country with the onset and withdrawal of winds from north and south (Tsegaye Tadesse,1994; Dula Shanko and Camberlin, 1998 as cited in Wakgari Furi., 2010).

According to Wakgari Furi, (2010), when ITCZ is located in the north of Ethiopia, the northeasterly winds from southwest reach most part of the country leading to the retreat of the north trade wind. During this period, the southerlies wind from the Atlantic Ocean and the easterlies wind from the Indian Ocean reach a large part of the country causing outsized rainfall including the study area. Its southward drift marks the onset of the trade winds from the north and causes the equatorial monsoons to retreat. This periodical shift of trade winds causes rainfall to be variable and seasonal in Ethiopia.

The physiography and topography of the drainage basin, together with the vegetation, influence the relationship between precipitation over the basin and the water drained from it.

The creation and distribution of precipitation are heavily influenced by the presence of the mountain ranges and other topographic features (Fetter, 1994; Nigussie Kebede., 2005).

4.2.2 Rainfall Patterns of the Study Area

Rainfall is the most widely measured meteorological parameter in the eastern upper Jemma river catchment. By systematically examining of rainfall records from metrological rain gauge stations demonstrates that; there are two recognizable rainy seasons common to the study area. The principal rainy season frequently extends from June through September and the short rainy season takes place in March until May while the remaining months are in most cases drier.

Table 4.1 Mean monthly distribution of RF (mm) within and around the study area

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Debre Berhan	11.8	16.4	38.5	55.3	43.2	55.0	316.9	273.9	84.4	21.8	8.3	4.4
Gudoberet	14.4	13.2	41.6	55.3	66.5	85.1	411.2	381.9	132.3	50.2	22.5	6.3
Jihur	8.5	26.2	41.2	45.8	27.7	61.4	291.2	271.8	81.4	12.9	6.5	4.4
Debresina	71.6	47.0	113.6	158.1	121.2	84.1	384.4	444.2	194.2	117.7	94.9	71.5
Ankober	72.2	41.3	128.1	129.3	98.1	67.8	305.3	463.3	176.3	72.9	31.0	36.6
Chacha	7.5	5.7	18.7	51.0	30.5	61.4	285.5	306.6	93.2	14.5	2.6	3.6
Seladingay	9.1	11.9	28.3	88.3	53.2	108.8	414.7	398.7	106.2	30.3	15.1	11.6
Enewari	6.2	16.9	55.0	78.0	67.2	97.3	350.5	351.6	103.2	11.5	6.1	7.3

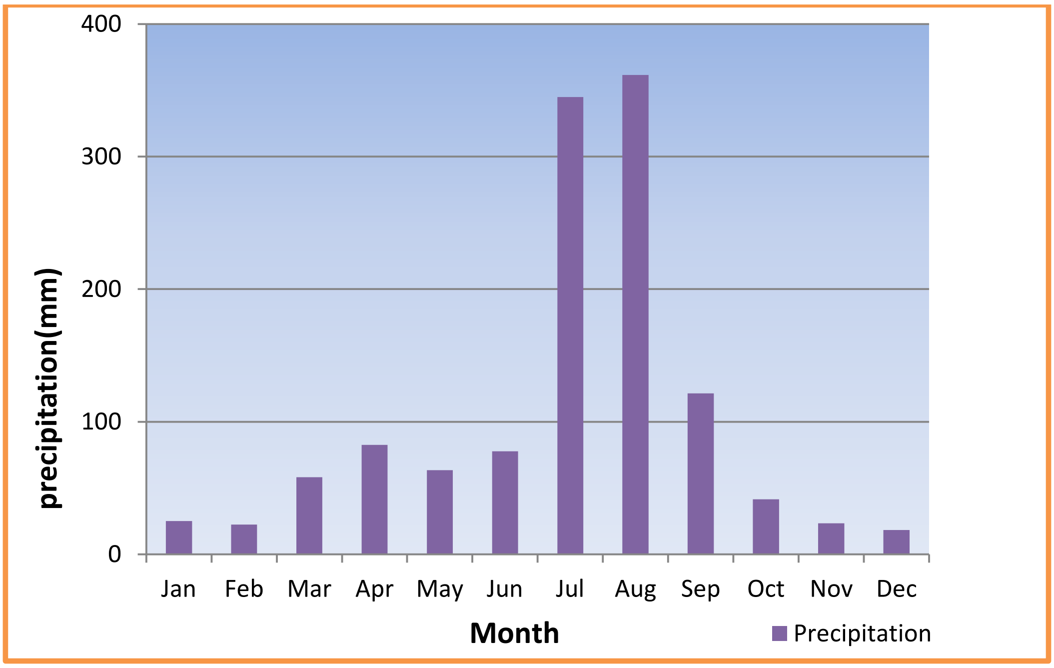


Figure 4.0 Mean monthly distribution of rainfall from the eight stations

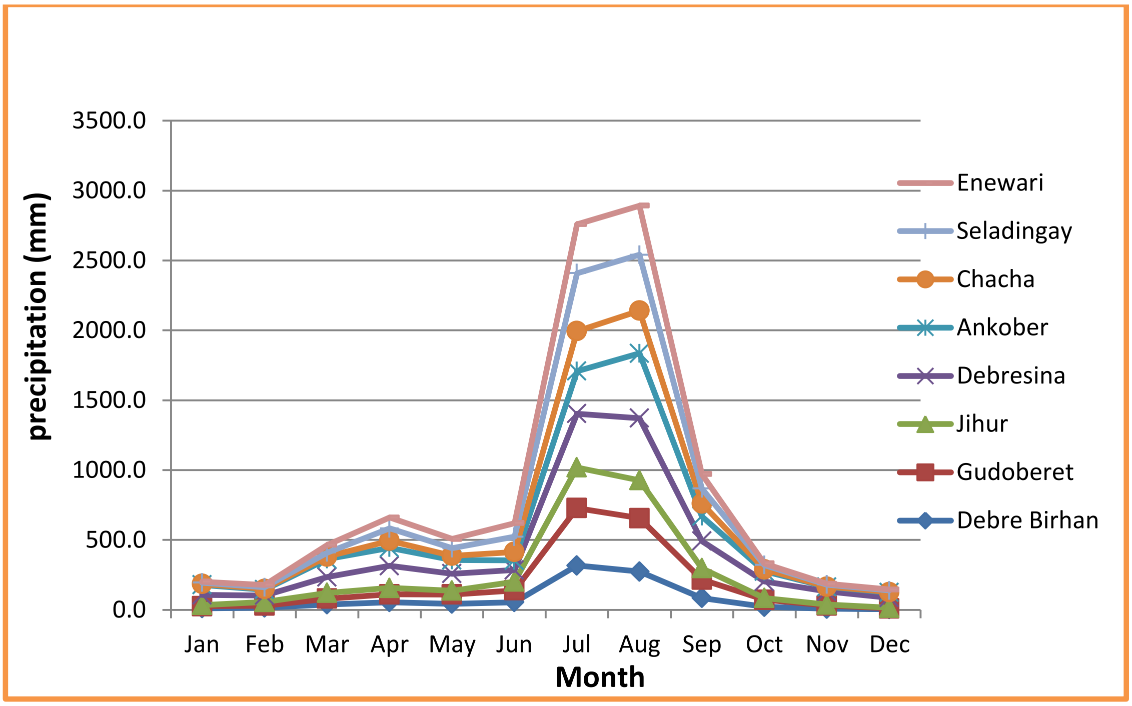


Figure 4.1 Seasonal and spatial distribution of rainfall from MAOE

As it is observed from the patterns of rainfall (Figure 15) the study area has two rainfall regimes (bimodal rainfall characteristics). During the month of March, April and May the area got small rain (bulg season) while July, August, and September months got greater rainfall or big rain (kiremt season). Therefore the pick rain recorded in the month of August during the summer season.

4.2.2 Determination of Areal Depth of Precipitation

According to Raghunath (2006) the average depth of rainfall over the area is determined by one of the following three methods: arithmetic means method, Thiessen polygon method, and Isohyetal method. For this work, all three methods were applied.

1. Arithmetic means methods: It is obtained by simply averaging arithmetically the amounts of rainfall at the individual rain-gauge stations in the area, *i.e.*

$$\mathbf{P_{ave} = \Sigma P_{1/} n} \quad \text{...} \quad \mathbf{(4.1)}$$

Where P_{ave} = average rainfall over the area, ΣP_1 = sum of rainfall amounts at individual rain-gauge stations, *and* n = number of rain-gauge stations in the area

Therefore the areal precipitation of the eastern upper Jemma river catchment by using this method is **1162.167** mm.

This method is fast and simple and gives good result in the flat country if the gauges are uniformly distributed and the rainfall at different stations do not vary very widely from the mean. These limitations can be partially overcome if topographic influences and areal representativity are considered in the selection of gauge sites (Raghunath, 2006).

2. Isohyetal methods: In this method, the point rainfalls are plotted on a suitable base map and the lines of equal rainfall (isohyets) are drawn giving consideration to orographic effects and storm morphology. The average rainfall between the successive isohyets taken as the average of the two isohyetal values are weighted with the area between the isohyets, added up and divided by the total area which gives the average depth of rainfall over the entire basin (Raghunath, 2006) i.e.,

$$P_{ave} = \sum A_{1-2}P_{1-2}/\sum A_{1-2} \quad \text{…………………………………………………} (4.2)$$

Where A_{1-2} = areas between isohyets $P1$ and $P2$

$P_{1-2}= (P_1+P_2)/2$

$\sum A_{1-2}$=A=total area of the basin

Table 4.2 Isohyetal method of calculating the areal depth of precipitation of the study area

ID	Isohythal range (mm)	Pi(mm)	Ai(Km²)	Ai/At	(Ai/At)*Pi	R(mm)
1	<1000	1000	144.1	0.114821	114.8207	
2	1000-1110	1055	375.4	0.299124	315.5753	
3	1110-1200	1155	272.6	0.217211	250.8789	
4	1200-1270	1235	250.4	0.199522	246.4096	
5	>1270	1270	212.5	0.169323	215.0398	
					Total mean areal rainfall (R)	**1142.724**

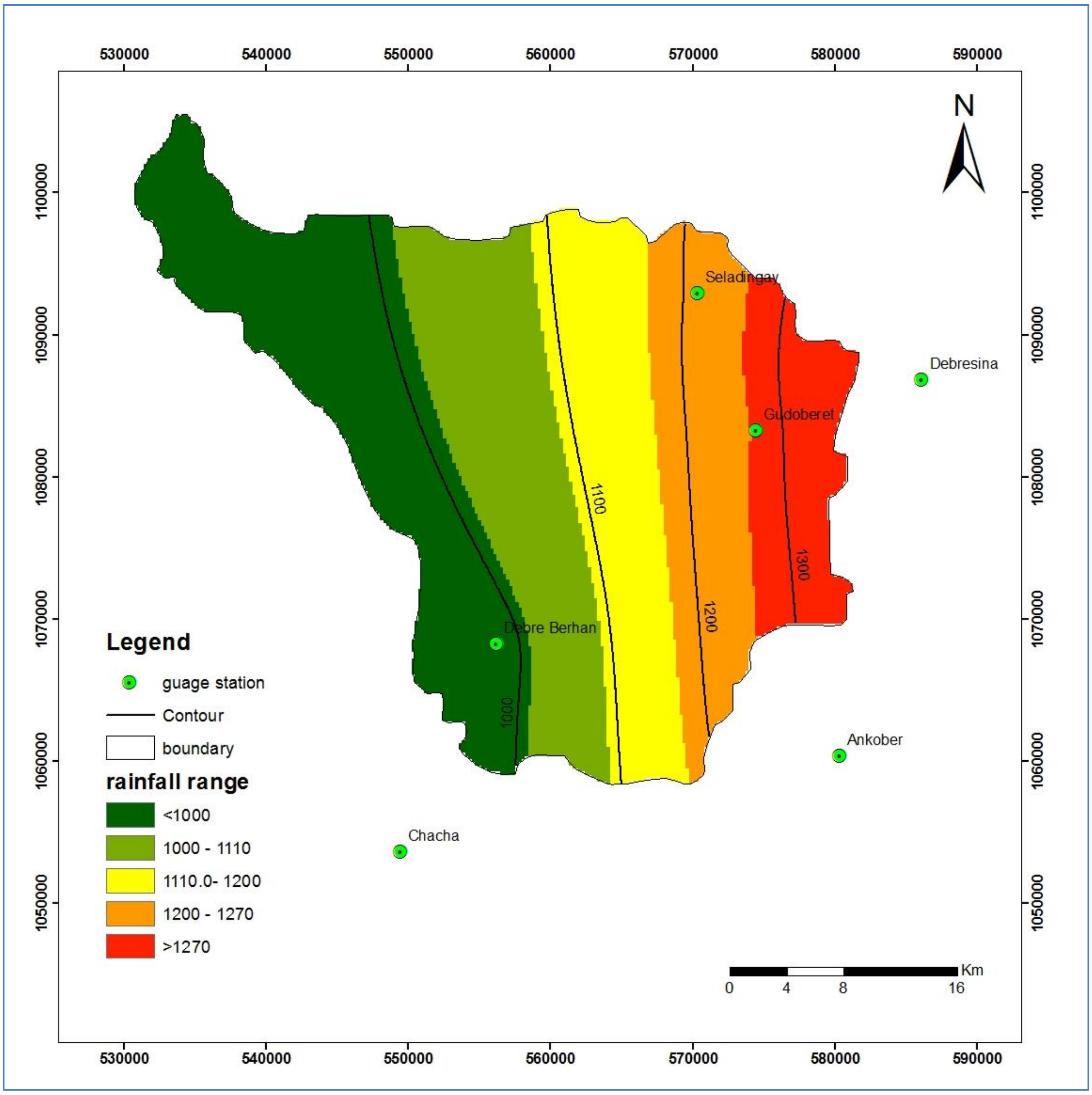


Figure 4.2 Isohyetal Map of Eastern upper Jemma river catchment

3. Theissen polygon method

The rainfall measurements at individual gauges are first weighted by the fractions of the catchment area represented by the gauges and then summed. On a map of the catchment with the rain gauge stations plotted, the catchment area is divided into polygons by lines that are equidistant between pairs of adjacent stations (Theissen, 1911 sited in Shaw, 2005). Therefore the areal rainfall is estimated as:

$$R = \sum Riai/A \text{.....................................(4.3)}$$

Where; R- the areal rainfall, Ri- is the rainfall at n rain gauge stations, ai- is the area of the individual polygon, and A- is the total area of the catchment.

Table 4.3 Theissen polygon method of calculating the areal depth of precipitation of the study area

Station	Precipitation (Ri in mm)	Area (ai in Km^2)	Riai	Riai/A
Debre birhan	930	510.47	474737.1	411.11
Gudoberet	1280.4	270.01	345720.8	299.38
Seladingay	1276.1	407.42	519908.7	450.23
Ankober	1622.4	67.08	108830.6	94.24
			Total Areal rainfall	**1254.98 mm**

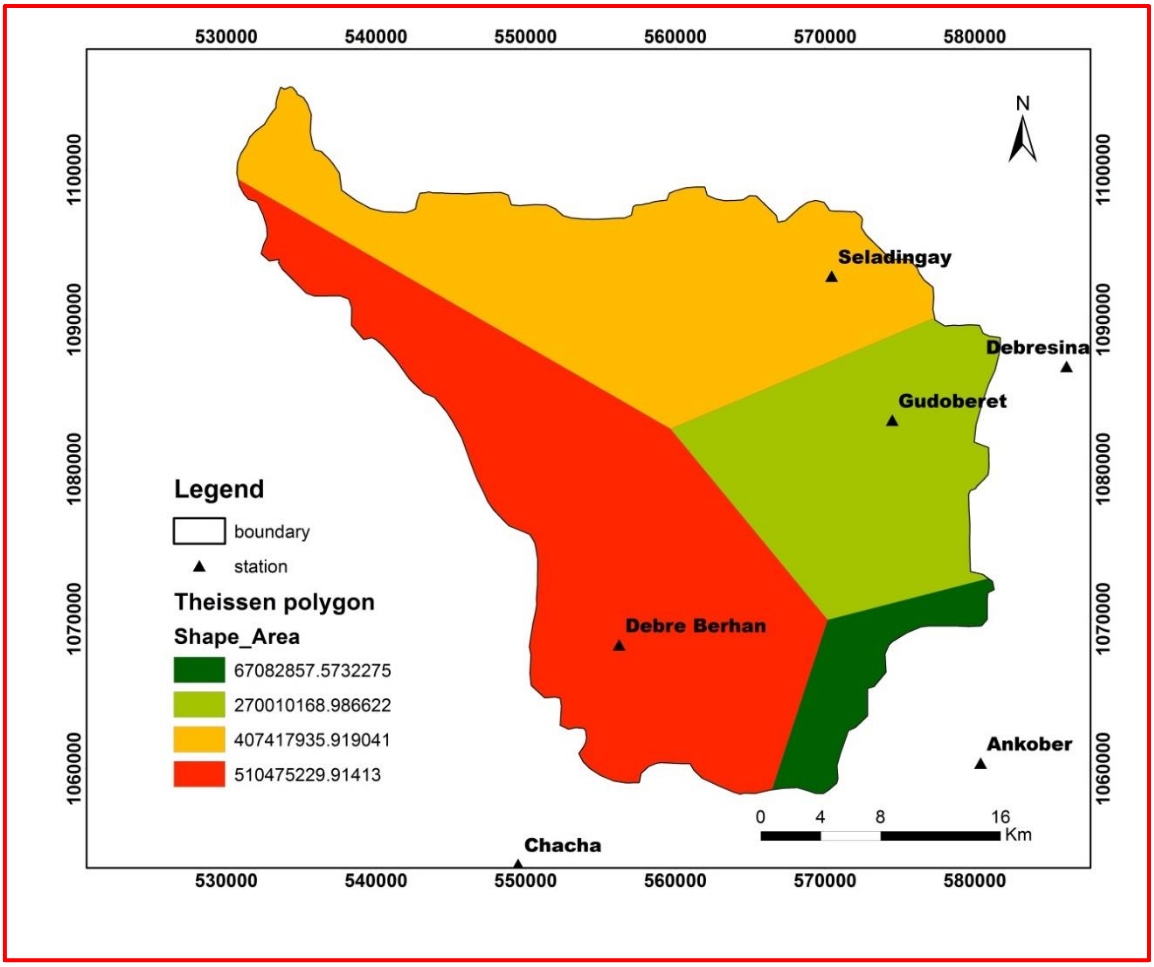


Figure 4.3 Theissen polygon map of the eastern upper Jemma river catchment

Therefore; for the analysis of this work the best estimate average values of Isohyetal and Theissen polygon methods were used. Thus; the real depth of precipitation in the eastern upper Jemma river catchment is equal to **1198.85 mm/year.**

4.3 Temperature

Temperature is one of the most important meteorological parameters to be considered in hydrometeorological characterization and for recharge estimation. The long term records of mean minimum and mean maximum values of temperature at Debre Birhan and Enewari stations and only maximum temperature at Godoberet stations are obtained from MAOE (table 4.4). The mean monthly temperature recorded at Enewari station is higher as compared to the values recorded at Debre Birhan station.

Table 4.4 Monthly maximum and minimum mean temperature variability of the three stations

Station		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Debre Birhan (1988-2018)	Max	19.9	20.8	21.06	21	21.7	22.1	18.5	18.14	18.9	18.9	19	19.07
	Min	4.76	6.06	7.7	7.82	7.31	7.5	8.58	8.76	7.1	3.52	2.32	3.03
	Average	12.33	13.43	14.38	14.41	14.50	14.8	13.54	13.45	13	11.21	10.66	11.05
Enewari (2000-2018)	Max	22.04	23.48	23.53	23.34	23.6	22.84	18.07	17.33	19.4	20.56	21.23	21.2
	Min	8.36	9.36	10.15	10.81	11.16	10.8	10.28	10.26	10	8.02	7	6.84
	Average	15.2	16.42	16.84	17.07	17.38	16.82	14.17	13.79	14.7	14.29	14.11	14.02
Gudoberet (1988-2001)	Max	19.7	18	18	17.83	18.27	18.83	17.1	17.06	16.53	16.03	16.41	16.76

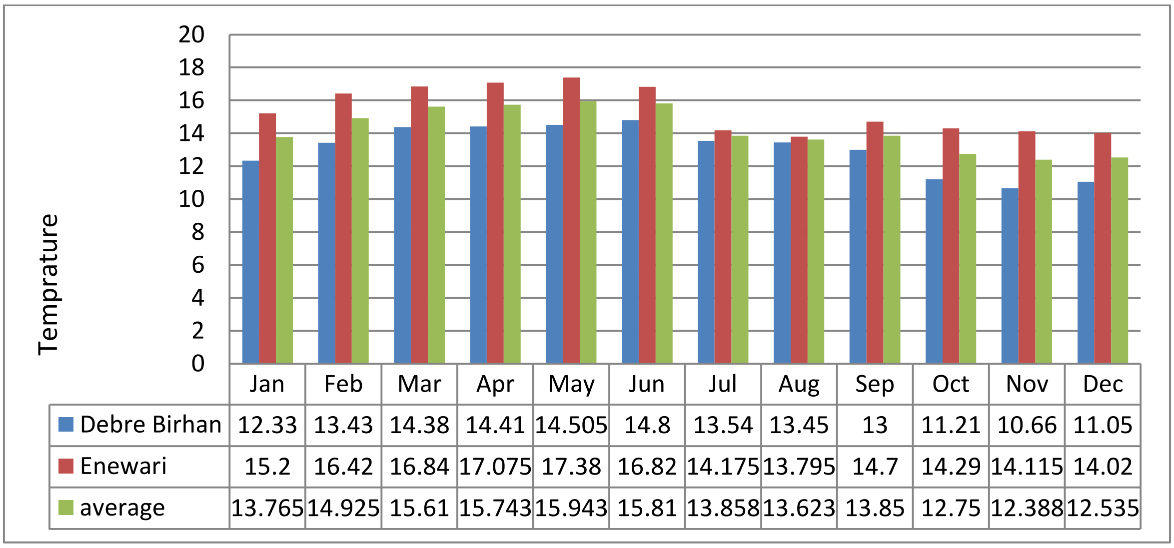


Figure 4.4 Monthly and average temperature of the study area from MAOE

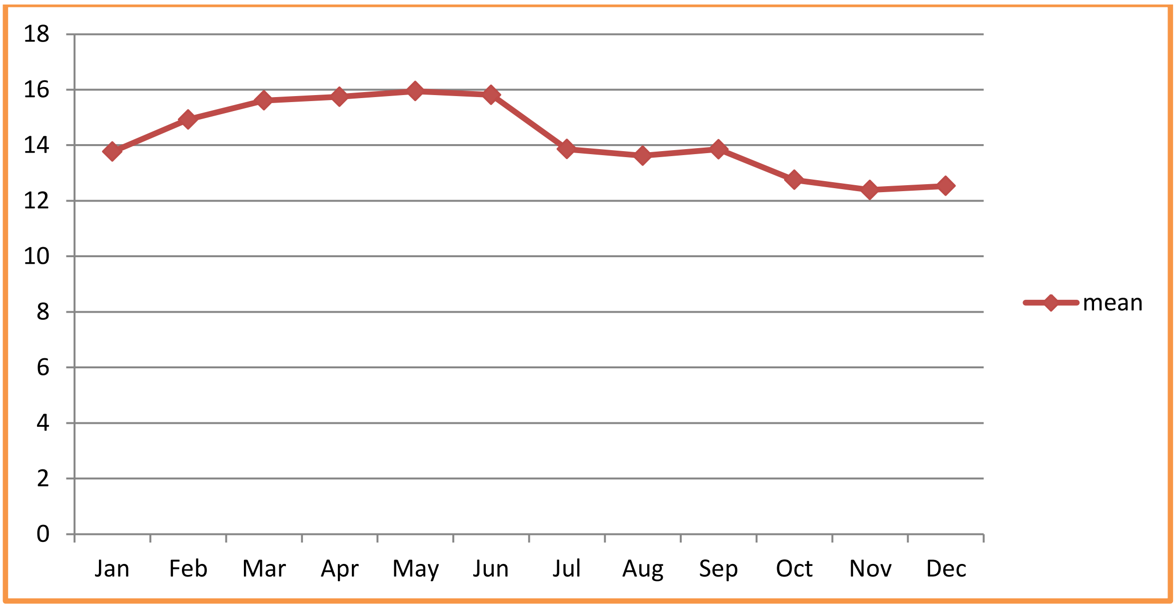


Figure 4.5 Mean monthly temperature of Debre Birhan and Enewari stations

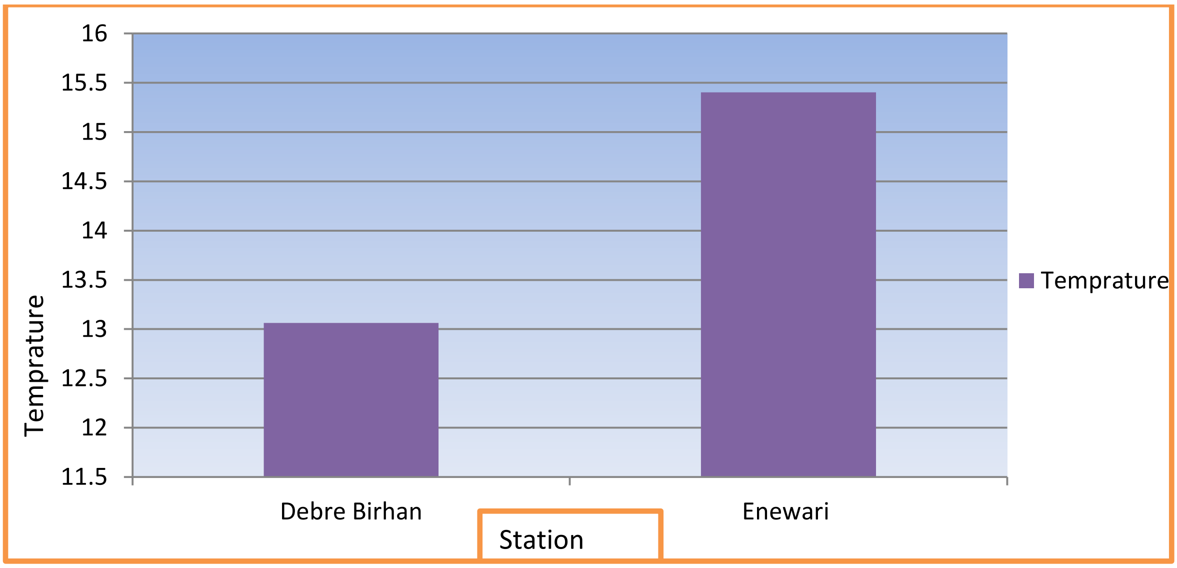


Figure 4.6 Mean annual Temperature of Debre Birhan and Enewari stations

4.4 Relative Humidity

The 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, 2005).

RH=(ed/ea) 100

where: - RH is relative humidity, ed is actual vapor pressure at the dew point temperature (Td); ea is saturated vapor pressure at air temperature(Ta)

Relative humidity indicates the relative moisture of content of the air. As the relative humidity becomes higher, the ability to absorb water vapor decrease and evaporation also slow down (Tenalem Ayenew and Tamiru Alemayehu, 2001; Fetter, 1994 as cited in Abel Abebe., 2017). The relative humidity is dimensionless quantity and commonly expressed in percentage (%). The available data from the MAOE for the study area are summarized in table 4.5.

Table 4.5 Mean monthly relative humidity (%) Debre berhan and Enewari stations

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Debre berhan	61.5	58.6	62.3	64.1	56.6	60.6	79.8	81.8	73.5	63.7	62.2	60.4
Enewari	51.1	50.1	54.8	57	58.4	65	89.21	89.2	78	62.3	58.2	52.6
Average	56.3	54.4	58.5	60.5	57.5	62.8	84.5	85.5	75.8	63	60.2	56.5

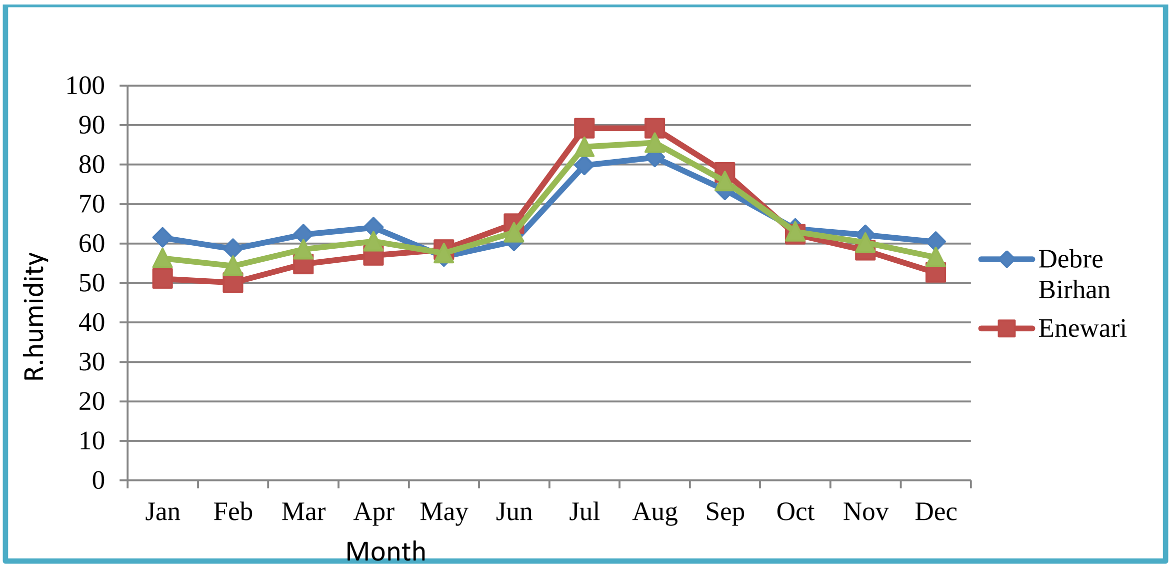


Figure 4.7 Graph of the mean monthly relative humidity of Debre Birhan and Enewari stations

4.5 Sunshine hour

Sunshine hour is the time in hours of sunshine in a day (Nigussie Kebede., 2005). Sunshine hour and evaporation are directly related. When the day is shiny there is high evaporation rate but if the day is cloudy the evaporation rate is low. The maximum sunshine hour recorded in the study area is in the months of January, February, and December.

Table 4.6 Monthly mean sunshine hours (hrs/d) of Debre Berhan and Enewari stations from MAOE

Stations	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Debre Berhan	9.3	8.6	8.0	7.2	7.8	6.5	4.2	4.6	6.0	7.5	8.8	9.1
Enewari	9.2	8.8	7.4	7.1	7.5	5.5	3.7	3.8	6.1	8.8	9.0	9.2
Average	9.2	8.7	7.6	7.2	6.0	6.0	4.0	4.2	6.1	8.1	9.0	9.2

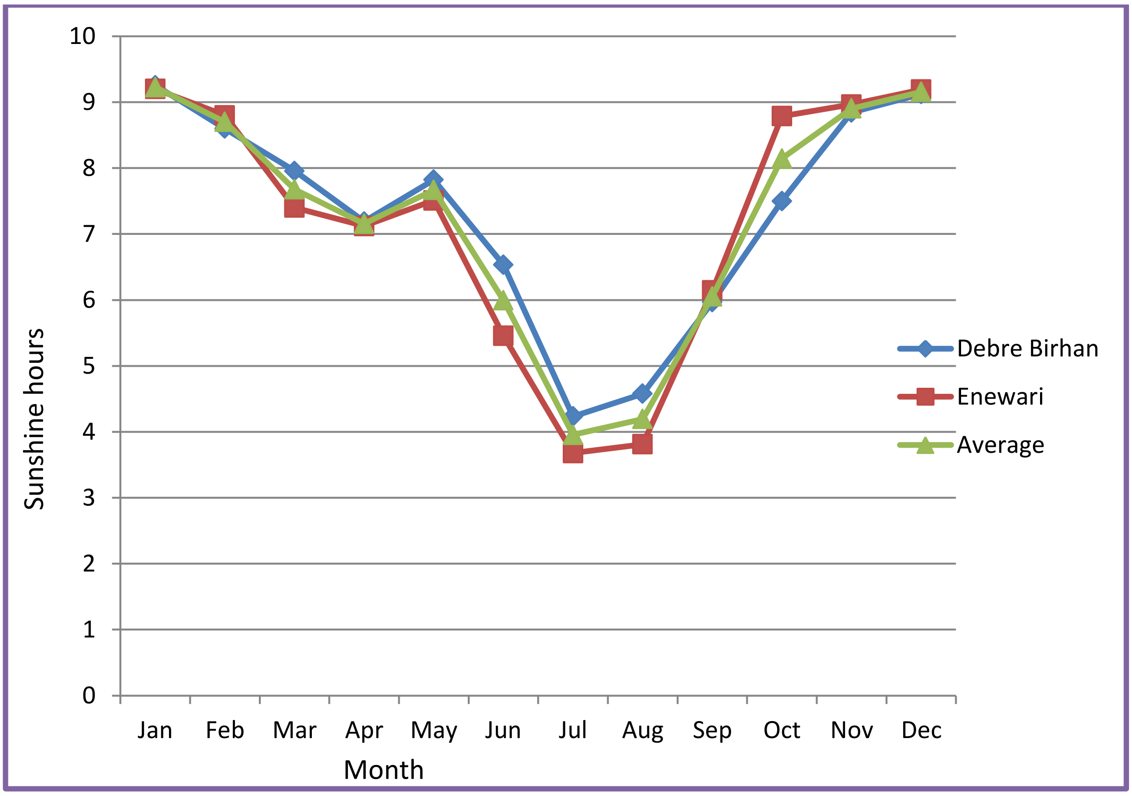


Figure 4.8 Mean Monthly pattern of sunshine duration in (hour/d) from MAOE

4.6 Wind speed

According to Shaw, (2005) as evaporation proceeds, the air above the water gradually becomes saturated and, when it is unable to take up any more moisture, evaporation ceases. The replacement of saturated air by drier air would allow evaporation to continue. Thus, wind speed is an important factor in controlling the rate of evaporation. Out of the eight stations in and around the eastern upper Jemma river catchment, the measurement of wind speed is present only at stations of Debre Birhan and Enewari.

Table 4.7 Monthly mean wind speed (m/s) of Debre Berhan and Enewari stations

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Debre Berhan	2.5	2.7	2.7	2.4	2.5	2.2	1.6	1.5	1.6	1.6	2.0	2.3
Enewari	3.1	3.6	3.4	3.6	3.8	2.6	1.8	1.7	2.1	3.1	2.5	2.6
Average	2.8	3.2	3.1	3.0	3.1	2.4	1.7	1.6	1.8	2.4	2.3	2.5

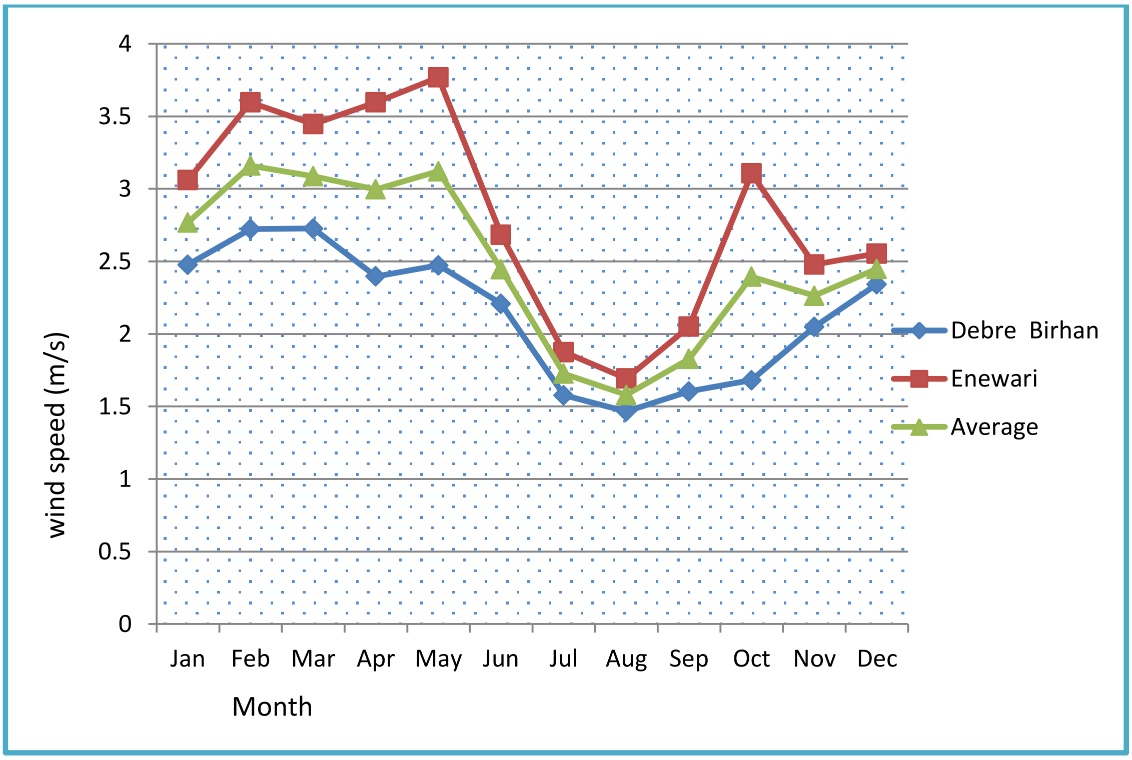


Figure 4.9 Monthly mean wind speeds

4.7 Evapotranspiration

According to Shaw, (2005) Evaporation from an open water surface is the direct transfer of water from lakes, reservoirs, and rivers to the atmosphere. This can be relatively easily assessed if the water body has known capacity and does not leak. The second form of evaporation loss occurs from the transpiration from vegetation. Evapotranspiration is usually thought of as the total loss by both evaporation and transpiration from a land surface and its vegetation. The value of evapotranspiration varies according to the type of vegetation, its ability to transpire and to the availability of water in the soil. Evapotranspiration is influenced by general climatic conditions.

The frequency of evapotranspiration at any particular place is influenced by different circumstances containing as part of the whole obtained energy are connected to solar radiation and, humidity, air temperature, wind speed above the surface, water serviceability, land cover features such as vegetation, and soil characteristics. Evapotranspiration cannot be measured directly (Bonan, 2002). Empirical formulas that use distinct meteorological data are used to determine mathematically potential evapotranspiration and actual evapotranspiration.

4.7.1 Estimation of Potential Evapotranspiration (PET)

According to Brutsaert, (1982) PET is the quantity of water that was evaporated under an optimal set of circumstances, among the unlimited supply of water. Thornthwaite, (1944) sited in Fetter, (2005) also introduced as PET, is equal to "the water loss, which will occur if at no time there is a deficiency of water in the soil for the use of vegetation and Thornthwaite was also recognized an upper bound to the amount of water an ecosystem will lose by evapotranspiration." The majority of the water loss due to evapotranspiration takes place during the summer months, with little or no loss during the winter. Because there is often not sufficient water available from soil water. To estimate the monthly basis evapotranspiration of the catchment, the Penman combined method was used.

4.7.1.1 Aerodynamic-Energy Budget (Penman Combined) Method

The Penman method of potential evapotranspiration calculation is also known as a combined method as it combines the energy budget and the mass transfer methods. The Penman method is used to calculate the PET using climatological parameters like; sunshine hours, temperature, relative humidity and wind speed. The method was later modified by (MAFF, 1967 as cited in Shaw, 2005) to allow for the condition under which evaporation plus transpiration takes place from a vegetated surface. The basic equation of PET is:

$$\text{PET} = \frac{\left(\frac{\Delta}{\gamma}\right)\text{Ht}+\text{Eat}}{\left(\frac{\Delta}{\gamma}\right)+1} \quad \text{.................................... (4.9)}$$

Where Ht is the available heat and related to:

$$\text{Ht}=0.75\text{RI}-\text{Ro} \quad \text{.. (4.10)}$$

RI= the incoming solar radiation, Ro=is the outgoing radiation, RI is the function of the Ra, the solar radiation (fixed by latitude and season) modulated by a function of the ratio, n/N, of measured to maximum possible sunshine duration and "n" is the bright sunshine over the same period, h/day.

$$Eat= 0.35(1+u_2/100)/(ed-ea) \quad (4.11)$$

Where; u_2= the mean wind speed at two meters above the surface in miles per day ea= saturated vapor pressure at air temperature (Ta), and ed = mean vapor pressure of the air. The saturated vapor pressure at air temperature is given by;

$$e_a (Ta) =6.11exp (17.3Ta/Ta+237.3) \quad (4.12)$$

In which vapor pressure in mb and temperature in ^{0}C.

The vapor pressure of the air (e_d) is given by;

$$Ed= EH\ e_a (Ta) \quad (4.13)$$

The incoming radiation can be found as;

$$RI (1-r) = 0.75Ra.fa (n/N) \quad (4.14)$$

r- is the albedo or reflection coefficient and for the eastern upper Jemma river catchment cover by matured forest, bushes and shrubs, grasses and cultivated crops, 0.25 are taken.

$$fa (n/N) = (0.16+0.62n/N) \quad (4.15)$$

The outgoing radiation can be written as;

$$Ro = \sigma T_a^4(0.47-0.075\sqrt{e_d})(0.17+0.83n/N) \quad (4.16)$$

Where T_a^4 is the theoretical blackbody radiation and σ is the Stefan Boltzmann constant (5.67 x 10^{-8} x Wm-2 T^{-4}).

Thus, the potential evapotranspiration of the study area is calculated and according to penman combined method, the PET of the area is **1376.64 mm/year**.

Table 4.8 Calculated potential evapotranspiration of Eastern upper Jemma river catchments using Penman combined method

Elements	Months												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annum (mm/year)
T(^{0}C)	13.76	14.92	15.61	15.74	15.94	15.81	13.85	13.62	13.85	12.75	12.38	12.53	
T(^{0}K)	286.91	288.07	288.76	288.89	289.09	288.96	287.01	286.77	287	285.9	285.53	285.68	
RH (%)	0.56	0.54	0.58	0.60	0.57	0.62	0.84	0.85	0.75	0.63	0.60	0.56	
U_2 (mile/d)	150.32	171.79	166.42	161.05	166.42	128.84	91.26	85.89	96.63	128.84	123.47	134.21	
n (hrs/d)	9.2	8.7	7.6	7.2	6	6	4	4.2	6.1	8.1	9	9.2	
N (hrs/d)	11.6	11.8	12	12.3	12.6	12.7	12.6	12.4	12.1	11.8	11.6	11.5	
n/N	0.79	0.73	0.63	0.58	0.47	0.47	0.32	0.34	0.50	0.68	0.77	0.8	
fa(n/N)	0.65	0.61	0.55	0.52	0.45	0.45	0.35	0.37	0.47	0.58	0.64	0.65	
Ra(mm/d)	13.9	14.8	15.2	15	14.8	14.9	15	15	14.8	14.2	13.1	12.5	
RI(1-r) (mm/d)	6.79	6.85	6.30	5.88	5.05	5.06	4.01	4.16	5.24	6.23	6.29	6.15	
e_a(mm/d)	11.73	12.7	13.22	13.35	13.49	13.49	11.84	11.61	11.84	11.04	10.71	10.82	
e_d (mm/d)	6.60	6.90	7.73	8.07	7.75	8.47	10.00	9.92	8.97	6.95	6.44	6.11	
σTa4	13.21	13.42	13.55	13.58	13.61	13.59	13.22	13.18	13.22	13.02	12.96	12.98	
Ro(mm/d)	2.33	2.12	1.85	1.74	1.49	1.48	1.21	1.27	1.64	2.12	2.36	2.41	
Ht	4.46	4.72	4.44	4.13	3.55	3.57	2.79	2.88	3.59	4.10	3.92	3.73	
E_{at} (mm/d)	4.49	5.50	5.11	4.81	5.34	4.01	1.22	1.09	1.97	3.27	3.33	3.85	
Δ/γ	1.68	1.52	1.97	2.51	1.67	1.70	1.97	2.03	1.46	1.83	1.50	1.73	
PET(mm/d)	4.47	5.03	4.66	4.33	4.22	3.73	2.27	2.29	2.93	3.81	3.69	3.77	1376.64
PET(mm/month)	136.05	153.10	141.96	131.73	128.54	113.74	69.08	69.87	89.35	116.01	112.28	114.93	

Where;

e_a = Saturation vapor pressure (mmHg)

e_d = Actual vapor pressure (mmHg)

RH = Relative humidity (%)

N = Maximum possible sunshine hours determined by latitude and season (10^0 N latitude is taken from standard tables for the study)

U_2 = Wind speed (mile/day)

n = Daily mean bright sunshine hour (hr/day)

fa = A function of sun shine hour

Ra = Solar radiation which depends on latitude and season (10^0 N latitude is taken from standard tables)

R1 = Incoming solar Radiation (mm/day)

r = Albedo (reflection coefficient for incident radiation for areas covered by matured forest bushes, shrubs and caltivated land== 0.25)

σ = Stephan-Boltzmann constant (5.67 x 10-8 x Wm^{-2} T^{-4})

T = Air Temperature (^oC)

Ro = outgoing solar radiation (mm/day)

H = Available Heat (mm/day)

Ea = Energy for evaporation (mm/day)

σT^4 = Theoretical black body radiation (mm/day)

Δ (mb/^{0}C) = Slop of saturation vapour pressure plotted against temperature

ý = Is known as psychometric constant (0.66 mb/^{0}C)

4.7.2 Estimation of Actual Evapotranspiration (AET)

The term actual evapotranspiration is used to describe the amount of evapotranspiration that occurs under field conditions (Thornthwaite, 1944). If there is abundant moisture in the soil, the actual evapotranspiration rate is equal to potential evapotranspiration. When as if the moisture content in the soil limited and vegetation unable to abstract enough water from the soil, then actual evapotranspiration become less than the potential evapotranspiration. The actual evapotranspiration of the eastern upper Jemma river catchment is calculated by using Thornthwait and matter method.

4.7.2.1 Thornthwait and Matter Method

The Thornthwait and Matter method (1957) is used to estimate the actual evapotranspiration by using soil moisture values and the monthly precipitation of the area depending on the land cover type and the soil type.

When the soil reaches a saturation condition with moisture it will hold no more water. In this case, actual evapotranspiration equals potential evapotranspiration (Shaw, 1988 sited in Abel Abebe, 2017). If the precipitation exceeds the potential rate of evapotranspiration, the actual rate of evapotranspiration will equal to the potential evapotranspiration. But if there is no enough rain to replenish the withdrawal by vegetation, the soil moisture becomes increasingly depleted and there for the actual evapotranspiration will be less than the potential evapotranspiration. In this case, the actual evapotranspiration will be calculated by adding the precipitation and the change in soil moisture (see table 4.11 and 4.12).

Table 4.9 Monthly actual evapotranspiration of Eastern Upper Jemma River catchments for fine sandy loam covered with moderately deep rooted crops (Corn, Cereals, Cotton, and Tobacco) and 150 mm maximum available water capacity root depth. All units in the table are in mm.

Item	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
P	25.14	22.32	58.14	82.64	63.46	77.61	344.96	361.49	121.40	41.48	23.4	18.22	1240.29
PET	136.05	153.1	141.96	131.73	128.54	113.74	69.08	69.87	89.35	116.01	112.28	114.93	1376.64
P-PET	-110.91	-130.78	-83.82	-49.09	-65.08	-36.13	275.88	291.62	32.05	-74.53	-88.88	-96.71	
Acc.Pot. WL	-371.03	-501.81	-585.63	-634.72	-699.8	-735.93				-74.53	-163.41	-260.12	
Sm	12.58	5.24	3.01	2.13	1.41	1.09	150	150	150	91.2	50.11	26.3	
ΔSm	-13.72	-7.34	-2.23	-0.88	-0.72	-0.32	148.91	0	0	-58.8	-41.09	-23.81	
AET	38.86	29.66	60.37	83.52	64.18	77.93	69.08	69.87	89.35	100.28	64.49	42.03	789.62
D	97.19	123.44	81.59	48.21	64.36	35.81	0	0	0	15.73	47.79	72.9	587.02
S	0	0	0	0	0	0	275.88	291.62	32.05	0	0	0	599.55

Table 4.10 Monthly actual evapotranspiration of Eastern Upper Jemma River catchments for clay covered with Deep rooted Eucalyptus trees, Alfalfa, Pasture Grass, Shrubs and 200 mm maximum available water capacity root depth.

Item	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
P	25.14	22.32	58.14	82.64	63.46	77.61	344.96	361.49	121.4	41.48	23.4	18.22	1240.26
PET	136.05	153.1	141.96	131.73	128.54	113.74	69.08	69.87	89.35	116.01	112.28	114.93	1376.64
P-PET	-110.91	-130.78	-83.82	-49.09	-65.08	-36.13	275.88	291.62	32.05	-74.53	-88.88	-96.71	
Acc.Pot. WL	-371.03	-501.81	-585.63	-634.72	-699.8	-735.93				-74.53	-163.41	-260.12	
Sm	33.88	17.78	12.02	9.33	6.91	5.75	200	200	200	138.03	91.2	57.54	
ΔSm	-23.66	-16.1	-5.76	-2.69	-2.42	-1.16	194.25	0	0	-61.97	-46.83	-33.66	
AET	48.8	38.42	63.9	85.33	65.88	78.77	69.08	69.87	89.35	103.45	70.23	51.88	834.96
D	87.25	114.68	78.06	46.4	62.66	34.97	0	0	0	12.56	42.05	63.05	541.68
S	0	0	0	0	0	0	275.88	291.62	32.05	0	0	0	599.55

Where; p = precipitation, PET = Potential evapotranspiration, AET = Actual evapotranspiration, Sm = Monthly soil moisture, ΔSm = Monthly change of soil moisture, D = Soil moisture deficit, Acc.pot.WL = Accumulated potential water loss, S = Surplus moisture

Table 4.11 Long term actual evapotranspiration (AET) of the eastern upper Jemma River catchment.

Sr.No	Soil type	Land use/land cover	Areal coverage (Km^2)	AET(mm)	Weighted AET (mm)
1	Clay	Deep-rooted Eucalyptus trees, alfalfa, pasture grass, shrubs	281.12	834.96	187.01
2	Fine sandy loam	moderately deep rooted crops (corn, cereals, cotton, and tobacco)	973.86	789.62	612.73
				Total	**799.76**

The long term actual evapotranspiration of the area as it is computed from two soil type and the corresponding land use land cover units and weighted by the corresponding area; annual actual evapotranspiration (AET) loss from the catchments is about **799.76 mm.**

4.8 Runoff

Runoff is the water that is not infiltrated and percolated into the soil, but it flows on the land surface. The type of soil, geology, land use practice, morphology, rainfall intensity and vegetation type of the area influences the occurrence and the amount of runoff.

Rainfall reaching the land surface can infiltrate into previous soil, which has a finite and variable capacity to absorb water. The infiltration capacity varies not only from soil to soil but also is different for dry versus moist conditions in the same soil. If a soil is initially dry, the infiltration capacity is high. If the precipitation rate is lower than the equilibrium infiltration capacity, then all precipitation reaching the land surface will infiltrate. If the precipitation rate is greater than the equilibrium infiltration capacity but less than the initial infiltration capacity, at the beginning all the precipitation will infiltrate, but when the infiltration rate drops below the precipitation rate, some of the precipitation will remain on the ground surface. Finally, if the precipitation rate is greater than the initial infiltration capacity some water will immediately remain on the land surface (Fetter, 1994).

In the Eastern upper Jemma River catchment which is 1255 Km^2, there are different tributary rivers to the Jemma River both perennial and intermittent. From the Rivers found in the study area, only Beressa River is gauged near Debre Birhan town. The data recorded from 1997 – 2014 was used. From the daily discharge data, 229.7million cubic meter (MCM) water leaves the catchment annually having both base flow and surface flow component. Thus, the surface runoff is 298.62 mm/y and the base flow component is 211.84mm/y. The daily discharge as it is collected from the ministry of water, irrigation and electricity is summarized in the figure below. As it is evidenced from the graph, the peak discharge of the river is during the summer season (rainy season) starting from Jun to September. This indicates that the amount of River discharge depends on the season of the year and also the rainfall amount.

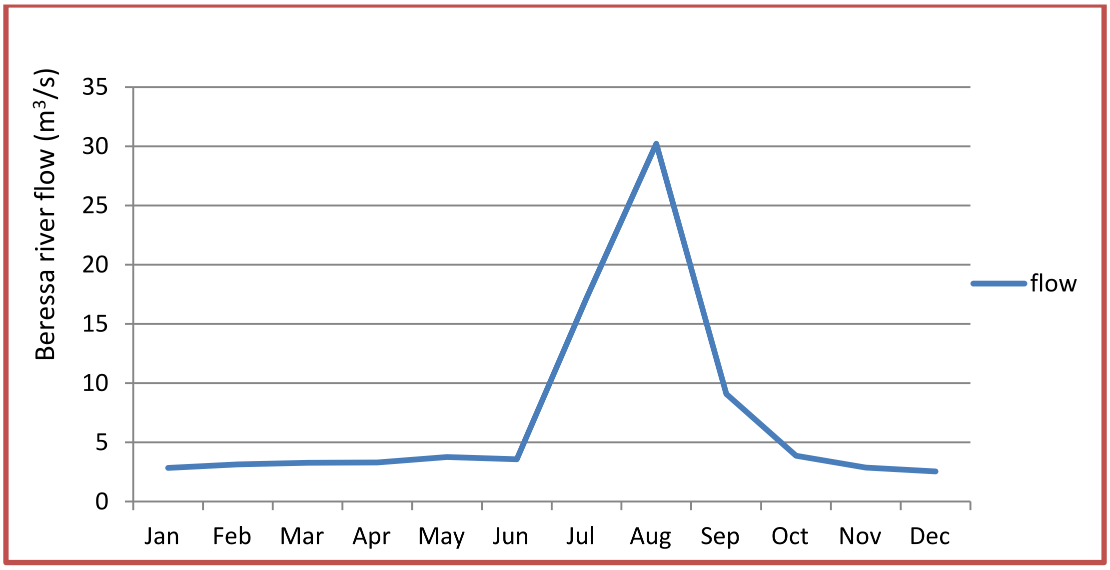


Figure 4.10 Line graph showing long term monthly mean discharge of Beressa River

CHAPTER FIVE

5.0 Results and Discussion

5.1 Groundwater Recharge Evaluation

According to Freeze and Cherry (1979), the development of groundwater resources can be viewed as a sequential process with three major phases. The first is an exploration stage, in which surface and subsurface geological and geophysical techniques are brought to bear on the search for suitable aquifers. The next step is an evaluation stage that covers the measurement of hydrogeological parameters, the design, and analysis of wells, and the calculation of aquifer yields. The third step is exploitation, or management phase, which must include consideration of optimal development strategies and an assessment of the interactions between groundwater exploitation and the regional hydrologic system. Evaluation of the resource and proper management of the known resource is very crucial. Therefore groundwater recharge evaluation is one of the important parameters to be known in groundwater development and management purposes.

Groundwater recharge can be defined in a broad sense as “an addition of water to a groundwater reservoir”. Four main modes of recharge can be distinguished (Xu, Y, and Beekman, HE (Eds), 2003): Downward flow of water through the unsaturated zone reaching the water table, Lateral and/or vertical inter-aquifer flow, Induced recharge from nearby surface water bodies resulting from groundwater abstraction and Artificial recharge such as from borehole injection or man-made infiltration ponds.

There are as many methods available for quantifying groundwater recharge as there are different sources and processes of recharge. Each of the methods has its own limitations in terms of applicability and reliability. The objective of the recharge study should be known prior to the selection of the appropriate method for quantifying groundwater recharge as this may dictate the required space and time scales of the recharge estimates (Scanlon et al., 2002 sited in Xu, Y and Beekman, HE, 2003).

Therefore; the groundwater recharge of the eastern upper Jemma river catchment is calculated by using three methods. These are:

1. Water balance method (WBM)
2. Base flow separation method (BFS) and
3. Chloride mass balance (CMB) methods

5.1.1 Water Balance of the Study Area

The water balance of a system (reservoir, a column of soil, aquifer, river basin,) represents all the gains and losses over a specific period. During water balance calculation both natural and artificial gains and losses must take into account. The principal gains that come into the system are precipitation and groundwater inflow, whereas the outflows are; evapotranspiration, runoff, and groundwater outflow.

Generally, the water balance looks like;

Inflow = outflow ± change in storage

$P+Gi=AET+Ro+Go+R\pm\Delta S$ ……………………………………..…….. (5.1)

Where; P is precipitation, AET is the actual evapotranspiration, Ro is run off, GI and Go are groundwater inflow and outflow respectively, **ΔS** is the change in storage and R, represents the infiltrated water to the subsurface(recharge).

Water balance techniques go after certain assumptions, such as; surface water divide corresponds with groundwater divide, no inflow from out and no outflow from the basin and abstraction by human is insignificant. Based on this assumption, the calculation of the water balance to evaluate the infiltrated water from long term averaged data, the equation can be reduced in to:-

$P = AET + Ro + R \pm\Delta S$

$R = P - AET - SRO$

Where; P= 1198.85 mm, AET=799.76 mm, SRO= 298.62 mm/year

Accordingly, the annual recharge of the eastern upper Jemma river catchment by using water balance method is **100.47 mm/year**. This indicates only 8.38 % of the annual precipitation is percolated to the groundwater reservoir.

5.1.2 Baseflow Separation Method

Baseflow is that part of the runoff in a river which is not the direct consequence of a rainfall event. Baseflow can be regarded as the outpouring of the groundwater reservoir feeding the rivers during rainless periods. As the groundwater reservoir has much greater retention and retarding effect than the catchment has on direct flow (surface flow and interflow), baseflow can be detected and separated from the total hydrograph (Frôhlich et al., 1994).

According to Andargie Yitbarek (2009), the major assumption in using base flow for estimating recharge is that base flow equals groundwater discharge from the aquifer storage and that groundwater discharge is roughly equal to recharge, assuming that losses from gauged watersheds caused by underflow, groundwater evapotranspiration, and abstraction are minimal.

In the eastern upper Jemma river catchment, there are several tributary rivers which feed to the Jemma River. But only Beressa River is gauged near to Debre Birhan town with the gauged area of 450 Km^2. Beressa River is separated by utilizing the software called river analysis package (rap) version 3.0.3. The software makes the base flow index, which is the groundwater contribution to the river and the flood flow index as for surface runoff.

Therefore, the annual base flow is 211.84 mm/year and the annual surface run off is 298.62 mm/year.

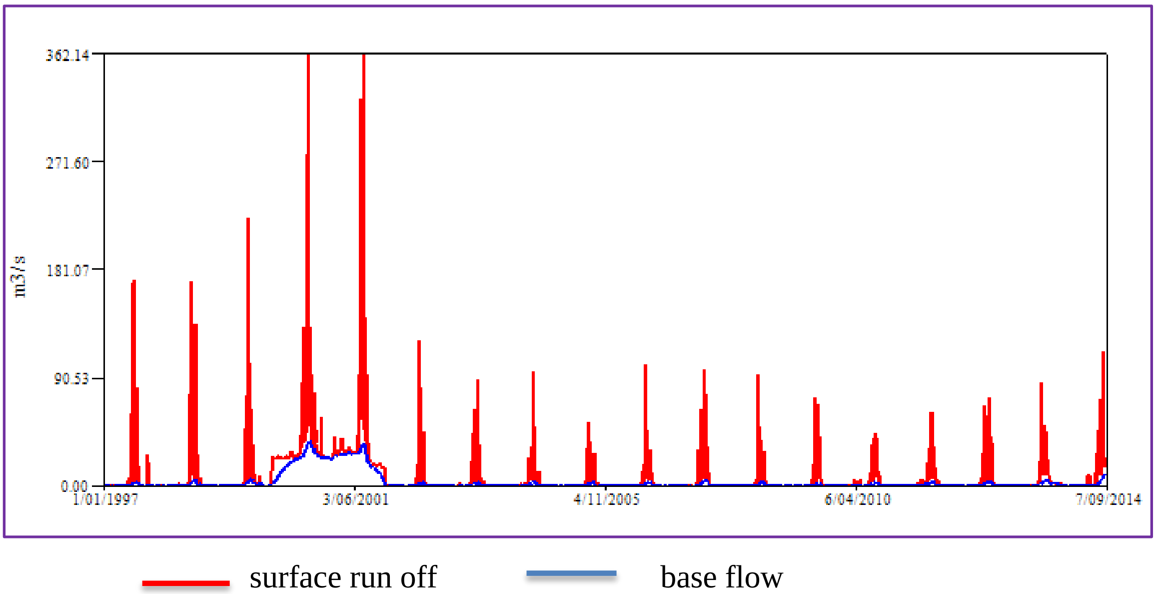


Figure 5.0 Base flow separation of Beressa River near Debre Birhan town by using rap.

- **Rainfall- River discharge relationship**

As it is explained by Shaw, (1988) the nature of the runoff to rainfall relationship over long periods depends primarily on the structure of the catchments area, but it can also be affected by the climate of the area. The relationship between runoff and rainfall is useful to understand the geomorphologic and hydrogeological condition of the catchments because runoff depends on size, shape, geology, topography, slope, land use and land cover of the catchments (Nigussie Kebede., 2005).

The most maximum rainfall occurred in the months of July and August, but the river discharge recorded is not that much higher compared to the rainfall. From the hydrogeological point of view, these relationship is explained as, even though there is maximum rainfall in the month of July and August , most part of it infiltrate to the subsurface to saturate up to its infiltration capacity. The catchments do not show fast response to rainfall. This means, there is a time lag between high rainfall and runoff. This explains relatively higher residence time and storage of groundwater.

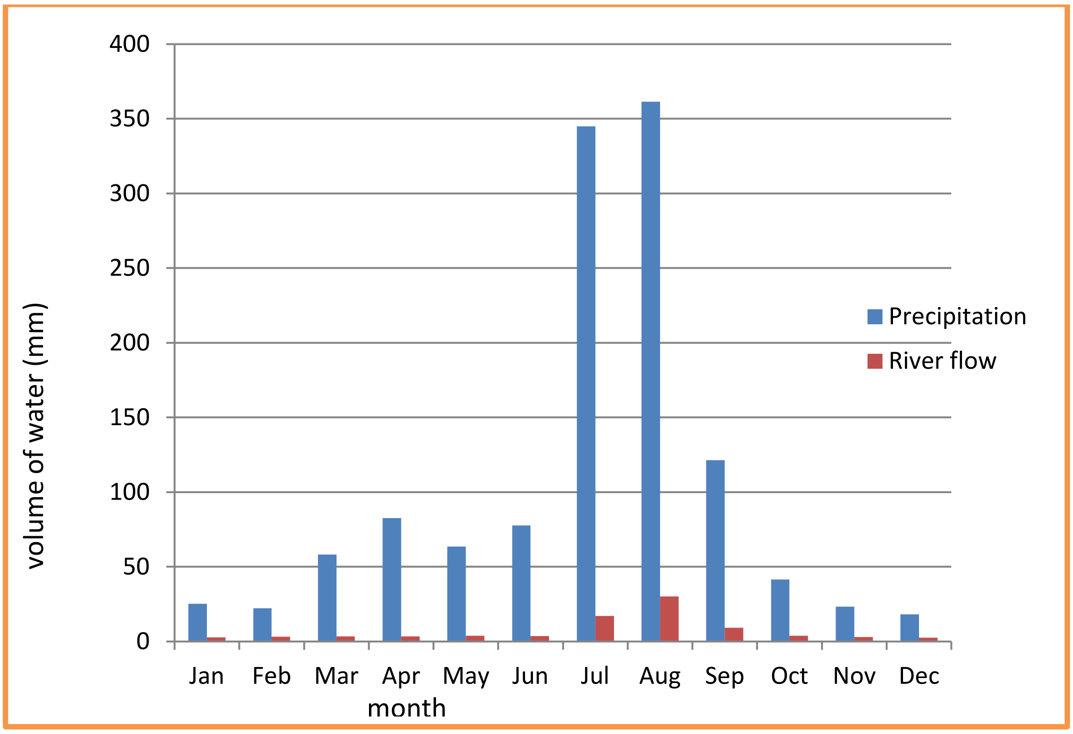


Figure 5.1 Bar graph showing the relationship between rainfall and river discharge

5.1.3 Chloride Mass Balance (CMB)

This method is based on the assumption of conservation of mass between the input of atmospheric chloride and the chloride flux in the subsurface. (Xu, Y, and Beekman, HE (Eds), 2003). Chloride is considered as a suitable environmental tracer since it is highly soluble, conservative and not substantially absorbed by vegetation. The chloride mass-balance method is suitable and cheap because of its simple data requirements.

The assumptions necessary for successful application of the chloride mass-balance method are (Marei, 2010):

1. The absence of additional chloride sources such as the dissolution of minerals, use of road salts and any potential source of pollution like wastewater.
2. Chloride is of a conservative nature in the system, meaning that the ion neither leaches from nor is absorbed by, aquifer sediments and does not take part in any particular chemical reaction.
3. The deepness of the groundwater table should be rich enough to prevent groundwater evaporation.
4. Surface runoff should be minimal.

Therefore recharge can be estimated by:

$$R= P*Cl^-_p/Cl^-_{gw} \qquad (5.2)$$

Where: R is the recharge in mm/year, P is the mean annual precipitation, Cl^-_p is the chloride concentration in the precipitation and Cl^-_{gw} is the chloride concentration in the groundwater.

In the present study, the samples collected from groundwater and rainfall was analyzed for the chloride concentration in Ethiopian construction design and supervision Works Corporation (ECDSWC) research, laboratory, and training center. The test method used was Mohr Argentometric method. The results obtained are 6.31 mg/l for chloride in rainfall, 13.53 mg/l chloride concentration in groundwater. Therefore; the recharge of the area can be estimated by chloride mass balance as:

R=1198.85mm/y*6.31mg/l/13.53 mg/l

=559.1 mm/year

Accordingly; in the eastern upper Jemma river catchment, 559.1 mm amount of water is added or recharged to the groundwater system annually.

- The limitations of applying chloride mass balance methods in the present study were; the samples of rainfall were collected at one time, and the samples were also collected at beginning of the rainy season (end of February).

Table 5.0 Summary of the results of recharge estimation by using the three methods

Method	Areal Precipitation	AET (mm/year)	SRO(mm/year)	Recharge(mm/year)
Water balance	1198.85	799.76	298.62	100.47
Baseflow separation				211.84
Chloride mass balance				559.1

Generally the three methods used to estimate the groundwater recharge of the area gave a wide range of values. The values as calculated by WBM, BFS, and CMB are: 100.47 mm/y, 211.84 mm/y, and 559.1 mm/y respectively. The contrasts among the different methods are due to the limitations of the individual methods, data usage, and analytical errors. From the three methods, the result obtained by water balance method is attractive as it is calculated by using different meteorological parameters.

5.2 Aquifer Characterization

An aquifer is a geologic media that can store and transmit water at rates fast enough to supply reasonable amounts of water to wells (Fetter, 1994). The aquifer in a given geologic media is largely a function of the degree of weathering, fracturing, and faulting, the nature of the geologic material, the sediment grain size, degree of sorting and packing. Accordingly, considering all the facts together with the spring location and corresponding discharge, topographic and geomorphic position, vegetation cover and settlement patterns were used to classify the different lithostratigraphic units into similar groups of hydrostratigraphic units which show homogeneity in their hydrogeological characteristics.

An aquifer is characterized according to subsurface geological and hydrogeological conditions. The nature and distribution of an aquifer in a geological system are controlled by lithology, stratigraphy and structural features. Thus, the lithology of the study area is dominantly Tertiary volcanic rocks with some Mesozoic rocks at the deep gorges of the rivers.

In the eastern upper Jemma river catchment there are 40 boreholes and out of these only 11 boreholes has pumping test data. Therefore; the classification of the different lithostratigraphic units into various aquifer types is based on both quantitative (pumping test analysis results) and qualitative descriptions. The qualitative descriptions are used due to lack of evenly distributed pumping test data, undulated and steep nature of the topography; the description and interpretation of the lithostratigraphic units are given qualitatively with their similarity in hydrostratigraphic units and having homogeneity in hydrogeological characteristics such as degree of weathering, fracturing, faulting, topographic features, spring discharge, and location. From the results of pumping test analysis and relative interpretations made, the lithostratigraphic permeability and groundwater potential classification are given and finally, hydrogeological map is produced with the scale of 1:50.000.

Depending on the available pumping test data analysis, degree of weathering, fracturing, faulting, topographic features, spring discharge, and placement; the relative lithostratigraphic permeability, aquifer productivity and groundwater potential zone of eastern upper Jemma river catchment are classified as follows:

5.2.1 Fissured Aquifer Developed on Basalts on the Plateau

The fractured, weathered and columunarly jointed basalt is found on the high lands of the area around Tarmaber forming a continuous ridge along the southeast and southwest of Debre Birhan town. This lithostratigraphic unit is considered to be found in the recharge area of the eastern upper Jemma River catchment. The unit is highly weathered and fractured.

From the analysis of the spring discharge data, and nature of fracturing, the upper basalt (Tarmaber - Megezez basalt) can be considered as highly permeable, moderate to low ground water potential. This is because the unit has high permeability due to higher fracturing but the storage is low. Thus the recharged rainwater leaves the aquifer quickly to the lower areas (discharge areas).

There is no any well which is drilled on this unit. The interpretation is mainly from field observations of degree of fracturing and weathering, discharge of springs and hand dug wells. The springs which are emanated on this formation has moderate to low discharge. From the data collected from the North Shewa water resource development bureau, the discharge of the springs and hand dug wells range from 0.05 l/s to 0.15 l/s and 0.01 to 0.04 l/s respectively.

5.2.2 Mixed Aquifer Developed in Fissured Ignimbrite, Rhyolite, Trachyte, Basalt and Sediments Intercalating Volcanic rocks on the Plateau.

The mixed aquifers of highly fractured Ignimbrite, Rhyolite and/or Trachyte and porous sediments are one of the major water-bearing formations of the area. It covers large gently undulating areas of the plateau. Ignimbrite and Trachyte form non-homogeneous hydrogeological environment, though the amount of groundwater in these rocks is variable from place to place depending on the frequency, intensity, and distribution of the fracturing system. On the basis of production wells drilled for Debre Birhan water supply, for Debre Birhan University, and for different fabrics, the inter-bedded volcanic rocks form semi-confined aquifers. This aquifer is being recharged directly by infiltration of rainfall and/or infiltration from porous aquifer developed in Quaternary sediments covering plateau area and from the overlying fissured basalt. The formation is drained by perennial and seasonal rivers like Beressa, Gado, Dalecha, Ayserawum, and Gedemsa Rivers. The springs like Quas Georgis, Shola, Filagenet, Mesino have Discharge between is 0.5 -1l/s.

The pumping test results of the Boreholes drilled in the fractured Ignimbrites dominantly have transmissivity value between 10-100 m^2/day with few exceptions. Mean transmissivity is 85.9 m2 /day. The hydraulic conductivity is between $5E^{-2}$m/d to5.26 m/d and discharge of 6-30 l/s. Therefore; the fractured Ignimbrite /Trachyte/ unit generally has high permeability and very high productivity.

5.2.3 Fissured Aquifer Developed in Basalts Outcropping in Deep Valleys.

The formation is found below the mixed aquifers of ignimbrite, rhyolite, and trachyte. The lower basalt is very similar to the upper fissured basalt in terms of fracturing and weathering. The formation is highly weathered and fractured so that it has moderate to low storage and high transmissivity. As it can be observed from the lineament density map, the lithostratigraphic unit is highly affected by fracturing, local fault, and joints which act as conduits for groundwater flow. The recharged water leaves the aquifer quickly to the lower parts of the area. The springs in this formation have low discharge (e.g. Lulmeda, 0.2l/s; Waginbo, 0.08 l/s and Eboybad school,0.49 l/s).

Since the lower basalt found in the deep gorges and forms steep cliffs, there is no drilled well within the study area. Therefore based on the degree of fracturing, weathering, spring discharges and inferring from the lineament density map, the unit has higher permeability and moderate to low storage.

5.2.4 Porous and Fissured Sandstone Aquifer in Deep Valleys.

The sandstone aquifer is found in the highly dissected valleys at the northern tip of the study area. The formation is medium-grained, sub-rounded grains, poorly to well sorted, compacted and thickly bedded to laminated, including the dominant crossbedding structure.

The sandstone unit is highly affected by secondary structures as it can be seen from the lineament density map. However, in the study area, there is no spring and well data to characterize this formation. Thus, the characterization is qualitative. Therefore, the formation is expected to have moderate to low groundwater potential.

5.2.5 Localized Aquifer with Intergranular Porosity and Permeability (Alluvial sediments, pyroclastic martial and intercalated sediment)

Localized aquifers of intergranular porosity and permeability are found intercalated with weathered trachyte and basalts. This aquifer is mainly found in the Dalecha well field and also in the northeastern tip of the area between Seladingay and Sassit. The lithological log from Dalecha well field reveals that the major aquifer is sand, gravely sand and pyroclastic materials. The lithologic log of the two wells found in the Dalecha well field is presented below.

The wells drilled in this aquifer for Debre Birhan town water supply purpose has no complete pumping test data, only the lithological log is available in the report. From the values of transmissivity and hydraulic conductivity obtained, the aquifer system has high productivity and high permeability. Transmissivity and hydraulic conductivity value is between 10-100m^2/d, 0.32544 m/d - 7.272m/d and discharge of 4- 10 l/s respectively.

Table 5.1 Lithological logy of DA_BH1 & DA_BH2

Depth (meters)	Lithology of DA BH2	Depth (meters)	The lithology of DA BH1
0 – 7	highly weathered volcanic ash	0 – 2	Topsoil yellow to brown color
7 – 10	weathered ignimbrite	2 – 26	highly weathered & fractured ignimbrite
10 – 12	Gravel with slightly weathered stuff	26 – 61	highly weathered & fractured trachyte
12 – 22	Gravel with highly weathered stuff	61 – 91	Sand
24 – 26	coarse sand with gravel	91 – 96	Gravel rounded & well sorted
26 – 30	Sandy gravel	96 – 105	highly weathered & fractured trachyte
30 – 35	coarse gravel with some sand	105 – 108	slightly weathered & fractured trachyte
35 – 44	Massive trachyte basalt		
44 – 48	highly fractured trachyte		
48 – 69	highly fractured trachyte		
79 – 95	Massive trachyte		

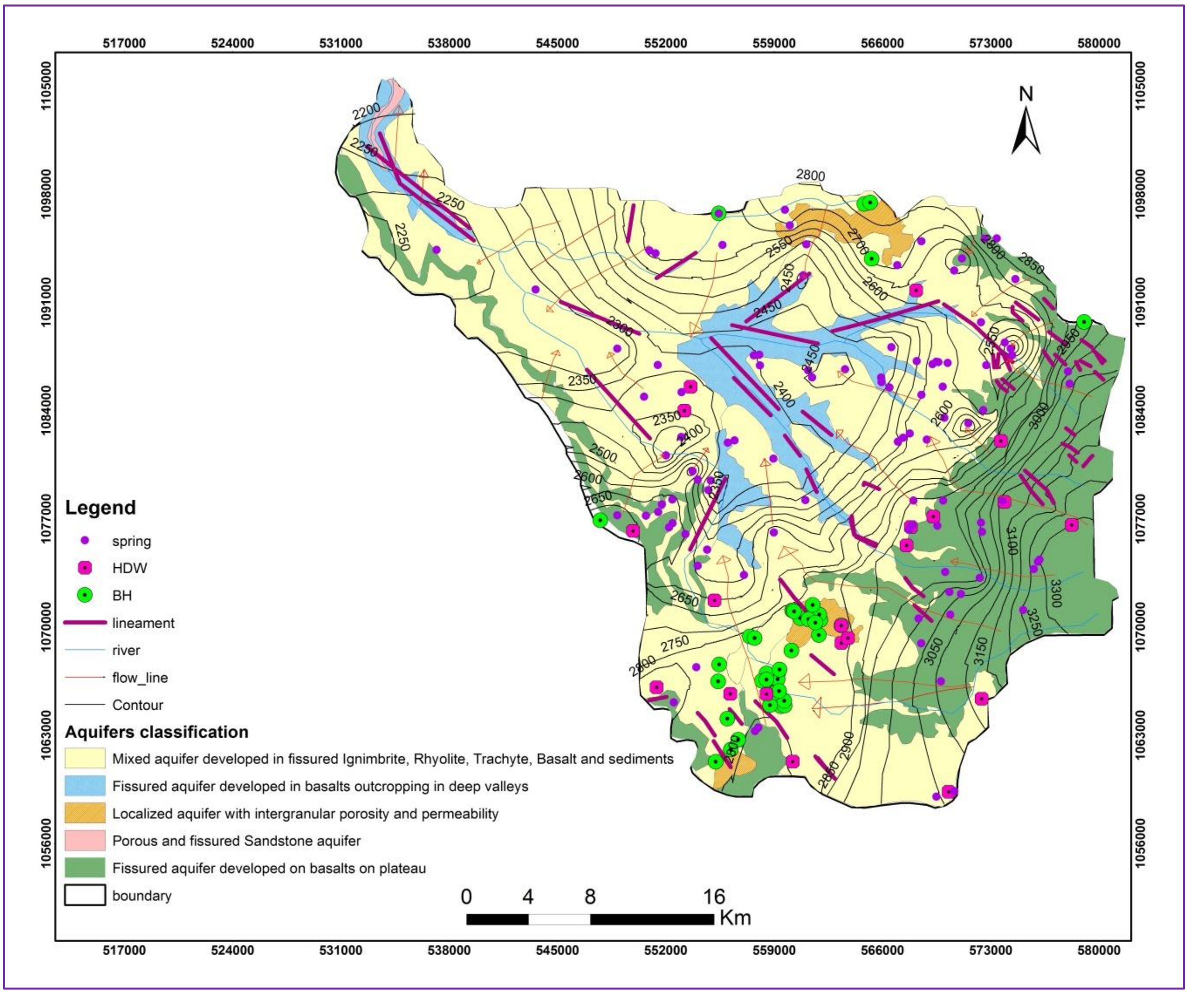


Figure 5.2 Hydrogeological map of eastern upper Jemma river catchment

Plate 5.0 Small discharge hand-dug wells in Beryo locality

5.3 EC, TDS, pH and T characterization of the study area

Nearly all groundwater originates as rain or snowmelt that infiltrates through the soil into flow systems in the underlying geologic materials. The soil zone has unique and powerful capabilities to modify the water chemistry, as infiltration occurs through this biologically active zone. The soil zone undergoes a net loss of mineral matter by the flowing water in recharge areas. As groundwater moves along flow lines from recharge to discharge areas, its chemistry is changed by the effects of a variety of geochemical processes (freeze and cherry, 1979).

According to (Hem, 1992) the chemical composition of natural water is resulting from many different sources of solutes, including gases and aerosols from the atmospheres, weathering, and erosion of rocks and soils, solution and precipitation reactions occurring beneath the soil surface, and cultural effects resulting from human actions. The slipway in which solutes are taken up or precipitated and the quantities present in solution are influenced by many environmental components, especially climate, social system and position of rock strata, and biochemical effects associated with the life cycle of plants and creatures, both microscopic and macroscopic.

Solutes contained in natural water represent the net result of a series of antecedent chemical reactions that have dissolved material from another phase, have altered previously dissolved components, or have eliminated them from solution by precipitation or other procedures. The chemical operations are influenced strongly by biologic activity in some environments and by a great many processes of a physical nature (Hem, 1992).

In whatever type of study if small samples are taken and examined to represent the whole substances, in that respect is inherent uncertainty because of possible sampling error. The extent to which small samples may be taken to be reliable representative of a great mass of material depends on various components such as the homogeneity of the material being sampled and the number of samples, and the size of the individual sample (Hem, 1992; Nigussie Kebede., 2005).

In the present study, depending on the aim of the research, only the in situ measurements of springs, rivers, and dug wells are depicted. The physical parameters that are going to be discussed are; hydrogen ion activity (PH), total dissolved solids (TDS), electrical conductivity (EC), and temperature (T). The measurement was taken by a portable instrument called PH-meter and EC-meter. The in situ measurements were compiled at different placements inside the survey region.

5.3.1 Hydrogen Ion Activity (pH)

PH is the measure of the degree of acidity and alkalinity and it is measured between the scales of 0 to 14. Pure or neutral water has a PH value of 7. The PH value of less than 7 is acidic and PH greater than 7 is basic.

In the study area, the PH measurement was made for rivers, springs and hand dug wells. The value ranges from 7.72 at Tsadkanie spring to 10.03 at Dalecha River. The measured PH values of hand dug wells fall within the range from 7.53 to 8.0. According to WHO standards, less than 6.5 is acidic, 6.5-8.5 is normal and greater than 8.5 is basic water. In the study area, 28 points are taken for the in situ measurements of PH. From these 18 points are within the WHO limits of normal water. Therefore most of the natural water is in a normal condition except Dalecha River which has a PH of 8.3, 9.72 and 10.03 at different locations of the river (see appendix 5).

5.3.2 Electrical Conductivity (EC)

Electrical conductivity (EC) is the degree of the easiness with which electrical current can pass through water. It can be measured accurately in the field using a portable conductivity meter. Therefore, both the spatial and temporal variability of EC can be measured with as high a resolution as desired (Moore et al., 2008). It is measured in micro Siemens per centimeter (μS/cm) at a specified temperature, usually 25 degrees Celsius.

In the study area, the EC measurement was collected by using a portable EC meter. As it can be seen from the data in the (appendix 5) there are 28 points of measurement. The highest value of the measurement indicates the most conductive water is for polluted water and the lowest measurement is for pure water. The highest EC value is measured in Dalecha River (867μs/cm), Beressa River (803μs/cm) and the lowest value is in Satrira river (660 μs/cm). All the others fall within this range (see appendix 5).

5.3.3 Total Dissolved Solids (TDS)

TDS can be related with any minerals, salts, metals, cations or anions dissolved in water. In general, the total dissolved solids concentration is the sum of the cations (positively charged) and anions (negatively charged) ions in the water.

(http://s3.amazonaws.com/chicagoriver/rich/rich_files/rich_files/503/original/tds.pdf).

Total dissolved solids are reported in mg/L. TDS can be calculated by multiplying a conductivity value by an empirical factor. Deriving TDS from conductivity is quicker and suited for both field measurements and continuous monitoring. When calculating TDS from EC, a TDS factor is used. The commonly used approximated factor is 0.65 which is dependent on the type of solid dissolved in water. (https://www.fondriest.com/environmental-measurements/parameters/water-quality/conductivity-salinity-tds).

Therefore; in the present study the relation between conductivity and total dissolved solids can be written as:

$$TDS\ (mg/l) = 0.65*EC \qquad (5.3)$$

Accordingly, the values of the measured EC and the calculated value of TDS are indicated in the (appendix 5) below.

Table 5.2 Water classification based on TDS values (source; freeze and cherry, 1979)

Category	**Total dissolved solids TDS (mg/l)**
Freshwater	0-1000
Brackish water	1000-10,000
Saline water	10,000-100,000
Brine water	More than 100,000

According to the classification of freeze and cherry (1979), the category of the physicochemical measurements in the eastern upper Jemma river catchment falls between 0-1000 mg/l. thus, the water is fresh.

The deliciousness of water with a total dissolved solids (TDS) level of less than about 600 mg/l is generally considered to be good; drinking-water becomes significantly and increasingly unpalatable at TDS levels greater than about 1000 mg/l (WHO, 2017).

The TDS is correlated with temperature. The highest TDS was measured at a higher temperature. As it can be seen from the data in the (appendix 5), the TDS values of the Beressa River and Dalecha River shows relatively higher reading. This increase in total dissolved solids can be considered to be resulted from waste disposal from towns. As it is observed during field work Dalecha River is full of contaminants like plastic bottles, and other wastes.

Along the course of the rivers, the TDS was observed to be increased from upstream to downstream. This indicated the water was interacted with different rocks along its flow path. The TDS values are considered to be low in higher altitude area and higher at lower altitude areas and this was observed from the collected data. Thus water flows from lower TDS value to higher TDS values.

Table 5.3 Statistical distribution of physicochemical parameters with respect to WHO Guidelines of Normal water

	PH	TDS (mg/l)	EC (μs/cm)	T ⁰C
Mean	8.54	453.6071	697.86	18.98
Maximum	10.03	563.55	867	22.3
Minimum	7.5	425.75	655	14
WHO Guidelines	6.5 – 8.5	< 1000	-	-

Plate 5.1 Water quality physical parameter field measurements: A) at Quasigeorgis spring, B) Dalecha river, C) Gomata spring, D) Bakelo spring

5.4 Groundwater Flow Dynamics

According to Kovalevsky et al., (2004) Groundwater is an important source of water; it provides the base flows for rivers, or act as an underground reservoir from which water can be pumped as a location into which water can be drained. Therefore it is the flow of groundwater which must be examined.

Commonly, groundwater moves very slowly; one hundred meters per year is a typical average horizontal velocity and one meter per year is a typical vertical velocity. When these velocities are multiplied by the cross-sectional areas through which the flows occur, the amounts of water involved in groundwater flow are often significant. Consequently, the essential feature of an aquifer system is the balance between the inflows, outflows, and quantity of water stored. Unlike a surface reservoir, the upper surface of the groundwater (the water table or phreatic surface) is not horizontal; a sloping water table results from the resistance to flow caused by the hydraulic conductivity. The actual groundwater flows cannot be measured directly. Consequently, an alternative method of identifying groundwater conditions is required and this is supplied by the groundwater head (or groundwater potential). The groundwater head at a location in an aquifer is the height to which water will rise in a piezometer (or observation well). So that the conditions at a specific position in an aquifer can be placed. Groundwater flows from a higher to a lower groundwater head (Kovalevsky et al., 2004; Rushton, 2003)

According to Todd, (1976), primary and secondary porosities of rocks play a significant role in groundwater occurrence, localization and flow, particularly in hard rock terrains. All aquifers contain some degree of heterogeneity and the fundamental characteristics of fractured rock aquifers are extreme spatial variability in hydraulic conductivity, and hence groundwater flow rate and pattern (Cook, 2003). The Lithostratigraphic and structural framework of geologic units control, aquifer hydrodynamic characteristics, aquifer productivity and limit conditions (Singhal and Gupta, 1999 sited in Tilahun Azagegn., 2014).

In most cases, the water table is a subdued replica of the land topography where groundwater divide matches with surface water divides. However, under certain conditions, groundwater flows across the surface water divides. The flow may continue through adjacent basins and to any intervening ranges, as long as the permeable rocks are continuous and sub-surface geometric architecture is favorable for groundwater movement (Fetter, 2001; Tilahun Azagegn., 2014).

To characterize the hydrodynamics of an area requires understanding the hydraulic properties, the geometric setup and groundwater level measurement. Thus, to characterize the flow dynamics in the current survey, groundwater level measurements were applied. Groundwater contours are produced and the flow directions of the groundwater were identified. Hand dug well information and spring discharges were also applied to characterize the aquifer.

The type of data for hydrodynamic characterization was collected from water point inventory during fieldwork, zonal water supply organizations, and drilling companies. The water point data used in the current study, including boreholes, hand-dug wells, and springs are summarized in the table beneath:

Table 5.1 Hydrodynamic data used in this study

No	Type of data	Water points	Description of water points	Remark
1	Boreholes	40	Depth range 76 – 259m SWL range 4 – 120.58m Transmissivity range 0.05- 466 m^2/d Discharge range (2-30 l/sec)	Most of the drilled wells are concentrated around Debre Birhan town only a few are found in Seladingay, Tarmaber and Sassit
2	Hand dug wells	26	Most of the dug wells are very shallow	The water level and depth of the dug wells are not known. Used to characterize the hydraulic properties
3	Springs	111		Sprigs are also used in hydrodynamic characterization

Groundwater flow directions were identified from the groundwater contours. Groundwater contours or flow nets are lines connecting points of the same groundwater elevation. The elevation of the groundwater is obtained by deducting the static water level from surface elevation. The patterns of the contours are very crucial for identifying the flow directions of groundwater in the area of interest. Therefore groundwater flow lines are perpendicular to the equipotential lines (contours). Consequently, from the groundwater contour map, Narrow contour spacing corresponding to high hydraulic gradients indicates a rapid change in elevations of water level compared with those of wider spacing indicating the presence of localized aquifers within the regional aquifer domain.

The flow direction in the eastern upper Jemma river catchment generally follows the surface morphology, the surface water flow and it is dependent on the structures. Perennial and intermittent rivers that feed local aquifer follow those alignment lineaments, where the groundwater flow also follows such pattern. The direction of existence of spring points of the tertiary volcanic rocks is some show structurally controlled, indicating the structural tendency of groundwater flow and there are also springs at the contact of the different formations.

Generally, the groundwater flow system in the eastern upper Jemma river catchment is easy to understand; as it generally follows the surface morphology and the surface water drainage system developed in the area. Therefore the flow direction as it is identified from the groundwater level contour map, it flows from the SE, S and SW corner towards N and NW corner of the Eastern upper Jemma River catchment. The outlet of the study area is at the northern tip of the catchment area. All water (surface and groundwater) flows to the lower regions of the catchment; which is found at the northern tip at the junction with Jemma River.

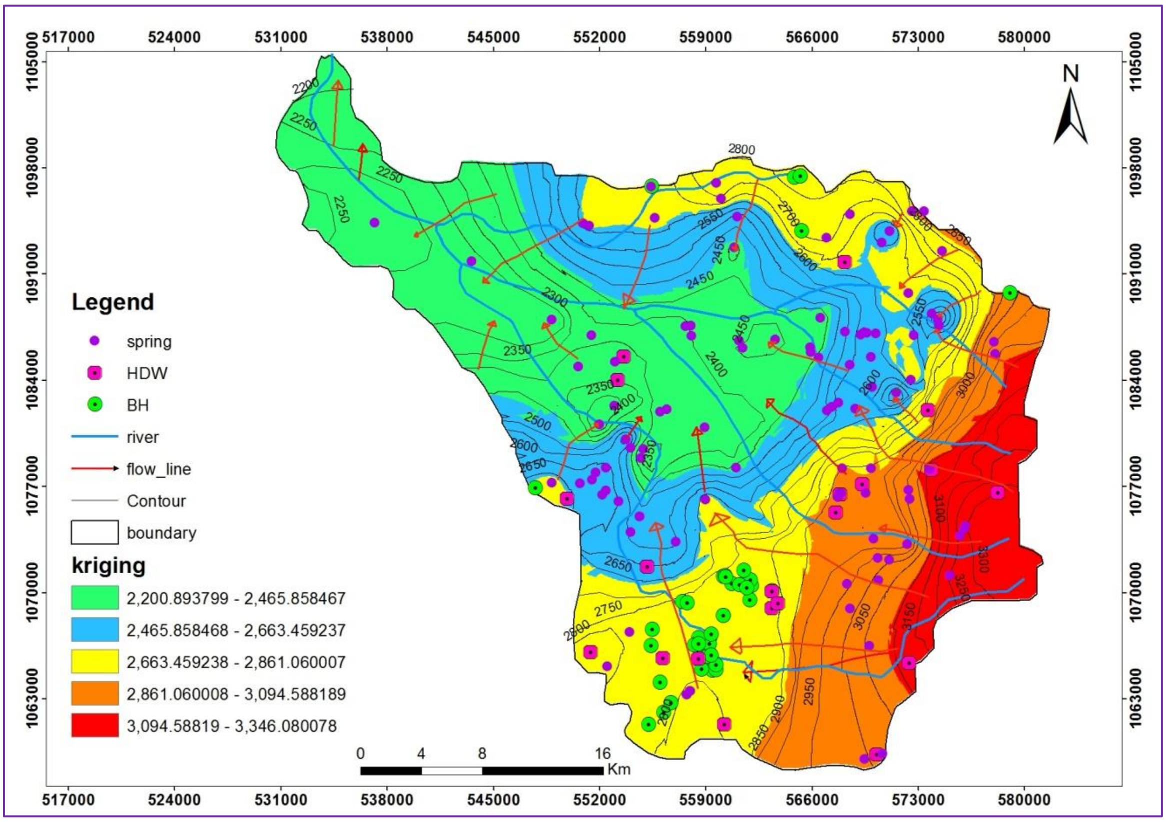


Figure 5.3 Groundwater level contour map showing the groundwater flow direction

- **Recharge and Discharge Areas**

A recharge area is that portion of the drainage basin in which the net saturated flow of groundwater is directed away from the surface and the water table is usually lies at some depth whereas discharge area can be defined as the movement of the net saturated flow of groundwater is directed towards the surface and the water table usually lies at or very close to the surface (Freeze and Cherry, 1979). .

The main recharge area of the eastern upper Jemma river catchment is the upper catchment of the study area that is topographically higher regions, undulated, rugged valleys and ridges on the way to Akober town, around Tarmaber town, and wofwasha forest. The lower elevated land of the study area gets recharged not only from precipitation, but also groundwater flow from the upstream side of the catchments (i.e. recharge from base flow is during the rainless season). Generally, recharge areas in the study area are found in the eastern and southeastern parts of the study area.

As it can be inferred from the groundwater contour maps, Discharge areas are low lands of the study area that is around Debre Birhan town (Dalecha well and Beressa well fields), around Seladingay, and Sasssit town.

CHAPTER SIX

6.0 Conclusion and Recommendation

6.1 Conclusion

- The study area is the eastern upper Jemma river catchment in the Northwestern Ethiopian plateau which covers an area of 1255 square kilometer and geographically bounded between 9°30’0” N to 10°6’0” N latitude and 39°25’0” E to 39°45’0” E longitude. There is a considerable elevation difference in the catchment; that is between 1554m -3679 meters above sea level. The general objective of the research was to characterize the groundwater dynamics and the major aquifer system

- The areal depth of precipitation was analyzed and calculated by arithmetic mean method, Isohyetal method, and Theissen polygon method. Thus, the average annual rainfall is calculated to be 1162.167 mm, 1142.72, and 1254.98 mm respectively. Accordingly; for the analysis of this work, the mean annual rainfall of the eastern upper Jemma River catchment was found to be the average values of the isohyetal method and Theissen polygon methods and it was averaged to be 1198.85 mm/year. The simple arithmetic mean is ignored due to the topography of the area and the non-uniform distribution of rain gauge stations. From the available meteorological data, the potential evapotranspiration (PET) and actual evapotranspiration (AET) was calculated. The PET was calculated by using Penman combined method and it was calculated to be 1376.64 mm/year. The AET of the area was calculated by Thorentwait and matter method. Hence; the AET was calculated to be 799.76 mm/year.

- The groundwater recharge of the eastern upper Jemma river catchment was evaluated by; water balance method (WBM), Base flow separation (BFS) method, and Chloride mass balance (CMB) methods. The annual recharge of the catchment from the water balance method was calculated to be 100.47 mm/year. This indicates only 8.38 % of the annual precipitation is percolated to the groundwater reservoir. This result shows that, only small portion of the precipitation is percolated to the groundwater system. The base flow separation of the Beressa River from the long term daily flows was carried out by using software called river analysis package (rap). The outputs of the software were the base flow index (0.415) and flood flow index (0.585). Therefore, the annual base flow of the

Beressa River is 211.84 mm/year and the annual surface runoff is 298.62 mm/year. The third method applied for the evaluation of recharge was the chloride mass balance (CMB) approach. Recharge was calculated from the chloride concentrations of the samples collected from rainfall and groundwater. The chloride concentrations of rainfall and groundwater were analyzed in Ethiopian construction design and supervision Works Corporation (ECDSWC) research, laboratory, and training center. The test method used was Mohr Argentometric method. The results obtained are 6.31 mg/l for chloride in rainfall, 13.53 mg/l chloride concentration in groundwater. Accordingly; the groundwater recharge of eastern upper Jemma river catchment by CMB method is 559.1 mm/year. Eventhough the groundwater was calculated by the three methods, the water balance method looks to be the best estimate as it is calculated by using all meteorological parameters. The variation of recharge amount from the three methods is due to the limitations of the individual methods and possible error during analysis.

- Geologically, the area is dominantly covered by Tertiary volcanic rocks. The major lithological units exposed in the study area from top to bottom includes; superficial deposits, upper basalt (Tarmaber_Megezez basalt), fractured and weathered Ignimbrite, trachyte, lower basalt (Kesem basalt), and Sandstone unit. The lithological units are affected by weathering, fracturing, and faulting. The lineaments were extracted from the landsat_8 image by using geomatics software and enhanced for the principal component analysis (PCA) by the Exelis Envi software before extraction. The lineaments, faults that were formed in the area have dominantly NE- SW and minor E-W orientation (see Figure.3.0, 3.1, and 3.2).

- The major aquifer types are identified by analyzing the available pumping test data, geological setting, and degree of fracturing, weathering and from the existence of springs (spring discharge). Thus, the aquifer types are classified as: Fissured aquifer developed on basalts on the plateau, mixed aquifer developed in fissured Ignimbrite, Rhyolite, Trachyte, Basalt and sediments intercalating volcanic rocks on plateau, Fissured aquifer developed on basalts outcropping in deep valleys, Porous and fissured Sandstone aquifer in deep valleys, and Localized aquifer with intergranular porosity and permeability (Alluvial sediments, pyroclastic martial and intercalated sediment). The main water-bearing aquifers are the high permeability and very high productivity mixed aquifer and high permeability and high productivity localized aquifer with intergranular porosity.

From pumping test results analyzed by aquifer test software, the mixed aquifer has transmissivity value between 10-100 m^2/day (with mean transmissivity is 85.9 m^2 /day), hydraulic conductivity is between $5E^{-2}$m/d to 5.26 m/d with few exceptions. Localized intergranular aquifers has also transmissivity between 10-100m^2/d, 0.32544 m/d - 7.272m/d and discharge of 4- 10 l/s respectively.

- During fieldwork, 28 points of in situ water quality measurements like PH, T, EC, and TDS(calculated result i.e. TDS = 0.65*EC) were carried out at different locations of the rivers, springs and hand dug wells. The PH value ranges from 7.72 at Tsadkanie spring to 10.03 at Dalecha River. From these, 18 points are within the WHO limits of good water quality. Therefore, most of the natural water is in a normal condition except Dalecha River which has a PH of 8.3, 9.72 and 10.03 measured at different locations of the river. The highest EC value was also measured in Dalecha River (867µs/cm), Beressa River (803µs/cm) and the lowest value is in Satrira River (660 µs/cm) and all the others fall within this range. The TDS value was calculated by multiplying a conductivity value by an empirical factor (0.65) and it was between 425.75 mg/l to 563.55 mg/l. All the TDS values in the study area are within the limits of WHO guidelines of good water.

- Groundwater flow dynamics in the eastern upper Jemma river catchment was characterized by using groundwater level measurements of 40 boreholes, 26 hand-dug wells, and data from 111 springs. The borehole data, hand dug wells of 20 points, springs data of 106 points were collected from North Shoa water resources development bureau and the rest was collected during field work by the researcher. From the groundwater level data, groundwater contour map was produced and the flow lines were also indicated. Static water level data provided crucial information about groundwater dynamics in the study area. The groundwater table contour map showed that groundwater dynamics of flow converges towards discharge areas. In areas where the groundwater table is nearer to the surface (small gradient), the groundwater contour lines (equipotential lines) were widely spaced. Whereas; in areas of the higher gradient (deep water table), the groundwater contour lines were narrow spaced as it is shown in the map (Figure 5.2 and 5.3). Generally, the groundwater flow system is controlled by surface morphology, structures (NE-SW, E-W) and flows from the southeastern, southern and southwestern corner towards north and northwestern corner of the eastern upper Jemma River catchment. The structures enhance the groundwater flow or act as conduits for flow.

6.2 Recommendation

Based on the available data, field observations and the results of this work, the following recommendations are given;

- In order to understand well and characterize the aquifer behavior and groundwater flow dynamics, full pumping test data with fair distribution in the catchment and analyzing stable isotopes of water are recommended.

- To apply chloride mass balance methods for recharge estimation, Collecting rainfall samples at the end of the rainy season with different times (variable time of sampling) is recommended

- Proper municipal and industrial waste management should be practiced and implemented in order to protect groundwater and surface water from further pollution.

- In order to increase infiltration rate or maximize groundwater potential, Land and water conservation activities should be practiced in highly degraded land of the catchment.

- Proper water management activities should be implemented and the boreholes should be monitored regularly.

References

Abel Abebe. (2017). Evaluation of Recharge and Shallow Groundwater Dynamics in the Upper Awash Basin, Central Ethiopia. Unpublished MSc thesis, Addis Ababa University, Addis Ababa, Ethiopia.

Ahimed Wolela. (2008). Sedimentation of the Triassic-Jurassic Sandstone Formation, Blue Nile Basin, Ethiopia. Journal of African Earth Sciences, **52**: 30-42.

Andarge Yitbarek. (2009). Hydrogeological and hydrochemical framework of complex volcanic system in the Upper Awash River basin, Central Ethiopia: with special emphasis on inter-basins groundwater transfer between the Blue Nile and Awash rivers. Unpublished Ph.D. thesis, University of Poitiers, France.

Angel M. (2006). "El Nino" The Oxford Companion to Ships and the Sea. Oxford University Press.

Aster Denechew and Seleshi Bekele (2009). Characteristic and Atlas of the Blue Nile basin and its subbasin. International Water Management Institute.

Bonan, G. (2002). Ecological Climatology Cambridge university press, U.K.

Brutsaert, W. (1982). Evaporation into the Atmosphere: Theory, History, and Applications. Springer, Dordrecht, 299.

Cook, P.G. (2003). A guide to regional groundwater flow in fractured rock aquifers. CSIRO, Australia, pp 115.

Daniel Gamachu. (1977). Aspects of Climate and Water Budget in Ethiopia. Addis Ababa University Press.

Daniel Meshesha, Dejene Hailemariam, and Abrham Mamo(2010). Geology of Debre Birhan Area, Geological Survey of Ethiopia Basic Geoscience Mapping Core Process, Addis Ababa, Ethiopia.

Development Studies Associates (DSA) and Shawel Consult International (SCI) (2005). Potential Survey, Identification of Opportunities and Preparations of Projects Profiles and Feasibility Studies, Part One: Potential Assessment Survey, Soil Survey, Draft Report. Amhara national regional state investment office.

Dula Shanko, Camberlin, P. (1998). The effects of the southwest Indian Ocean Tropical Cyclones on Ethiopian drought. Int. J. Climatol. **18**:1373–1388.

Ethiopian Mapping Agency. (1981). National Atlas of Ethiopia. Preliminary edition, Addis Ababa, Ethiopia.

Fetter, C.W. (1994). Applied hydrogeology. Third edition, Prentice-Hall, New Jersy, 695PP.

Freeze, R. A., and Cherry, J. A. (1979). Groundwater. Prentice-Hall, New Jersy, 616pp.

Frôhlich, K., & Frôhlich, W., and Wittenberg, H. (1994). Determination of groundwater recharge by baseflow separation: a regional analysis in northeast China. FRIEND: Flow Regimes from International Experimental and Network Data **In:** *Proceedings of the Braunschweig Conference*. IAHS Publ. no. 221.

Gani, N. DS., Abdelsalam, M. G., Gera, S. and Gani, M. R. (2008). Stratigraphic and structural evolution of the Blue Nile Basin, Northwestern Ethiopian Plateau. Geological Journal, **44**(1): 30-56.

Hem D. J. (1992). Study and interpretation of chemical characteristics of natural water. Third edition, United States Geological Survey water supply paper 2254, United States government printing office, Washington, 264pp.

https://www.fondriest.com/environmental-measurements/parameters/water-quality/conductivity-salinity-tds/ accessed on March 11, 2019

http://s3.amazonaws.com/chicagoriver/rich/rich_files/rich_files/503/original/tds.pdf accessed on March 26, 2019.

Kazmin, V. (1979). Stratigraphy and Correlation of Cenozoic Volcanic Rocks in Ethiopia. Reports of Ethiopian Institute of Geological Survey, **106:** 1-26.

Kazmin, V., Berhe, S.M. and Walsh, J. (1980). Report on the Geological Map of Ethiopian Rift Valley. Ethiopian Institute of Geological Survey, Addis Ababa, Ethiopia.

Kieffer, B., Arndt, N., Lapierre, H., Bastien, F., Bosch, D., Pecher, A., Gezahegn, Y., Dereje, A., Weis, D., Jeram, D.A., Keller, F. and Meugniot, C. (2004). Flood and shield basalt from Ethiopia: Magmas from the African super swell. Journal of Petrology, **45**: 793-834.

Kovalevsky, S.V., Kruseman, P.G. and Rushton, K.R. (2004). An international guide for hydrogeological investigations. UNESCO, IHP-VI, series on groundwater NO.3.

Marei, A., Khayat, S., Weise, S., Ghannam, S., Sbaih, M. & Geyer, S. (2010). Estimating groundwater recharge using the chloride mass-balance method in the West Bank, Palestine. Hydrol. Sci. J. 55(5), 780–791.

Mekdes Nigatie. (2012). Characterization of Aquifers and Hydrochemistry in Volcanic Terrain of Central Ethiopia. Unpublished M.Sc. thesis, Addis Ababa University, Addis Ababa, Ethiopia.

Mengesha Tefera, Tadiwos Chernet and Workineh Haro. (1996). Explanation of the Geological Map of Ethiopia, 2nd edition. Ethiopian Institute of Geological Survey, Addis Ababa, Ethiopia.

Ministry of Agriculture, Fisheries & Food (MAFF). (1967). Potential Transpiration. Tech. Bull. 16., HMSO.

Moore, D.R., Richards, G., and Story, A. (2008). Electrical Conductivity as an Indicator of Water Chemistry and Hydrologic Process. Streamline Watershed Management Bulletin, **11**: (2).

Nigussie Kebede. (2005).Water resources potential evaluation of Beressa river catchment, in North Showa, Amhara region. Unpublished MSc thesis,Addis Ababa University Addis Ababa, Ethiopia.

Raghunath, H.M. (1987).Groundwater. Second edition, New age international publisher, 563pp.

Raghunath, HM. (2006). Hydrology, principles, analysis, design. Revised Second edition, New age international publisher, New Delhi.

Rushton, R.K. (2003) Groundwater Hydrology: Conceptual and Computational Models. John Wiley & Sons Ltd, Birmingham, UK.

Seifu, K., Yves, T., Tamiru, A. and Tenalem, A. (2005). Groundwater recharge, circulation and geochemical evolution in the source region of the Blue Nile River, Ethiopia. Applied Geochemistry, **20**: 1658–1676.

Seifu Kebede. (2013). Groundwater in Ethiopia. Springer Hydrogeology.

Scanlon, B.R., Healy, R.W. and Cook, P.G. (2002). Choosing appropriate techniques for quantifying groundwater recharge. Hydrogeology. J., **10**(1): 18-39.

Shaw, E.M. (1988). Hydrology in practice. Second edition, Chapman and Hall, New York, 539pp.

Shaw, E.M. (2005. Hydrology in practice. Third edition, Chapman and Hall, New York, 539pp.

Singal, B..S. and Gupta, R.P. (1999). Applied Hydrogeology of Fractured Rocks. Springer, London, pp 429.

Tamiru Alemayehu, (2006). Groundwater Occurrence in Ethiopia, Addis Ababa University, Ethiopia.

Tadesse Shewakena. (2013). Numerical groundwater flow modeling of Beresa and Gado rivers catchment, Debre-Berhan area, North Shoa zone, Amhara regional state. Unpublished MSc thesis, Addis Ababa University, Addis Ababa, Ethiopia.

Tenalem, A., Molla, D. and Wohnlich, S. (2008). Hydrogeological framework and occurrence of groundwater in the Ethiopian aquifers. Elsevier publisher, Journal of African Earth sciences, **52**: 97–113.

Tesfaye Tessema. (2015). Ground Water Potential Evaluation Based on Integrated GIS and Remote Sensing Techniques, in Bilate River Catchment: South Rift Valley of Ethiopia. American Scientific Research Journal for Engineering, Technology, and Sciences (ASRJETS), **10**(1): 85-120.

Thiessen, A.H. (1911) Precipitation for large areas. *Mon. Weath. Rev.*, **39:** 1082–1084.

Thornthwaite, C. W. (1944). Report of the committee on transpiration and evaporation. Transactions, American Geophysical Union **25**:687.

Thornthwait, W.C. and Matter method, R.J. (1957). Instructions and tables for computing potential evapotranspiration and the water balance. Drexel Institute of Technology, Centerton, New Jersey, **3** (x).

Tilahun Azegegn. (2008). Hydrogeochemical characterization of aquifer systems in Upper Awash River Basin and adjacent Abay plateau using geochemical modeling and isotope hydrology. Unpublished MSc thesis, Addis Ababa University, Addis Ababa, Ethiopia.

Tilahun Azagegn., Asfawossen Asrat., Tenalem Ayenew and Seifu Kebede. (2015). Litho-structural control on interbasin groundwater transfer in central Ethiopia. Elsevier publisher, Journal of African Earth Sciences, **101**: 383–395.

Tilahun Azagegn,.(2014). Groundwater Dynamics in the Left Bank Catchments of the Middle Blue Nile and the Upper Awash River Basins, Central Ethiopia. Unpublished Ph.D. Thesis, Addis Ababa University, Addis Ababa, Ethiopia.

Todd, D.K. (1976). Groundwater Hydrology (2nd edition), John Willey and Sons, New York, pp 535.

Tsegaye Tadesse.(1994). The influence of the Arabian Sea storms: depressions over the Ethiopian weather. ***In:*** *Proceedings of the International Conference on Monsoon Vanability and Prediction*, ICTP, Trieste, 9–13, WMO: TD **619**: 228–236.

UNFAO (Food and Agriculture Organization of the United Nations) (1998). World Reference bases for soil resources, a frame work for international classification, report No. 84. Rome.

Valadon, Y. (1992). Variability of tropical cyclones over Southwestern Indian Ocean. J. Afr. Meteorol. Soc., 1: 45–51.

Wakgari Furi. (2010). Hydrogeology of complex volcanic systems in the continental rifted zone. Integrated geochemical, geophysical and hydrodynamic approach. Middle Awash basin, Main Ethiopian Rift, Ethiopia. Unpublished Ph.D. thesis, university of Poitiers, France.

WHO (World Health Organization). (2017). Guidelines for Drinking-water Quality. Fourth edition incorporating the first addendum, Geneva.

Xu, Y, and Beekman, HE (Eds). (2003). Groundwater Recharge Estimation in Southern Africa UNESCO IHP Series No. 64, UNESCO, Paris.

Zanettin, B., Gregnanin, A., Justin Visentin, E., Morbidelli, M. and Piccirillo, E.M. (1974). Geological and petrological researches on the volcanics of central Ethiopia. Padova, Italy.

Appendices

Appendix 1. Borehole Data within the Study Area

No	Source	Well ID	UTM (E)	UTM (N)	Elevation (m)	SWL (m)	Depth (m)	T(m^2/d)	K(m/d)	Q (l/s)
1	Borehole	DBH1	558876	1066132	2766	15	165	22.6	0.51	10.5
2	Borehole	DBH2	559437	1064890	2770	6.9	183	10.8	0.216	7.85
3	Borehole	DBH3	559692	1064931	2770	4.55	140	12.3	0.245	11.24
4	Borehole	DBH4	559668	1065235	2777	21.6	141	6.16	0.123	6
5	Borehole	DBH5	558737	1064959	2782	7.9	142	15.1	0.339	11.5
6	Borehole	DBH6	559070	1065768	2766	5.3	171	51.9	1.17	12
7	Borehole	DA-BH1	562012	1070477	2788	12.79	108	10.8	0.3024	5
8	Borehole	DA-BH2	561930	1070821	2791	11.68	95	98.064	2.5776	6
9	Borehole	DA-BH4	561898	1069503	2792	9.2	125	0.05	0.00104112	4
10	Borehole	DA-BH5	563354	1070121	2800	7.4	150	0.2	0.00335	3.5
11	Borehole	DA-BH6	560712	1070580	2778	7.92	108	165.6	3.3984	6
12	Borehole	DA-BH7	561506	1071443	2787	11.45	76	244.6	7.272	8
13	Borehole	BE-BH2	559277	1067055	2766	6.25	100			8
14	Borehole	BE-BH4	559247	1066639	2756	6.25	93	266.4	5.302	8
15	Borehole	BE-BH5	559341	1065874	2758	2.85	102	76.9	1.805	10
16	Borehole	DA-BH-EX1	561229	1070522	2784	6.66				
17	Borehole	DA-BH-EX2	561685	1070295	2783	11.45				
18	Borehole	ARARI	555236	1061291	2798	8.4	98.42	68.43	1.9008	7
19	Borehole	DBU-BH1	558511	1067004	2755	8.26	211	8.02	0.0954	20
20	Borehole	DBU-BH2	558230	1066536	2752	8.59	222			25
21	Borehole	DBU-BH3	558519	1066616	2754	8.46	203	243	2.70	30
22	Borehole	AQUA-BH1	560167	1071080	2789	11.72				

23	Borehole	MEM-BH1	555460	1067589	2785	8.6				
24	Borehole	AQUA-BH2	560250	1071097	2784	11.8				
25	Borehole	AQUA-BH3	560301	1071022	2782	71.29				
26	Borehole	TTI	557442	1069410	2762	33.5				
27	Borehole	Divinpros	557750	1069300	2817	29.6				
28	Borehole	MAC	555400	1066500	2844	11.9				
29	Borehole	HA-BH1	556210	1062084	2791	2.31	150	466	5.26	7
30	Borehole	HA-BH2	556691	1062725	2793	4	166	4.95	0.0589	4
31	Borehole	DT-BH1	560133	1068487	2769	9.75				
32	Borehole	HA-BH3	555997	1064081	2797	115.85				
33	Borehole	Lotran Dam	560133	1068487	2769	9.75	259			15
34	Borehole	Seladingay/STBH_1	564836	1097392	2865	27.3	100			14
35	Borehole	Seladingay/STBH_2	565227	1097476	2868	28.45	119			5
36	Borehole	Sassit	555435	1096776	2718	120.58	180	52.9	0.881	5.5
37	Borehole	Tarmaber	579054	1089754	3009	78.22	143			26.6
38	Borehole	Aysofe	565324	1093842	2851	32.35	151	37.44	0.63648	7.2
39	Borehole	Goshebado	547775	1076918	2772	91.86	175	11	0.3056	3.25
40	Borehole	Bbh4	559369	1067258	2780	5.3	106.49	80.78	2.21	5.3

Appendix 2. Hand dug wells

1. Primary Hand Dug Well Data Collected During Fieldwork

No	Locality	X	Y	Z	Q (l/sec)	Geology	Pump type
1	Beryo	563571	1072746	2846	0.25	Ignimbrite	Hand pump
2	Kimbo Ager	567014	1071542	2876	0.2	Ignimbrite	Hand pump
3	Setegn Georgis	578704	1085559	3167	0.1	Basalt	Motorized
4	Filagenet	561243	1097898	2822	0.25	Ignimbrite	Hand pump
5	Tsadkanie	568195	1098079	2864	0.2	Ignimbrite	Hand pump
6	Tinishu Bura	572194	1076435	2923	0.25	Basalt	Motorized

2. Secondary Hand Dug Well Data from North Shoa Water Resources Development Bureau

No	HDW sp. Locality	X	Y	Z	Q(l/s)
1	Belet Enba	573886	1078124	3155	0.01
2	Wenz	570290	1059364	3006	0.2
3	Webi	560211	1061321	2830	0.067
4	Gedamoch	567840	1076495	2884	0.05
5	Joromeda	553206	1084031	2659	0.068
6	Gedemasa	567570	1075310	8875	0.2
7	Anbo wenz	553609	1085578	2574	0.13
8	Denbibie	549886	1076243	2652	0.2
9	Tiqurit	578240	1076629	3338	0.02
10	Tachlegida	569303	1077175	2808	0.02
11	Tosign amba	573661	1082061	2981	0.04
12	Tach Dengora	572421	1065383	3096	0.012
13	Tulmba	563353	1070123	2800	0.03
14	Beresa minch	558512	1065682	2775	0.01
15	Golbo	556178	1065696	2794	0.2
16	Boralie	563361	1068994	2798	0.002
17	Boralie	563779	1069312	2803	0.02
18	Weynye afaf	555159	1071752	2783	0.01
19	Mutu Kerisa	551407	1066118	2783	0.008
20	Gulo Mesik	568183	1091810	2296	0.15

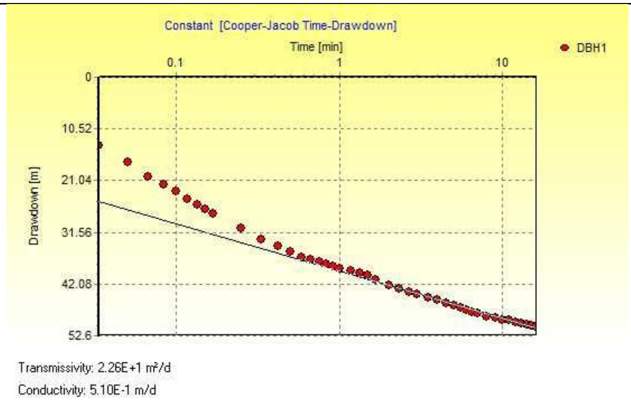
Appendix 3 Springs found in the Eastern Upper Jemma River Catchment from North Shoa water Resources Development Bureau.

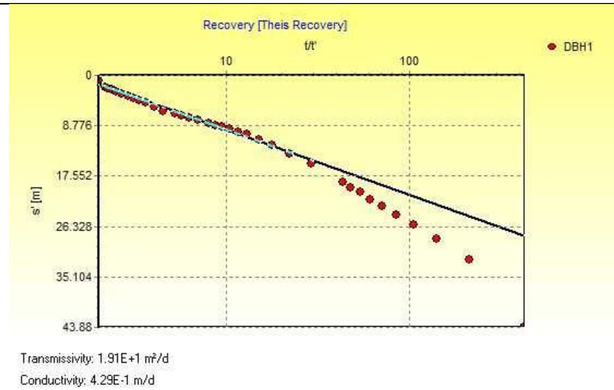
No	Sp. locality	X	Y	Z	Q (l/s)
1	Bosena	572378	1076770	2932	366
2	Lowol	548877	1088035	2220	67
3	Kerye	568515	1068970	2988	185
4	Geta Marefia	569792	1066512	3080	52
5	Kosh Wenz	556448	1082096	2457	65
6	Meka Wenz	556018	1081946	2354	84
7	Shol	558962	1080912	2322	62
8	Tinchel Meda	572443	1076179	3056	0.001
9	Alega	573780	1078187	3260	0.02
10	Gundagundit School	570660	1059405	3018	0.07
11	Ashal	569496	1059048	2996	0.06
12	Tach Anba	575110	1071131	3308	0.06
13	Gedensa	567723	1076316	2883	0.08
14	Kolo	569569	1076577	2875	0.05
15	Nefatig	551762	1077950	2681	0.03
16	Kitir	574307	1088030	1794	0.03
17	Godguadit	574393	1087605	2728	0.05
18	Dodot	573917	1088429	2703	0.45
19	Setegn Georgis	578105	1085755	3134	0.15
20	Zenbaba	537196	1094420	2187	0.066
21	Sisit	570011	1083559	2755	0.076
22	Gunagunit	569910	1085567	2660	0.08
23	Aydagn	568227	1087229	2545	0.06
24	Beles Minch	558092	1086950	2368	0.02
25	Mehanba Kebelie	567346	1082268	2759	0.03
26	Cherie Minch	567774	1082548	2730	0.015
27	Mislenie	548874	1077248	2763	0.075
28	Sengaberet	570064	1073585	2874	0.08
29	Aloberet	552518	1065149	2822	0.071
30	Aroyogof	557066	1073384	2461	0.05
31	Shola	552432	1078270	2665	0.65
32	Debiramba	552441	1076736	2652	0.064
33	Ayuminch	568344	1070574	2924	0.05
34	Karatedie	570344	1072290	2986	0.04
35	Hadad aniba	553027	1085218	2509	0.03

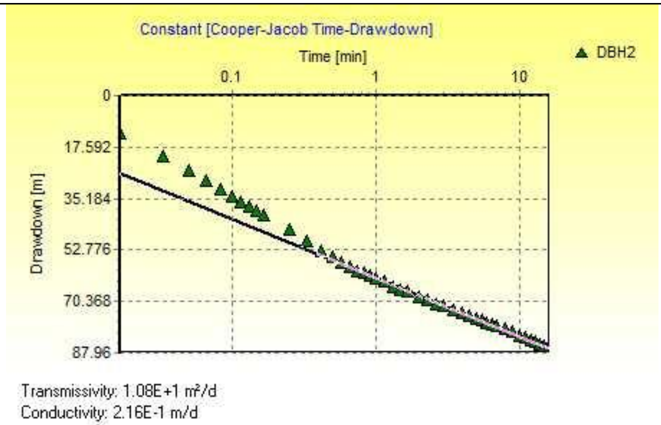
36	Jara	552019	1081125	2102	0.02
37	Lowol	563595	1086700	2486	0.025
38	kes Amba	561208	1086629	2371	0.018
39	Ahad Mesk	561463	1086167	2513	0.06
40	Debir Amba	572722	1086968	2742	0.038
41	Adabay	572527	1084049	2884	0.16
42	Anfar Anba	567865	1076598	2882	0.03
43	Kelem Amba	551523	1077458	2627	0.072
44	Bisabit	554687	1075022	2513	0.056
45	Bisabit	554687	1075022	2513	0.056
46	Mesino Midir	567010	1082011	2235	0.025
47	Mesino Midir	568874	1082142	2645	0.012
48	Aydebis	571568	1083203	2157	0.11
49	Berie Afaf	570397	1070818	3032	0.05
50	Koracha	571091	1072162	3035	0.03
51	Zinb Amba	551488	1086976	2355	0.02
52	Nenfaso	553008	1082324	2224	0.03
53	Gur Amba	550612	1084927	2553	0.05
54	Timhrt bet	552218	1076467	2642	0.006
55	Weyira	554068	1079556	2344	0.012
56	Zelam washa	553281	1076035	2642	0.2
57	Bekayu	554916	1079495	2222	0.1
58	Lulmida	565949	1085868	2362	0.2
59	Tachilo Limida	565922	1086173	2337	0.1
60	Kurt Abit	568528	1085045	2561	0.12
61	Sededo Meda	569637	1087154	2684	0.05
62	Memargeja	569494	1087181	2642	0.1
63	Amignie Midir	570223	1087104	2550	0.01
64	Gunagunit	566475	1085514	2517	0.08
65	Baydegimo	557701	1087595	2053	0.015
66	Wenbero	566327	1806614	2340	0.02
67	Ahaya	566582	1088132	2380	0.012
68	Filageda	569247	1087028	2677	0.028
69	Zenbabit	554765	1078881	2225	0.04
70	gundagundit	553739	1080109	3103	0.06
71	Weyin Wuha	554067	1073986	2510	0.012
72	Tach Legida	569934	1078199	2805	0.015
73	Tachmilki	557990	1063509	2826	0.062
74	Aylefi	576061	1074250	3309	0.127

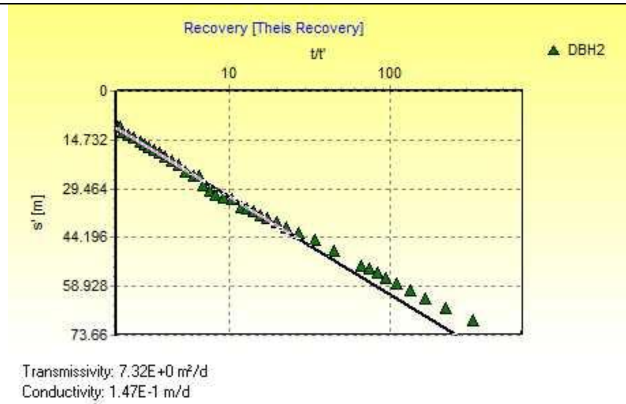
75	Tid Ager	575802	1073768	3261	0.2
76	Dodot	572302	1073201	2807	0.02
77	Abuacho	576166	1074384	3343	0.015
78	Genet	567948	1076596	2878	0.075
79	Guagn Dega	572386	1089743	2760	0.08
80	Mekelakeya	574607	1092533	2855	0.08
81	Jib gur	557782	1063288	2820	0.02
82	Kelem amba	550725	1077227	2554	0.07
83	Neto	561034	1078233	2362	0.012
84	Ansas	578001	1086549	3067	0.08
85	Bura	568020	1078198	2958	0.004
86	Gilie mesik	555672	1094744	2743	0.47
87	Shola	566973	1093434	2812	0.89
88	Aratyo	572618	1095152	2934	0.53
89	Aratyo	572618	1095152	2934	0.53
90	Anday gur	573402	1095168	2947	0.09
91	Koshim tegen	570645	1093082	2690	0.89
92	Ebaybad school	558057	1087639	2790	0.49
93	Motolomi	555435	1096776	2718	8
94	Dinishiq school	558993	1076138	2834	1.02
95	Ahya gala bado	559708	1097011	2827	0.079
96	Qetemq mesik	561100	1094785	2381	0.089
97	Waginbo	560900	1092783	2380	0.08
98	Shola	571148	1093864	2378	0.12
99	Mat	551340	1094202	2701	0.677
100	Abay Wonz	543594	1091858	2270	0.095
101	Aguat Wuha	550954	1094383	2698	0.079
102	Mesino	568527	1094982	2726	0.645
103	Cheko	560022	1096013	2843	0.077
104	Jib Gur	557782	1063288	2820	0.02
105	Abay Dega	557982	1063521	2891	0.01
106	Adadi	553981	1067425	2792	0.08

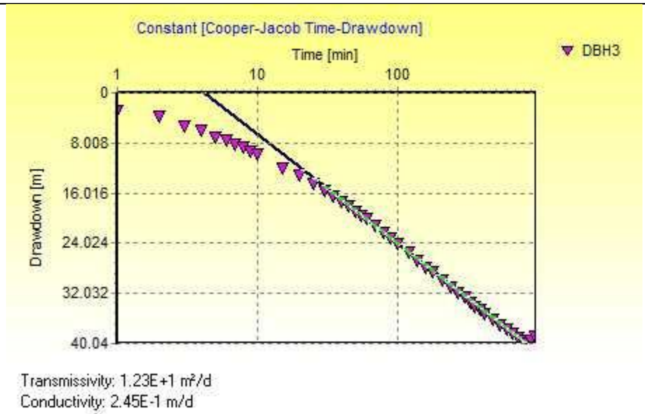
Appendices 4. Graphs of Pumping Test Results Analyzed by Aquifer Test Software

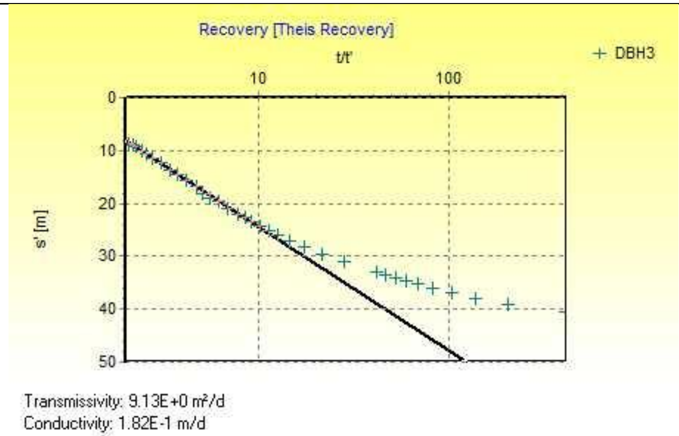


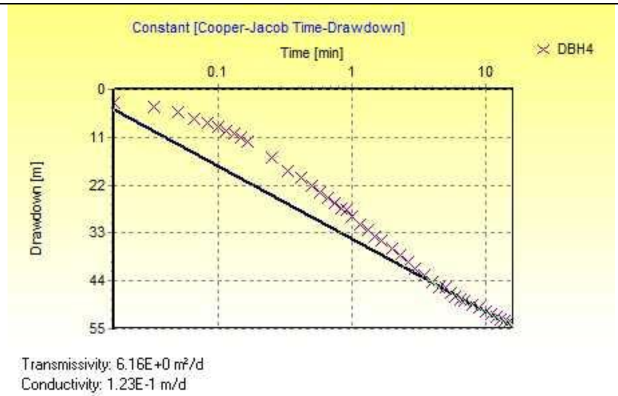


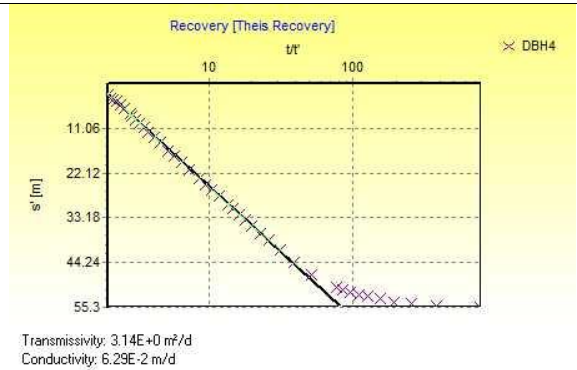


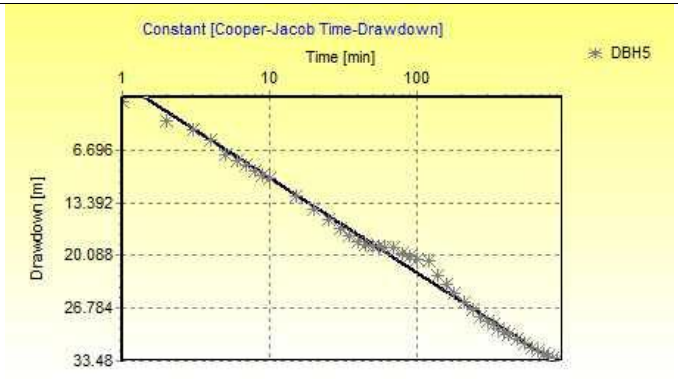



Constant [Cooper-Jacob Time-Drawdown]
Time [min]
DBH3
Drawdown [m]
Transmissivity: 1.23E+1 m²/d
Conductivity: 2.45E-1 m/d

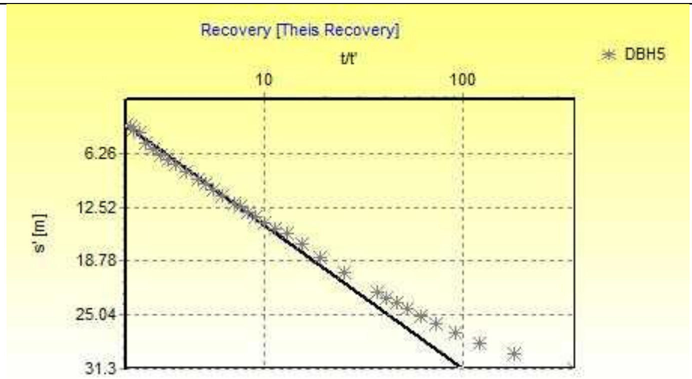

Recovery [Theis Recovery]
t/t'
DBH3
s' [m]
Transmissivity: 9.13E+0 m²/d
Conductivity: 1.82E-1 m/d


Constant [Cooper-Jacob Time-Drawdown]
Time [min]
DBH4
Drawdown [m]
Transmissivity: 6.16E+0 m²/d
Conductivity: 1.23E-1 m/d

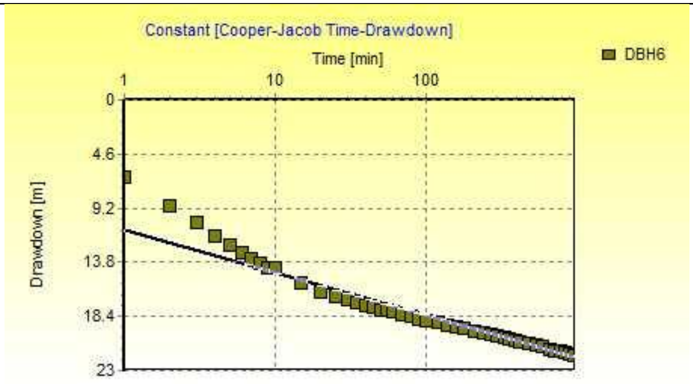

Recovery [Theis Recovery]
t/t'
DBH4
s' [m]
Transmissivity: 3.14E+0 m²/d
Conductivity: 6.29E-2 m/d



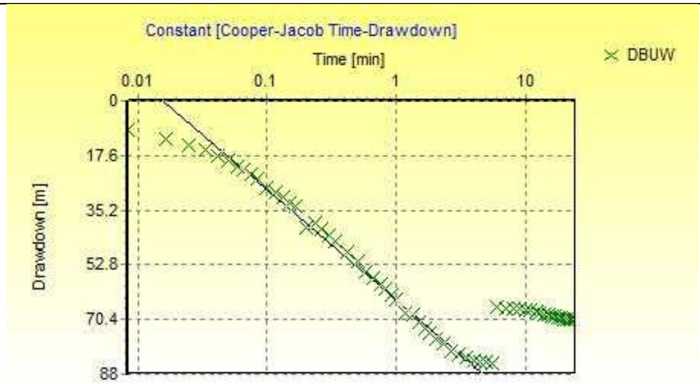
Transmissivity: 1.51E+1 m²/d
Conductivity: 3.39E-1 m/d



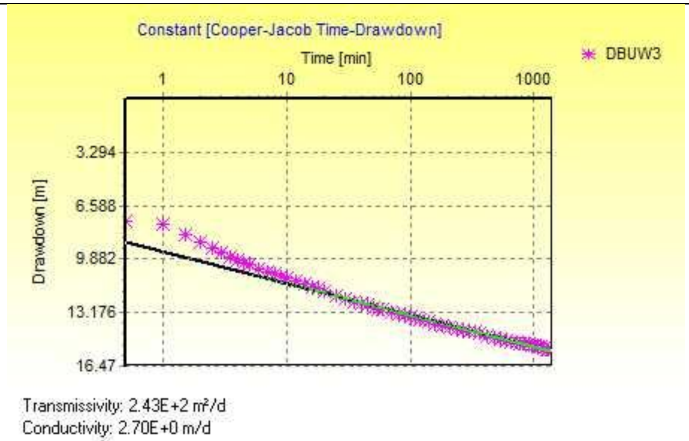
Transmissivity: 1.09E+1 m²/d
Conductivity: 2.45E-1 m/d

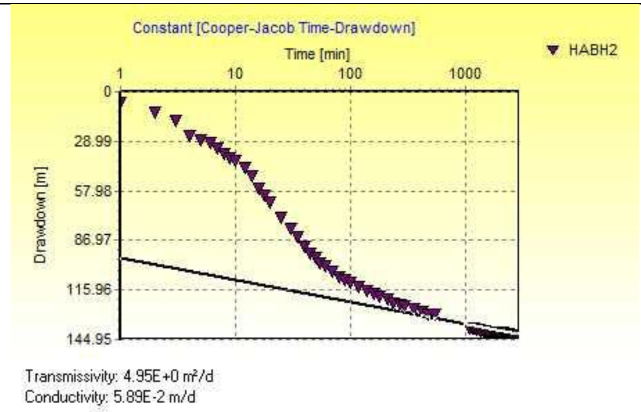


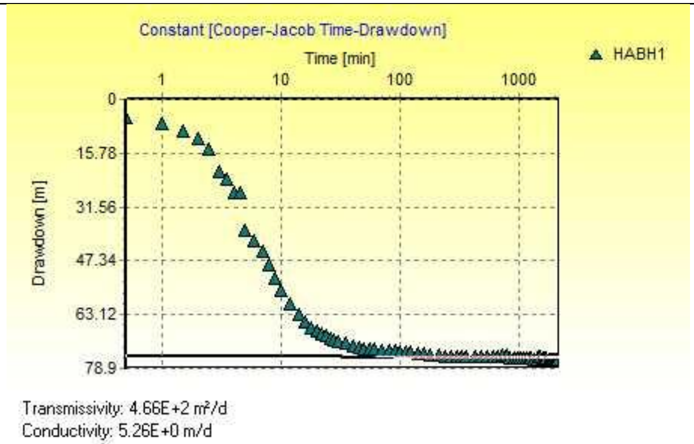
Transmissivity: 5.19E+1 m²/d
Conductivity: 1.17E+0 m/d

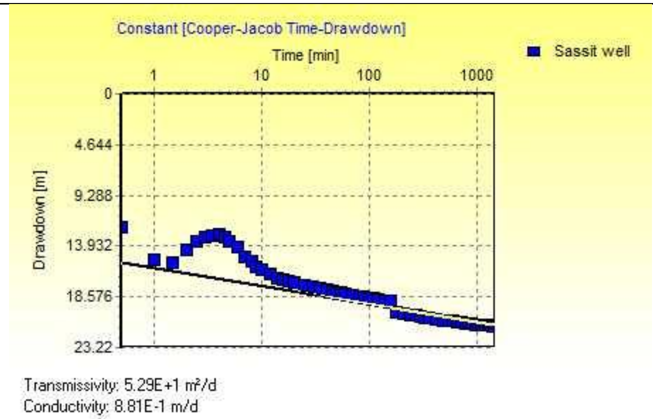


Transmissivity: 8.02E+0 m²/d
Conductivity: 9.54E-2 m/d


Constant [Cooper-Jacob Time-Drawdown]
Time [min]
DBUW3
1
10
100
1000
Drawdown [m]
3.294
6.588
9.882
13.176
16.47
Transmissivity: 2.43E+2 m²/d
Conductivity: 2.70E+0 m/d


Constant [Cooper-Jacob Time-Drawdown]
Time [min]
HABH2
1
10
100
1000
Drawdown [m]
0
28.99
57.98
86.97
115.96
144.95
Transmissivity: 4.95E+0 m²/d
Conductivity: 5.89E-2 m/d


Constant [Cooper-Jacob Time-Drawdown]
Time [min]
HABH1
1
10
100
1000
Drawdown [m]
0
15.78
31.56
47.34
63.12
78.9
Transmissivity: 4.66E+2 m²/d
Conductivity: 5.26E+0 m/d


Constant [Cooper-Jacob Time-Drawdown]
Time [min]
Sassit well
1
10
100
1000
Drawdown [m]
0
4.644
9.288
13.932
18.576
23.22
Transmissivity: 5.29E+1 m²/d
Conductivity: 8.81E-1 m/d

Appendices 5. In situ physicochemical measurements of the rivers, springs and hand dug wells in the study area

No	Source	Name	X	Y	Z	Formation	PH	T°c	EC (µs/cm)	TDS (mg/l)	Type	Obs.date
1	River	Beressa	556958	1068151	2731	Basalt	8.2	14.2	743	482.95	Perennial	23/2/2019
2	River	Beressa	557226	1067912	2739	Basalt	7.5	16.5	775	503.75	Perennial	23/2/19
3	River	Beressa	556433	1069297	2728	Basalt	8.3	20.6	803	521.95	Perennial	23/2/19
4	River	Dalecha	560542	1070723	2778	Basalt	9.72	19.1	867	563.55	Intermitent	23/2/19
5	River	Dalecha	860488	1070598	2774	Basalt	8.36	16	749	486.85	Intermitent	23/2/19
6	River	Dalecha	583605	1070693	2752	Basalt	10.03	17.6	687	446.55	Intermitent	23/2/19
7	River	Bakelo	568316	1071395	2842	Ignimbrite	8.48	18.3	693	450.45	Perennial	24/2/19
8	River	Bakelo	568331	1071441	2845	Ignimbrite	8.42	16.7	694	451.1	Perennial	24/2/19
9	River	Gadilo	569270	1071622	2861	Ignimbrite	9.35	20.6	695	451.75	Perennial	24/2/19
10	River	Gadilo	569296	1071654	2847	Ignimbrite	9.09	20.5	696	452.4	Perennial	24/2/19
11	River	Gonagunit	571260	1073746	2865	Basalt	9.54	21	676	439.4	Perennial	24/2/19
12	River	Gundagundit	571243	1073748	2838	Basalt	9.3	20.3	678	440.7	Perennial	24/2/19
13	River	Gura	572311	1076614	2900	Basalt	9.07	21	679	441.35	Perennial	24/2/19
14	River	Arat dildiy	573717	1080041	2937	Basalt	9.35	21.4	670	435.5	Perennial	24/2/19

15	River	Hulet wonz	577932	1084860	3029	Basalt	8.45	20.1	665	432.25	Perennial	24/2/19
16	River	Satira	577757	1084018	3093	Basalt	8.63	21.1	660	429	Intermitent	24/2/19
17	River	Gudoberet	574866	1082201	2984	Basalt	8.12	22.3	675	438.75	Perennial	24/2/19
18	River	Tsadkanie	568190	1098086	2859	Ignimbrite	7.75	19.2	692	449.8	Perennial	1/3/19
19	Spring	Gomata	567713	1071287	2862	Ignimbrite	7.72	14.0	694	451.1	Perennial	24/2/19
20	Spring	Setegn georgis	578704	1085559	3167	Basalt	9.23	16.9	667	433.55	Perennial	24/2/19
21	Spring	Tinishu bura	572194	1076435	2923	Basalt	8.43	18.1	670	435.5	Perennial	24/2/19
22	Spring	Filagenet	561303	1097662	2773	Ignimbrite	8.35	18	680	442	Perennial	1/3/19
23	Spring	Quasi georgis	556768	1097662	2773	Ignimbrite	7.83	19	687	446.55	Perennial	1/3/19
24	Dam	Deressa dam	559562	1067787	2776	Ignimbrite	8.21	20.5	655	425.75	Perennial	30/2/19
25	HDW	Beryo	563571	1072746	2846	Ignimbrite/rhyolite	8.0	18.5	664	431.6	Hand pump	24/2/19
26	HDW	Kimbo ager	567014	1071542	2876	Rhyolite/ ignimbrite	7.53	18.7	704	457.6	Hand pump	24/2/19
27	HDW	Filagenet	561243	1097898	2822	Ignimbrite	8.02	21	667	433.55	Hand pump	01/03/2019
28	Beressa dam	Nr.Ansas Mariam	559562	1067787	2776	Basalt	8.21	20.5	655	425.75	Perennial	30/02/19

Appendices 6. Meteorological data

1. Mean monthly rainfall data of the eastern upper Jemma river catchment from 1988- 2018

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Debre Berhan	11.8	16.4	38.5	55.3	43.2	55.0	316.9	273.9	84.4	21.8	8.3	4.4	929.9
Gudoberet	14.4	13.2	41.6	55.3	66.5	85.1	411.2	381.9	132.3	50.2	22.5	6.3	1280.5
Jihur	8.5	26.2	41.2	45.8	27.7	61.4	291.2	271.8	81.4	12.9	6.5	4.4	879
Debresina	71.6	47.0	113.6	158.1	121.2	84.1	384.4	444.2	194.2	117.7	94.9	71.5	1902.5
Ankober	72.2	41.3	128.1	129.3	98.1	67.8	305.3	463.3	176.3	72.9	31.0	36.6	1622.2
Chacha	7.5	5.7	18.7	51.0	30.5	61.4	285.5	306.6	93.2	14.5	2.6	3.6	880.8
Seladingay	9.1	11.9	28.3	88.3	53.2	108.8	414.7	398.7	106.2	30.3	15.1	11.6	1276.2
Enewari	6.2	16.9	55.0	78.0	67.2	97.3	350.5	351.6	103.2	11.5	6.1	7.3	1150.8
Average	25.1	22.3	58.1	82.6	63.4	77.6	344.9	361.5	121.4	41.4	23.3	18.2	1240.2

2. Mean Monthly maximum and minimum temperatures of the area

Station		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Debre Birhan (1988-2018)	Max	19.9	20.8	21.0	21	21.7	22.1	18.5	18.14	18.9	18.9	19	19.0
	Min	4.76	6.06	7.7	7.82	7.31	7.5	8.58	8.76	7.1	3.52	2.32	3.03
	Average	12.3	13.4	14.4	14.41	14.5	14.8	13.54	13.45	13	11.2	10.6	11.0
Enewari (2000-2018)	Max	22.0	23.4	23.5	23.34	23.6	22.8	18.07	17.33	19.4	20.6	21.2	21.2
	Min	8.36	9.36	10.2	10.81	11.2	10.8	10.28	10.26	10	8.02	7	6.84
	Average	15.2	16.4	16.8	17.07	17.4	16.8	14.17	13.8	14.7	14.3	14.1	14.0
Gudoberet (1988-2001)	Max	19.7	18	18	17.83	18.2	18.8	17.1	17.06	16.5	16.0	16.4	16.8

3. Mean monthly relative humidity (%) Debre Birhan and Enewari stations

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
d/birhan	61.5	58.6	62.3	64.1	56.6	60.6	79.8	81.8	73.5	63.7	62.2	60.4
Enewari	51.1	50.1	54.8	57	58.4	65	89.21	89.2	78	62.3	58.2	52.6
Average	56.3	54.4	58.5	60.5	57.5	62.8	84.5	85.5	75.8	63	60.2	56.5

4. Monthly mean sunshine hour (hrs/d) of Debre Berhan and Enewari stations

Stations	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Debre berhan	9.3	8.6	8.0	7.2	7.8	6.5	4.2	4.6	6.0	7.5	8.8	9.1
Enewari	9.2	8.8	7.4	7.1	7.5	5.5	3.7	3.8	6.1	8.8	9.0	9.2
Average	9.2	8.7	7.6	7.2	6.0	6.0	4.0	4.2	6.1	8.1	9.0	9.2

5. Mean monthly relative humidity (%) Debre Berhan and Enewari stations

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
D/berhan	61.5	58.6	62.3	64.1	56.6	60.6	79.8	81.8	73.5	63.7	62.2	60.4
Enewari	51.1	50.1	54.8	57	58.4	65	89.21	89.2	78	62.3	58.2	52.6
Average	56.3	54.4	58.5	60.5	57.5	62.8	84.5	85.5	75.8	63	60.2	56.5

Appendices 7. Summary of mean monthly of Beressa River (near Debre Birhan town) flow in m3/s

year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1997	0.478	0.457	0.534	0.834	0.677	1.323	28.732	20.569	0.721	4.164	0.805	0.337
1998	0.44	0.304	0.309	0.556	0.877	0.609	13.322	42.155	8.258	0.852	0.248	0.182
1999	0.155	0.119	0.156	0.128	0.172	0.358	21.42	36.81	4.827	1.465	0.096	0.049
2000	23.294	23.573	23.227	23.886	25.742	25.348	52.343	103.63	50.147	35.389	26.049	23.375
2001	23.754	28.618	31.113	28.046	29.331	27.265	77.173	97.07	30.623	17.963	17.198	15.84
2002	0.382	0.363	0.42	0.331	0.411	0.563	2.154	24.399	6.872	0.266	0.192	0.228
2003	0.216	0.249	0.182	0.783	0.374	0.545	9.336	11.722	3.165	0.241	0.016	0.029
2004	0.014	0.433	0.618	0.764	0.658	1.315	8.318	20.882	2.62	0.405	0.171	0.129
2005	0.122	0.103	0.11	0.173	0.308	0.326	9.01	12.596	4.839	0.359	0.222	0.261
2006	0.241	0.26	0.284	0.357	0.353	0.397	6.116	16.903	4.988	0.289	0.241	0.253
2007	0.207	0.215	0.222	0.477	0.302	0.653	10.692	26.186	9.137	0.424	0.278	0.227
2008	0.215	0.191	0.165	0.203	0.322	0.433	12.95	13.422	4.661	0.33	0.343	0.263
2009	0.275	0.205	0.209	0.299	0.277	0.399	8.875	14.172	1.601	0.479	0.271	0.352
2010	0.329	0.339	0.354	0.935	1.308	0.496	6.023	15.044	3.954	0.503	0.361	0.356
2011	0.32	0.313	0.382	0.453	1.088	1.422	6.162	16.092	5.206	0.509	0.419	0.388
2012	0.4	0.374	0.339	0.519	0.77	1.34	9.734	18.796	6.404	0.526	0.451	0.425
2013	0.35	0.338	0.362	0.475	0.456	0.519	17.059	18.388	6.642	1.829	1.351	0.531
2014	0.139	0.164	0.163	0.206	4.562	1.271	9.89	35.009				

Appendix 8. Selected hydrogeological logs of boreholes in the study area

1. Dalecha Borehole_2 (DA-BH2)

Depth (meters)	Lithology
0 – 7	highly weathered volcanic ash
7 – 10	weathered ignimbrite
10 – 12	Gravel with slightly weathered stuff
12 – 22	Gravel with highly weathered stuff
24 – 26	coarse sand with gravel
26 – 30	Sandy gravel
30 – 35	coarse gravel with some sand
35 – 44	Massive trachyte basalt
44 – 48	highly fractured trachyte
48 – 69	highly fractured trachyte
79 – 95	Massive trachyte

2. Beressa Borehole -2 (BBH-2)

Depth (m)	Lithology
0-4	Topsoil
4 – 31	highly weathered ignimbrite
31 – 40	Rock fragment
40 – 62	highly weathered ignimbrite
62 – 73	highly weathered & fractured ignimbrite
73 – 78	highly weathered ignimbrite
78 – 86	Sand mixed highly weathered ignimbrite
86 – 88	Rock fragment (undifferentiated)
88 – 92	moderately fractured ignimbrite
92 – 100	slightly fractured to massive ignimbrite

3. Dashen Brewery Borehole_3 (DBH3)

Depth (m)	Lithology	Description
0-1	Clay	Dark brown clay
1-42	Trachyte	Coarse-grained weathered and fractured trachyte
42-55	Trachyte	Highly weathered and fractured coarse-grained trachyte 1st water strike zone
55-86	Trachyte	Extremely weathered and fractured trachyte which has changed to almost sand during drilling. Collapse zone and major aquifer
86-140	Trachyte	Coarse-grained highly fractured and water-bearing 102m-108m, 114m-120m, 126m-136m

4. Dashen Brewery Borehole _5 (DBH5)

Depth (m)	Lithology	Description
0-4	Clay	Yellowish brown
4-52	Ignimbrite	Jointed and fractured
52-98	Ignimbrite	Fractured and weathered, but Highly weathered and fractured 52m-68m, 78m-98m
98-114	Pyroclastic deposit	Reworked pyroclastic deposit (main aquifer)
114-126	Ignimbrite	Highly fractured and moderately weathered
126-154	Ignimbrite	Weathered

5. Dashen Brewery Borehole _6 (DBH6)

Depth (m)	Lithology	Description
0-8	Ignimbrite	Weathered
8-12	Ignimbrite	
12-14	Tuff	Weathered
14-24	Tuff	Reddish brown weathered
24-30	Gravel	Nonsorted gravel derived from ignimbrite rock
30-48	Basalt	Fractured slightly weathered coarse-grained basalt
48-60	Basalt	Fractured Coarse-grained
60-70	Basalt	Coarse-grained
70-78	Basalt	Highly weathered coarse-grained
78-84	Basalt	Highly fractured and weathered basalt (major Aquifer)
84-90	Contact zone	Backed tuff mixed with basalt chips (Aquifer)
9096	Basalt	Weathered coarse-grained
96-120	Basalt	Weathered and fractured coarse-grained vesicular basalt (Major Aquifer)
120-132	Basalt	Weathered and fractured coarse-grained (Aquifer)
132-138	Basalt	Coarse-grained
138-146	Trachy-Basalt	Highly fractured, weathered and coarse-grained (Major Aquifer)
146-158	Basalt	Coarse-grained
158-164	Trachy-Basalt	Highly fractured, weathered and coarse-grained (Aquifer)
164-170	Basalt	Slightly fractured

6. Debre Birhan University well-3 (DBUW3)

Depth (m)		Lithology
From	To	
0	4	Topsoil
4	6	Welded Tuff
6	26	Slightly weathered ignimbrite
26	32	Highly weathered ignimbrite
32	38	Slightly weathered ignimbrite
38	46	Highly weathered & fractured ignimbrite
46	60	Slightly weather ignimbrite
60	70	Moderately weathered and highly fractured rhyolite
70	76	Slightly weathered rhyolite
76	84	Slightly weathered and fractured rhyolite
84	98	Highly weathered ignimbrite
98	100	Moderately weathered and fractured rhyolite
100	104	Moderately weathered and fractured ignimbrite
104	108	Slightly weathered ignimbrite
108	112	Slightly fractured basalt
112	122	massive basalt
122	126	Slightly weathered basalt
126	142	Slightly weathered & fractured basalt
142	144	Welded tuff
144	154	Highly fractured and moderately weathered basalt
154	156	Highly weathered ignimbrite
156	160	Moderately weathered and fractured basalt
160	164	Highly weathered ignimbrite
164	172	Highly fractured and moderately weathered basalt
172	178	Welded Tuff

7. Habesha Brewery Borehole 2 (HA-BH2)

0-12	Red clay soil
14-Dec	Baked clay
14-20	Tuff
20-28	Scoria
28-34	Tuff
34-84	Pyroclastic material
84-88	Clay
88-100	Undifferentiated rock fragment (Main aquifer)
100-108	Slightly fractured basalt
108-110	Scoria
110-116	Undifferentiated rock fragment
116-120	Scoria
120-126	Massive basalt
126-132	Fractured basalt
132-152	Slightly fractured and massive basalt
152-154	Fractured basalt
154-166	Massive basalt

8. Tarmaber Borehole

Drilled Depth(m)		Lithologic Description
0	12.2	Topsoil
12.2	38.5	Moderately Weathered ignimbrite
38.5	45.7	Moderately weathered Agglomerate
45.7	58.9	Massive ignimbrite
58.9	63	Slightly weathered ignimbrite
63	69.1	Massive ignimbrite
69.1	75.2	Moderately weathered and fractured Basalt
75.2	81.3	Slightly weathered and fractured basalt
81.3	85.4	Massive Basalt
85.4	91.5	Moderately Weathered agglomerate
91.5	97.6	Slightly weathered and fractured basalt
97.6	101.7	Moderately Weathered basalt
101.7	107.8	Massive Basalt
107.8	115.9	Moderately fractured basalt
115.9	117.9	Massive Basalt
117.9	119.9	Highly fractured and slightly weathered basalt
119.9	124	Slightly weathered and fractured basalt with scoria
124	126..1	Massive Basalt
126.1	128.1	Moderately fractured basalt
128.1	130.1	Massive Basalt
130.1	132.1	Moderately fractured basalt
132.1	136.2	Moderately fractured Trachyt
136.2	143	Slightly weathered trachyte