SCHOOL OF GRADUATE STUDIES

DEPARTMENT OF EARTH SCIENCES

Characterization of the groundwater systems and aquifers in Jerer Valley, Somali Regional State, Eastern Ethiopia

By
Mohammed Mukhtar Muallim

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTERS OF SCIENCE IN HYDROGEOLOGY

Advisor
Prof. Tenalem Ayenew

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

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Many thanks,

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Abstract

The Jerer valley which is part of the Shebelle river basin covers an area of 10,816 km2. It is located between the geographical coordinates of 7˚56'79"N to 9˚61'23"N Latitude and 42˚58'04"E and 44˚31'60"E Longitude.

The mean annual rainfall is 507.42 mm, while average monthly temperature is 26 ^{o}C. PET and AET are estimated to be 1218.3 mm and 498.4 mm respectively.

The general objective of the research is to evaluate the hydrogeological characteristics of groundwater systems concerning aquifer type, groundwater recharge estimation and groundwater flow dynamics. To meet the objectives, multiple methodologies and approaches have been applied in the area of investigation including intensive literature review, primary and secondary data compilation and historic data analysis is carried to observe the past trend of the hydrologic and hydrogeological systems.

In this research, the aquifer systems have been characterized from an area of high permeable to an area of very impermeable. Boreholes tapping water from Adigrat sandstone and Hamanlie formations were identified the best aquifers in the study area.

Groundwater recharge to these aquifers which is most possibly from precipitation on the northwestern mountains has been estimated to be about 13 mm/year. The observed regional groundwater flow has the same trend as surface water flow; towards southeast.

The geochemical data of dissolved major and minor constituents in the groundwater samples indicates the main processes responsible for the geochemical evolution are: (1) sea water intrusion; (2) leaching process of underlying rock mediated by pH; (3) Minerals weathering process and (4) dissolution of carbonate minerals characterized by high loadings of Ca, and Mg.

The research recommends the need for additional hydro-meteorological stations as well as detailed hydrogeological study in the area.

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List of Acronyms

AET - Actual Evapotraspiration

APWL -Accumulated potential water loss

BH-Borehole

EC - Electrical Conductivity

FAO - Food and Agricultural Organization.

GIS - Geographical Information System

HDW- Hand Dug Well

ITCZ - Inter Tropical Convergence Zone

JICA- Japan International Cooperation Agency

MCE- Mesfin Consulting Engineers

P - Precipitation

PET - Potential Evapotraspiration

pH - Negative of the logarithm to the base ten of the hydrogen ion concentration.

RTI- Radar Technology International

SAR - Sodium Adsorption Ratio

SHAAC- SHAAC Engineering PLC.

SMD - Soil moisture deficit

SRWRDB- Somali regional water resources Development bureau

SWWDSE – Somali water works Design and Supervision enterprise

TDS - Total Dissolved Solids

UNESCO - United Nations Educational Scientific and Cultural Organization

UNICEF-United Nations Children's Fund

UTM -Universal Transverse Mercator

WAPCOS - Water and Power Consultancy Service (India) Ltd

WHO - World Health Organization

WWDSE- Water Works Design and Supervision Enterprise

CHAPTER 1- INTRODUCTION

1.1 Background

Water is essential for sustaining life and access to drinking water is a fundamental need and a human right, vital for health and well-being. The health and economic benefits of improved water supplies to households and individuals (especially women, children and older people) are well documented. The demand for water resources is increasing day by day due to ever increasing population, mostly from developing countries. This has resulted in demanding the abstraction of more water from the subsurface stratum and forcing the decision makers to search for more sources, which in turn needs a sophisticated way of assessing the underground resources.

According to Seifu Kebede (2013) there is variable definition for groundwater. Agronomists define groundwater as any water below the ground. For engineers groundwater is often termed as subsurface water and occurs below the ground. For hydro geologists groundwater is water in the saturated zone. A number of other names are attributed to groundwater. This includes sub surface water, under groundwater and groundwater.

Groundwater provides an important source of drinking water over much of the world. It also has the fundamental importance of maintaining river and stream flows during periods without rain and also supporting wetland sites (Brassington 2007).

According to SRWRDB (2010) groundwater in Somali region is likely to be classified as fossil groundwater with current limited recharge based on inflow from highland as well as percolation of rainwater. While no data exists on groundwater capacity or movements, the recharge through rainwater can be judged as very limited when considering the potential evapotranspiration in comparison with the amount and intensities of rainfall. Therefore, adequate groundwater exploration and management appears to be the key to ensure that potable and safe water is available for the entire population of the region and that groundwater availability on a sustainable basis is guaranteed.

In general, water supply situation in many parts of the Somali Regional State is known to be exceptionally severe and this is due to low effective rainfall as well as lack of proper understanding of the region's Hydrogeology. Hence, several deep well drilling projects were undertaken in the region, however, due to lack of prior Hydrogeological knowledge, the success rate of groundwater development or drilling wells has been very low (SHAAC 2009).

It is obvious that groundwater is the major and most feasible source of water supply particularly in areas of arid climatic zones like Somali region where the study area is located. The area has a limited average rainfall ranging 321 – 770mm annually which is erratic in nature and with minimum associated perennial surface water resource distribution in the area.

Therefore, further and detailed water resources investigations (hydrogeological investigations) was needed in order to indicate possible ways and mechanisms for sustainable, potable and feasible water resource in the area. On the basis of this concept, this academic research was proposed to give some detailed picture on the hydrogeological characteristics of Jerer valley. The study in general focuses and incorporates the evaluation of the hydrochemistry and the ground water flow, recharge condition and aquifer characterization.

1.2 Objectives and scope of the study

1.2.1 General Objective

The general objective of the research is to evaluate the hydrogeological characteristics of groundwater systems concerning aquifer type, groundwater recharge estimation and groundwater flow dynamics.

1.2.2 Specific Objectives

The specific objectives of this study include the description and characterization of the major aquifer systems and units in the area. The objectives also include the estimation of the groundwater recharge of the catchment; determine the local groundwater flow system, description of the hydrochemistry of the groundwater from the analysis of the water chemistry data and discussing the hydrogeological implications behind the hydrochemical variations.

1.2.3 Scope of the study

The scope of the study includes the acquisition and compilation of all the necessary secondary and primary data from previously done works in the area and on field assessments. For the hydrologic analysis of the area for instance hydrometeorology data of over twenty years have been considered.

A field assessment and actual field observation of the hydrogeological nature of the area and water well data observations and measurements in open wells has also been carried out to further strengthen and filtering the available data source. Furthermore, hydrochemical data collection and analysis includes insitu field measurements of the physical and some chemical parameters and water sample collections at various water source points for furtherer laboratory analysis of the basic cations and anions concentration and other important parameters.

The final scope of the study incorporates the analysis of all available data obtained from multiple sources and interpreting them in accordance with the specific purpose of the study and finally giving some picture about the hydrogeology of the area supported with different maps.

1.3 Methodology

To fulfill the various scopes of the study outlined above, multiple methodologies and approaches have been used in the area of investigation. Intensive literature review, secondary data compilation and historic data analysis is carried to observe the past trend of the hydrologic and hydrogeological systems.

Water level measurements was collected and compiled from both open dug wells and shallow and deep boreholes to observe its possible interaction with the river water for potentiometric head mapping to show the groundwater flow system.

Field observations were supported with the digital images of the areas analyzed with various computer softwares for the preparation of different maps of the study area.

The quantification of some components like the evapotranspiration was done from both empirical methods and from soil water balance.

The hydraulic parameter of the hydrologic units of various aquifers is determined from pumping test data and Lithological logging data compiled from a total of 15 wells (shallow to deep wells).

For the hydrochemical characterization of the groundwater in the area, waster samples collection from previously drilled wells and dug wells have been made, and in addition to this a new hydrochemical data set has been generated by taking additional samples from different boreholes and analyzed it for chemical and physical parameters, where a total of 49 samples have been used for this evaluation. To observe the field condition of the water samples from various sources field measurements of some parameters like pH, Temperature, EC and TDS was carried out using EC and pH meter. Therefore, the hydrochemical database used in this study in general includes water samples from 29 boreholes (shallow and deep) and 20 hand dug wells around the middle Jerer. The chemical analysis data is used for classification of water into different hydrochemical groups or water types.

1.4 Previous Works

The geological, structural and stratigraphical understanding of Somali region derived from Oil Exploration works which were believed to be commenced in the 1920s. However, formal surface geological mapping, geophysical exploration and drilling investigations by various oil companies, viz. Sinclair Petroleum Company, Elwerath Oil Company, Tenneco Ethiopia Company (USA), Whitestone Ethiopia Petroleum Company (USA), Voyager Petroleum Company (Canada), Maxus Energy Corporation, and Ethiopian Hunt Oil Company conducted from 1945 to 1997. The works of these petroleum companies are summarized in Raaben et al. (1979) and Geleta (1998). Moreover, the Soviet Petroleum Exploration Expedition conducted drilling of development wells at Calub and Hilala, locally known as Jehdin and Elale, during the period of 1986 – 1991 (WWDSE 2012)

Furthermore, the geological map of Ogaden Basin largely resulted from the petroleum exploration companies were compiled from the Geological Maps of Ethiopia (Kazmin 1972 and Tefera et al. 1996) and Geological Map of Ethiopia and Somalia by (Merla et al., 1973; 1979) at scale of 1:2,000,000.

The geology of Shebelle River Basin conducted by the WWDSE, MCE and WAPCOS (2004) gives detailed account of the geology & economic mineral deposits that exist in the basin. Even though the coverage is very regional and data are scarce or even lacking at some places, it is still a good starting for projects in the Shebelle river basin. The study categorizes the geology of the basin into three major groups, namely, Precambrian crystalline basement rocks, Late- Paleozoic to Early Neogene sedimentary rocks, and Neogene to Quaternary volcanic rocks.

In 2013 JICA in collaboration with KOKUSAI KOGYO CO., LTD conducted a study to study on Jerer and Shebelle sub basin. Their study included study of the geology, hydrogeology and hydrology of the area. Although the study area is very wide however, it classified and characterized aquifer units in details by using clear satellite images.

UNESCO in collaboration with RTI (2012) has adopted the WATEX© System approach developed by Radar Technologies International (RTI) in upper Fafan-Jerer area to achieve comprehensive, rapid, large-scale Hydrogeological investigations to improve the effectiveness of drought mitigation efforts in the region. The WATEX© process has revealed the East Karamara Graben Aquifer, buried between a depth of 50 to 450 m along the Jerer Valley, over a distance of 200 km opened to the South East and 5 to 20 km width. The groundwater capacity of this graben aquifer is estimated from 3 to 7 billion m^3, with a possible extension to 36 billion m^3 of drinkable quality water.

WWDSE (2012) conducted detailed land use studies in Jerer valley and lower Fafan. The study contained a hydrology part which provided a helpful tool for the assessment of water potential in the area. They estimated the mean annual surface runoff Jerer River at upper Jerer sub basin is 7.32MMC. The annual surface runoff of this river at the Middle Jerer sub basin is 5MMC. When it reaches at the lower Jerer sub basin its annual surface runoff value becomes 7.14MMC.

SHAAC (2009) conducted hydrogeological mapping of Somali region with limited objectives and this study can be considered as reconnaissance study, but it maybe nevertheless used as a base for future detailed hydrogeological mapping of the region.

Ethio-France Cooperative Program (1972) studied the geology and hydrogeology of Shebelle basin. The study was conducted in the most arid southern of the basin which is only regularly supplied by the two main rivers: the Shebelle river with a permanent flow and Fafan with an intermittent flow. The aim of this study was to delineate the geological units that may constitute utilizable reservoirs. The study was a synthesis of the researches carried out from 1967-1971 by the Hydrogeological division of the Wabe Shebelle program.

Hadwin et al. (1973) studied the geological formation and their water bearing characteristics and summarized the groundwater development problems of the region as inadequate recharge, salinity and drilling problems. Their work is the base for all the then hydrogeological studies conducted in Ogaden (Somali region).

Lastly, Shachnai (1972) as part of the livestock development project Jigjiga region studied the Hydrogeology of the most upper Jerer and described in detail the tectonic setting of the Ogaden.

As was seen above all studies conducted so far, some work was done on geology, hydrology, land use, climate, and scheme assessments of the basin except very few works on conventional site Hydrogeological and geophysical investigations for locating boreholes. Therefore, the current research is expected to describe the hydrogeological characteristics of the groundwater systems concerning aquifer type, groundwater recharge estimation and mechanism and groundwater flow direction as well.

CHAPTER 2: OVERVIEW OF THE STUDY AREA

2.1- Location and accessibility

The study area is located in the northern part of Somali regional state particularly Jigjiga (Fafan) and Degahbour (Jerer) zones. Jigjiga town which is the capital city of the region is situated southeast of Addis Ababa at about 630 km asphalt road running from Addis Ababa through Harar to Jigjiga.

The area is found mainly within the main Shebelle basin, which is the largest Ethiopian basin with a size of about 202,697 km2, but it has a relatively low runoff of 3.16 billion m3 and average river flow of 80 m^3/s. This is probably due to the dominant arid character of the climate.

The general trend of drainage in the area is from the elevated northwestern mountainous area to the southeastern lowland plain area of the Shebelle basin.

The study area starts from the mountainous areas north of Jigjiga and extends down to about more than 200 km up to the confluence of Jerer and Fafan Rivers near Birkod area in the Southeast direction. It covers an area of 10,816 km^2 of Shebelle Basin which is perennial only on the main river and all tributaries including Jerer stream is seasonal. The mean annual Rainfall of the sub-basin ranges from 321 mm at Degahbour at the middle Jerer to 769.2mm at Lafe Ise at the uppermost Jerer. The study area is located between the geographical coordinates of 7˚56'79"N to 9˚61'23"N Latitude and 42˚58'04"E and 44˚31'60"E Longitude.

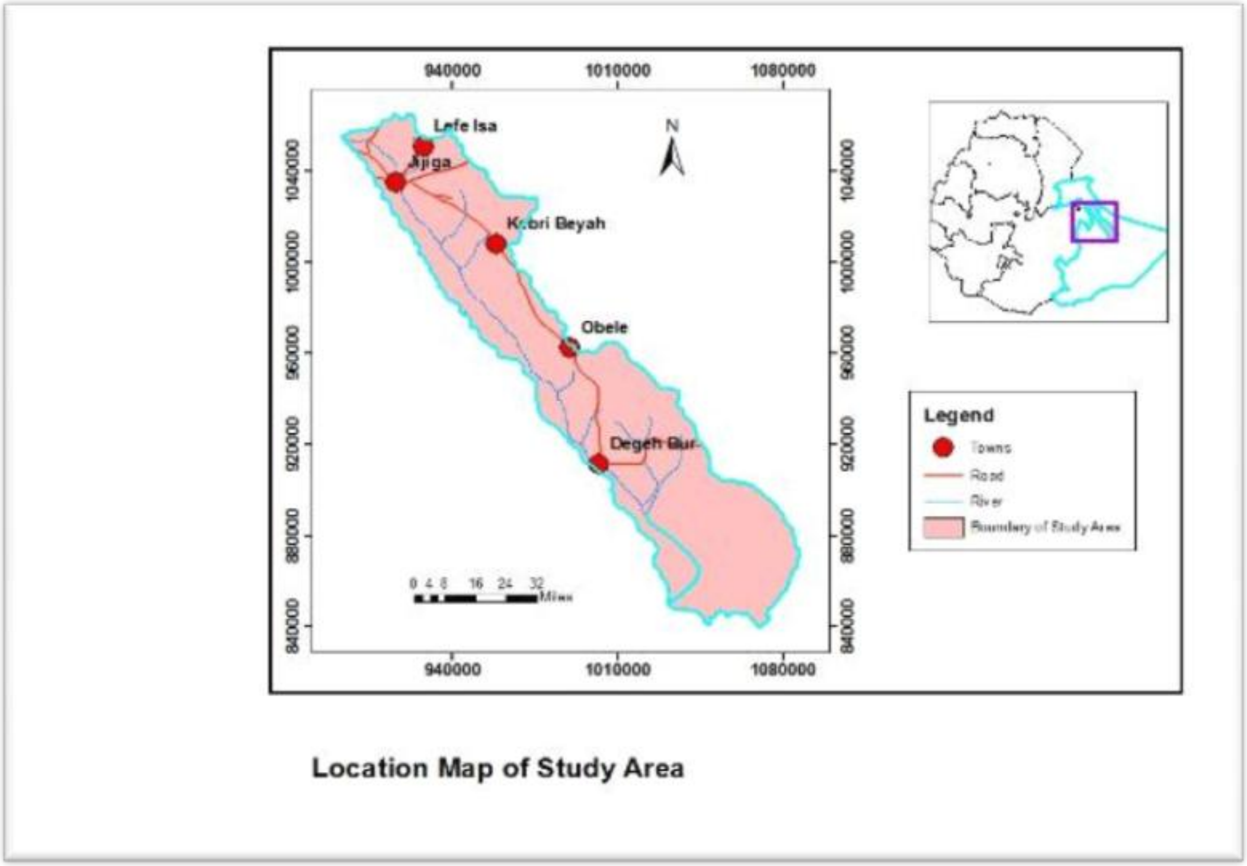


Figure 2.1 Location Map of study area

The study area is bordered in the west by the narrow Karamara range which stretches all along the NW-SE direction separating the Jerer Valley in the East from the Fafan Valley in the West and on the East by the Marda Fault separating Shebelle and Ogaden- Warder basins. Regarding accessibility, there exists an asphalted road that runs from Jigjiga, the northern tip of the catchment to Birkod, the southeastern end of the study area. In addition to this, there are other types of roads; mainly dry weather that radiate to the left and to the right from some towns and villages like Kebribeyah, Ararso, Obele, Degahbur and Jigjiga.

2.2 Climate

The climatic regime of the Shebelle River depends on the relief which slopes from the northwest down to the southeast (BECOM-ORSTOM 1972). The basin is characterized by bimodal type rainfall pattern. The north western and eastern part of the Shebelle basin (around Kofele, Adaba, Deder, Harar and Jigjiga) receive most of their rainfall during July, August and September associated with the northward passage of the ITCZ. From September to November, the ITCZ moves back to southward direction, causing a rapid end to the rainy season during September/October. By December and January the ITCZ moves further southwards into Kenya (WWDSE 2012).

From about mid March to May (Belg season) the pressure system changes to Warm, moist and unstable air from the Indian Ocean moves in from the east and converges with stable continental air mass from the Sahara high pressure cells.

Distinctly, the southeastern part of the low lying areas of the Shebelle basin that is east of 42^o and south of 8^o (Around Degahbour, Kebridehare, and Gode) receive no rainfall in July and August. It rather has two rainfall seasons. The first season is from March to May, and the second season is from October to November. The March to May rains is caused by moisture advected from Indian Ocean, while the October – November rains may be associated to the retreat of the ITCZ in the southward direction.

Hence, the study area in general is designated as hot semi arid climate zone. The climatic variables such as maximum and minimum temperature, wind speed, relative humidity, and sun shine duration are important for the estimation of evapotranspiration. For the analysis of evapotranspiration, these variables are computed from seven meteorological stations. The considered stations are: Jigjiga, Kebribeyah, Jinacksan, Lefe Ise, Harshin and Degahbur stations, which are found within the study area or very close to the boundary.

2.2.1 Rainfall

According to the classification of the climate and agro climatic resource of Ethiopia, the rainfall pattern in the Jerer valley is bimodal type (Fig 2.2) and it gradually decreases from North to the South (table 2.1). There are three measuring stations with daily data for the period 1991- 2014 and there are also other stations with daily but observation years were short. The variation of rainfall for the meteorological stations in the Jerer Valley is presented below. The values range from 769.22mm/year in the North to 321 mm/year in the South.

Table 2.1 Mean Monthly Rainfall at Gauging Stations in the study area

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual (mm)
Jigjiga	13.44	18.57	43.92	100.81	80.43	38.13	65.01	81.02	85.79	44.3	16.86	8.5	**596.78**

Obele	7.21	2.03	29.5	73.25	67.68	23.3	4.9	3.29	49.3	67.18	15.86	6.5	**350.00**
Jinacksan	15.22	5.99	75.97	123.21	47.55	36.36	85.44	109.49	78.83	37.2	30.49	1.17	**646.92**
Kebribeyah	18.68	20.9	45.33	79.67	87.73	29.2	39.9	90.33	83.94	75.5	47.4	11.32	**629.90**
Aware	7.21	2.03	29.5	73.25	67.68	23.3	4.9	3.29	49.3	67.18	15.86	6.5	**350.00**
Birqod	7.21	2.03	29.5	73.25	67.68	23.3	4.9	3.29	49.3	67.18	15.86	6.5	**350.00**
Hadew	3.58	4.17	26.1	82.54	96.76	67.8	58.62	83.68	63.35	44.67	14.6	7.08	**552.95**
Degahbur	3.21	2.03	17.7	73.25	67.68	17.16	2.9	5.29	39.7	65.7	16.88	9.5	**321.00**
Lafa Ise	13.22	23.86	55.14	101.77	96.99	64.28	129.93	147.22	81.14	31.07	12.09	12.53	**769.24**
Average	**9.89**	**9.07**	**39.18**	**86.78**	**75.58**	**35.87**	**44.06**	**58.54**	**64.52**	**55.55**	**20.66**	**7.73**	**507.42**

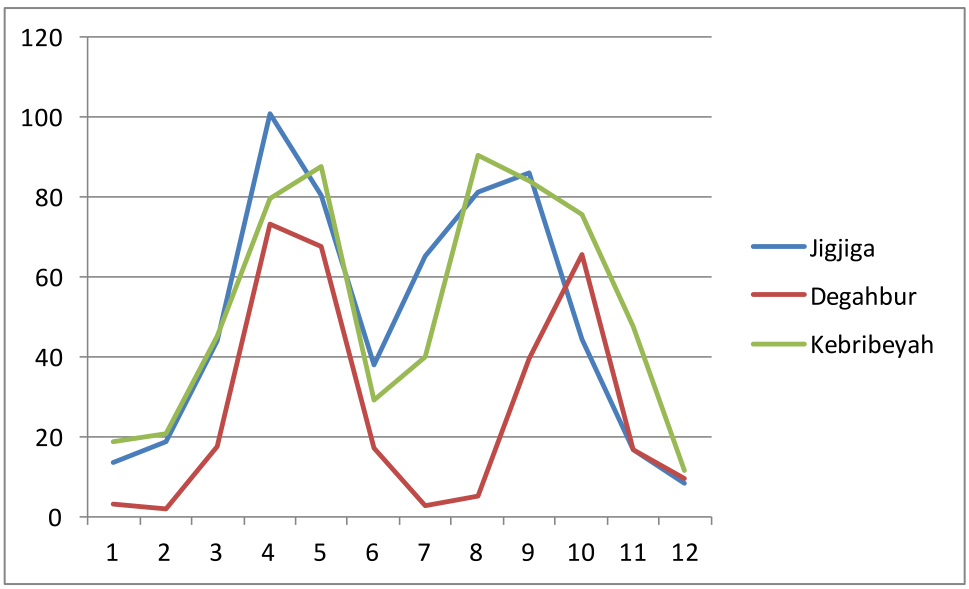


Fig 2.2 Rainfall patterns at study area

2.2.2 Temperature

Temperature record of the study area was collected from Ethiopian National Meteorological Agency database. The duration of the record was from 1990 to 2014 at Jigjiga, Degahbour, and Harshin, while the same parameter was recorded from Kebribeyah and Lafa Ise in 2011 to 2014 and 2009-2013 respectively. The annual maximum and minimum temperature at Jigjiga station are 28 ^{0}C and 9 ^{0}C respectively. At Kebribeyah station they are 26.9 C$^{\circ}$ and 11.8 C$^{\circ}$ respectively. At Degahbour station, the maximum and minimum temperature is 31.7C$^{\circ}$ and 15.4 degree centigrade respectively. The mean annual temperature at Jigjiga, Kebribeyah, Lefe Ise and Degahbour is 18.4, 19.3, 22.6 and 23.6 C° respectively.

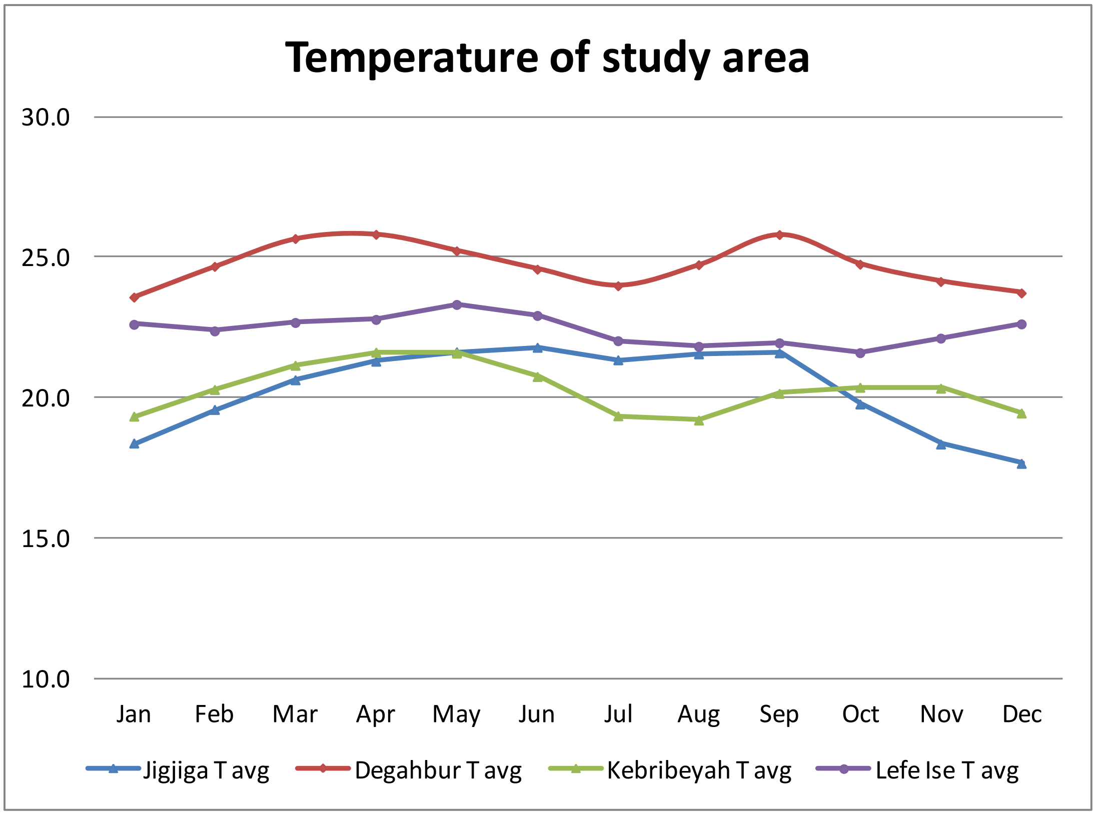


Figure 2.3 Mean monthly temperature of the study area

2.2.2- Sunshine duration, wind direction and wind speed

The sunshine duration, wind direction and wind speed record at the study area is very limited. Only three stations; Jigjiga and Degahbour within the study area and Kebridehar station which is close but outside the boundary of reference have sunshine parameters. The sunshine duration record from 1999-2014, which is found at the Jigjiga station, only six years are without missing monthly record. Hence, the mean annual sunshine duration at this station is 3205.4 hours.

According to JICA (2012) at Jigjiga there are many days of wind from North or North-East in October to February. And most days the wind speed is over 5m/s. From March, the wind-direction gradually shifts from East to South; the wind speed becomes less than 5m/s. In May, the wind blows from all directions and from June to September wind from the southwest increases and for most days the wind speed is over 5m/s. Mean annual value of 1.36 m/sec or 45.6 miles/day.

2.3 Topography and Drainage of the study Area

Jerer valley is located in the eastern part of the Southeastern Plateau, characterized by rugged and high relief topography, which gradually gives way to the gently dipping plains of the Ogaden Region. Jerer River, tributary of the Wabi Shebele, as well as the head ward streams of the Ogaden River Basin originate from the Southeastern Plateau. However, the eastern part of the study area is characterized by sparsely distributed drainage patterns (Fig 2.4)

The topography of the area is dominated by fluvial including surface processes such as weathering, erosion and transportation; and volcanic landscapes coupled with tectonic structures such as fractures/faults and type of the underlying rock formations (WWDSE 2013). The actions of waters (rivers and streams) controlled by tectonic structures and volcanic activity to a lesser degree played roles in shaping the landforms of the project area. As such, drainages are very well developed mainly in Fafem valley and right side of the Jerer valley. The Karamara mountain range serves as starting zone of the tributary streams flowing east – southeast to Jerer valley.

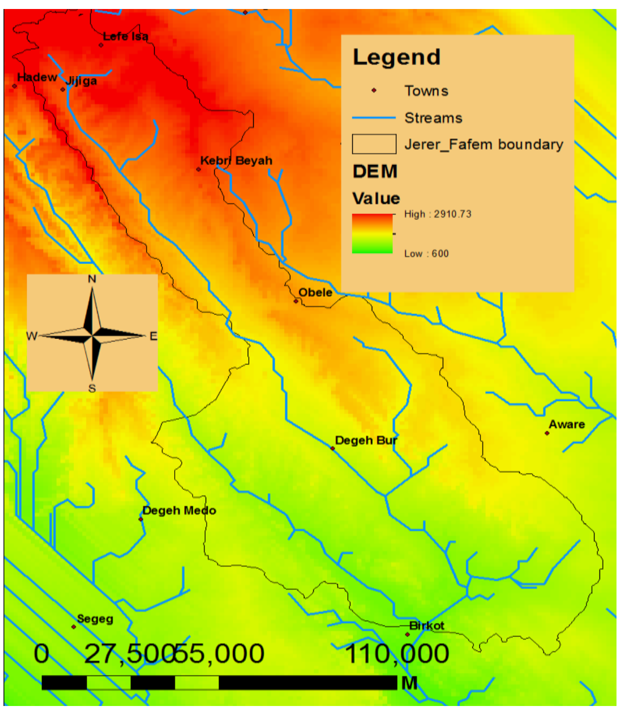


Figure 2.4 Drainage pattern & DEM

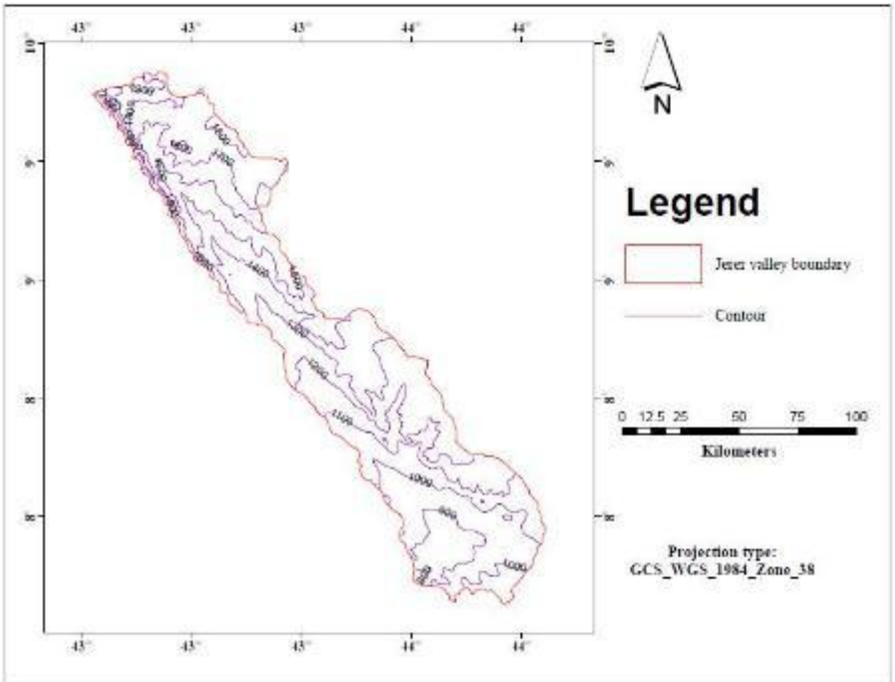


Figure 2.5 Contour Map of the study area

According to Schramm (1980) watershed is classified depending on size of the catchment. Accordingly, 1) Water resources region (250,000 – 750,000 sq.km) 2) River basin (25,000 – 75,000 sq.km), 3) Watershed/ Catchment (2,500 – 7,500) and 4) sub-watershed (less than 2,500 sq. km). According to above classification, the Jerer valley is categorized under watershed area of 2,000-7,500 km^2. Physiographically the Jerer sub basin is divided into the following major land forms;

a. Plain and undulating side slope
b. Plain and low plateau with hill and moderately dissected side slope
c. Low, moderate and high relief hills with plains
d. High to mountainous relief hills

Hence, based on the elevation the study area which is Jerer Valley is divided into three sub basins namely upper, middle and lower Jerer. The upper part of Jerer sub-watersheds is relatively flat and narrow while the middle and lower Jerer are also flat with broad Valley.

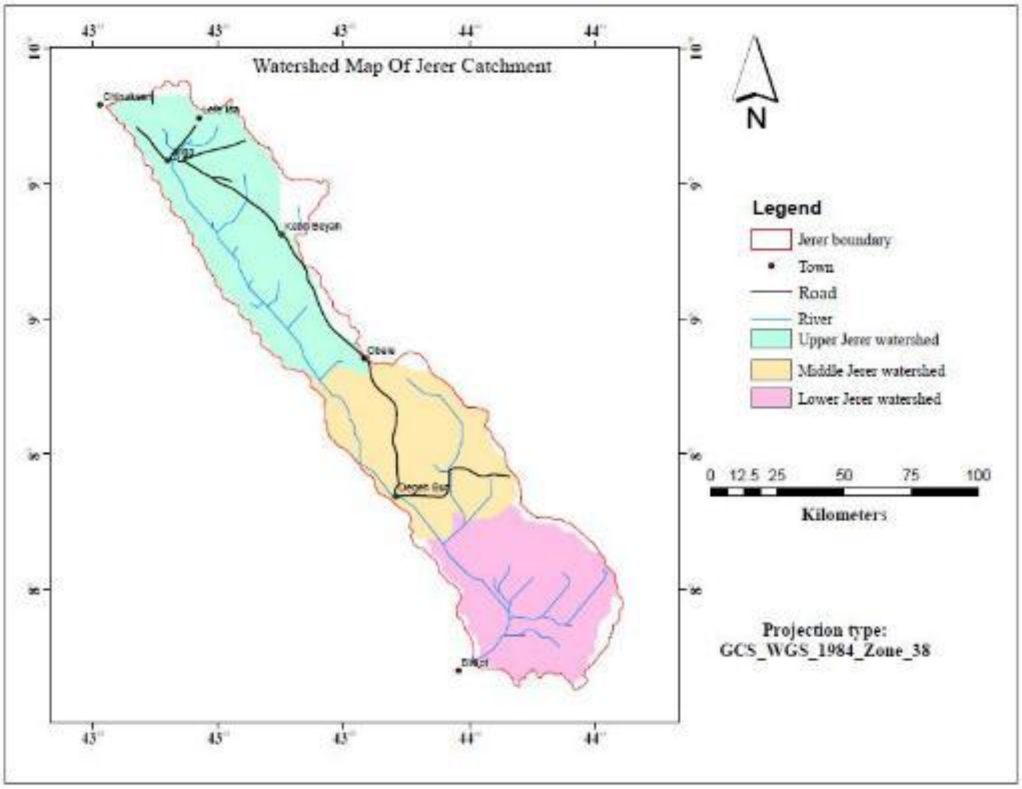


Figure 2.6 sub-watershed map of study area

2.4 Land Use/Land Cover

Shrub lands that comprise 73.12% of the study area is the dominant cover types of the sub-basin followed by Bare lands and cultivated lands that constitute 10.23% and 8.26% respectively. The rest of the study area is covered by grasslands and settlement areas comprising 8.09% and 0.3% of the study area respectively. The land use pattern of the Jerer Sub Basin can broadly be grouped in to five main land use order. These include:-Settlement, Cultivation, Animal husbandry, Mixed Farming, and Extraction/ Collection of natural resources (MOA 2012).

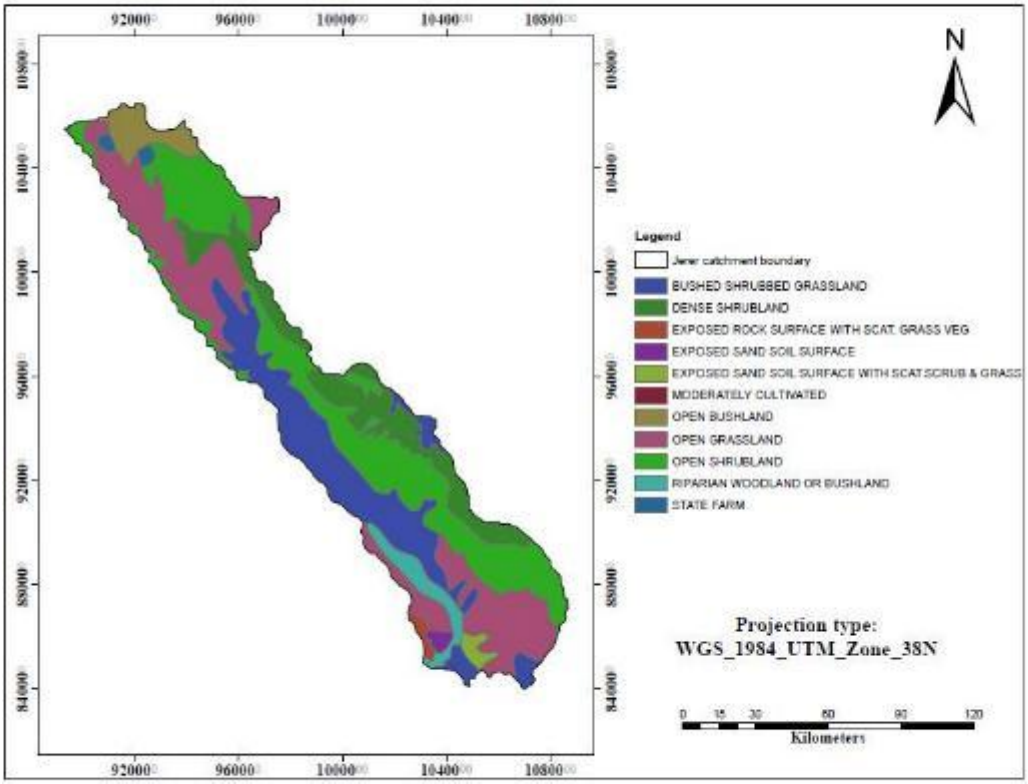


Figure 2.7 Land use/cover map derived from ethio land use

2.4.2 Vegetation Cover

The Jerer sub-basin is characteristically covered by scattered shrubs and thorny bushes/trees (mainly dwarf acacia). Relatively, the Jerer as well as its head ward tributaries are characterized by more dense vegetations.

(a) **(b)**

Figure 2.8 some land cover features (a) bare land (b) open shrub land in Jerer sub-basin

CHAPTER 3: GEOLOGY

3.1. Regional Geology

During the past decades different geologists and different oil companies have studied the geology of Somali Region (aka Ogaden) of Ethiopia. Because much geological works has been carried out in more or less in isolated agencies, there is a confusion of nomenclature concerning limestone and overlying gypsum (Hadwin et al. 1979). To avoid such confusions the classification of the rocks of the Ogaden follows the geological map of Ethiopia (Kazmin 1973) at a scale of 1:2,000,000.

Hence, based on the knowledge acquired from the existing geological maps and findings of oil exploration companies the oldest unit outcropping in the region is the Precambrian basement rocks upon which all the younger formations were deposited. It contains the oldest rocks in the region with ages of over 600 million years. They are exposed in areas where the younger cover rocks have been eroded away, namely in parts of Jigjiga and Liban Zones (SHAAC 2009).

The Precambrian contains a wide variety of sedimentary, volcanic and intrusive rocks which have been metamorphosed to varying degrees. Geochronological studies carried out by Teklay et al. (1998) on Precambrian basement rocks of eastern Ethiopia around Harar and Hirna not far from the study area indicated Archean to Paleoproterozoic ages. Precambrian basement rocks of eastern Ethiopia are classified into three group viz. lower, middle and upper complexes and presumed to contain rock components older than all other Precambrian basement occurrences in southern, southwestern, western and northern parts of Ethiopia (WWDSE 2013)

At the end of Precambrian times uplift occurred, which was followed by a long period of erosion. All sediments which were deposited during the Paleozoic interval, which lasted some 375 million years, have been largely removed by erosion. Therefore, Paleozoic sediments cannot be observed in Somali Region (SHAAC 2009).

Subsidence occurred in the Mesozoic, which began some 225 million years ago, and a shallow sea spread initially over the eastern part of Somali region and then extended farther north and west of the country as the land continued to subside. Sand, now sandstone, was deposited on the old land surface. Deposition of mudstone and limestone followed as the depth of water increased.

According to (Gelete 1998) as cited in the (WWDSE, 2013), the Mesozoic sedimentary successions including mainly the basal Adigrat sandstone and limestone formations unconformable overlie the Precambrian basement that forms the floor of the Ogaden Basin. In some places, particularly south of the study area, older Karoo sediments including Gumburo Sandstone, Bokh Shale and Calub Sandstone, which are mainly fluvial and lacustrine deposits, underlie the Adigrat Sandstone. These older clastic sedimentary successions were deposited in grabens in basement terrain. Sedimentary rock distribution in Ogaden Basin, i.e. eastward gradation of carbonates and evaporates into basinal shale. Purcell (1981) suggests deepening of the depositional basin geometry in Ogaden. Earlier Purcell (1976) described uplift and subsidence of the eastern and western Ogaden, respectively, along the Marda Fault Zone, which is generally presumed to dip due northeast with local opposite dipping faults. Furthermore, Neogene sedimentary rocks: Jessoma sandstone; Auradu limestone; Taleh anhydrite, gypsum, dolomite and clay; Karkar limestone with intercalation of marl were deposited in eastern portion of the Ogaden Basin, mainly to the east of Marda Fault zone.

The Neogene rocks cap both the Precambrian basement and Mesozoic – Cenozoic sedimentary successions along the Karamara mountain range in the northern part of the study area close to the southeastern margin of the Main Ethiopian Rift (MER) margin.

These sedimentary successions are generally absent in other parts of Ethiopia. Apart from the sediments sporadic Neogene volcanic rocks Ashange basalt (Tefera et al. 1996) occur overlying both the Mesozoic and Neogene sedimentary rocks. Superficial sedimentary deposits, alluvial deposits in the major river valleys, colluvial deposits at the base of the ridges, and alluvial sediments on the plateaus/plains are not uncommon (Gachet 2012).

Table 3.1: Summary of Sedimentary Rock Formations in SE Ethiopia (WWDSE, 2013)

Lithostratigraphy	Age	Lithologic Description	Depositional Environmental
Alluvial, colluvial & Elluvial sediments	**Quaternary**	Sediments	
Karkar Formation	**Neogene**	Limestone with intercalation of marls, shale, and chalky limestone	
Taleh Formation		Evaporitic unit containing, anhydrite, gypsum, dolomite, and clays	
Auradu Formation		Biogenic limestone alternating with beds of chalky or gypsiferous limestone alternating with green to brown shale	
Jessoma Formation		Fine to coarse grained sandstone and marls	Fluvial – shallow marine
Belet Uen Formation	**Cretaceous**	Fossiliferous, sandy and cherty limestone with shale & gypsum. Marls, sandstone, & gypsiferous limestone also occur	Reefal
Ferfer Gypsum (Faf)		Grayish brown dolomite, shale, anhydrite, marl, interbeds limestone (equivalent to Amba Aradom Formation).	Supra-tidal – inner shelf
Mustahil Formation		Limestone inter-bedded with shale and marls	Reefal
Korahey Formation		Thickly bedded gypsum alternating with dolomite and thin limestone. It is also known as Main Gypsum Formation	Inner shelf
Gabredarre Formation		Light colored oolitic limestone, marls, & shaly limestone	Outer – inner shelf
Urandab Formation	**Jurassic**	Sequence of dark shale, marl and gypsiferous limestone (equivalent to Agula Shale).	Basinal – outer shelf
Upper Hamanlie		Cryptocrystalline limestone, grey to white and is fine grained	Inner – outer shelf
Middle Hamanlie		Mainly evaporites, like grey anhydrite and dark grey dolomite (equivalent to Antalo limestone)	Supratidal – inner shelf
Lower Hamanlie		Densely cemented, bottom part fossiliferous, fine grained, grey to dark grey rock (equivalent to Antalo limestone).	Inner shelf
Adigrat sandstone	**Upper Triassic**	Fine to medium grained, sorted or non-sorted at places cross-bedded, yellow, reddish brown to white sandstone	Fluvial – marginal marine
Gumburo Sandstone	**Paleozoic**	Sandstone with overbank sediments	Fluvial
Bokh Shale		Lacustrine shale, siltstone and minor sandstone	Lacustrine with marine influence
Calub Sandstone		Arkosic sandstone and lithic conglomerate and sandstone	Fluvial with glacial influence
Basement Rocks	**Precambr ian**	Various basement rocks	

3.1.1 Tectonics in the area

The Precambrian basement rocks of south eastern and eastern Ethiopia consist mainly of high-grade Gneisses, Migmatites, metamorphic Granites and low grade rock assemblages (Mohr 1963; Kazmin 1972). Some geologists have classified the high grade rocks as a part of the Mozambique belt rocks and the low grade rocks as the Arabo-Nubian shield. With this in minds the Precambrian rocks of Ethiopia appear to be separated into these two belts, the Mozambique belt (from the south) and the Arabo-Nubian shield (from the north), which join together here.

The two main geological processes, the transgression events and the tectonic events of the rift system, were described by (Fekadu, 2005). The processes resulted in the deposition of a Mesozoic sedimentary sequence spreading over a large area from the eastern escarpment to the Ogaden Basin. The transgression started in the early Jurassic or late Triassic and continued until the Middle Jurassic with its continuation in the Cretaceous age. The sequence consists of Adigrat, Hamanalie, Uarandab and Gebredarre formations. Ethiopian volcanic provinces are broadly classified into Trap and Aden Series based on eruptions that took place prior or after the East African rift formation. In eastern Ethiopia both series are exposed. The pre-rift sequence occurs on the plateau while the Aden Series occurs on the rift escarpment and on the rift floor.

Geological and tectonic systems were shown on Geological map of Ethiopia at a scale of 1:2,000,000 (GSE 1978) and detailed work was performed by Tadesse and Workineh (2009) on the Geological map of the Harar map sheet at a scale of 1:250,000 published by GSE in 2009

3.1.2 Stratigraphy of Somali Region

According to the geological map of Ethiopia and Geological map of Webi Shebele and Harar sheet, the following stratigraphic units were mapped in Somali region from bottom-up. The local geological units of the study area can be characterized according to their Lithological characteristics (WWDSE 2013)

3.1.2.1 Precambrian Basement Formation

Basement outcrops are present in two major areas in Somali Region of Ethiopia—in Jigjiga in the north, and in the far south Liban zone near the Kenya border. In both the north and the south, basement consists of metamorphic rocks intruded by granite or granodiorite. The metamorphic rocks are gneiss, schist, quartzite, and marble.

3.1.2.2 Paleozoic

Up to 80m of sandstone have been recorded in pocket areas of deep valleys southwest of Harar, for example the Geletti. They are moderately cemented, coarse to fine grained and well bedded. Their lateral extent is small, and they appear to occupy erosion hollows in the underlying basement rocks. Southwards however they are of much greater importance as potential aquifer. At east of Somali region; Bokh 691.5 meter were met at Galadi 736.1 meter which was originally thought to be Adigrat but most of which is probably Paleozoic (Hadwin, Aytinaffisu and Mangesha 1979).

3.1.2.3 Mesozoic

Mesozoic sedimentary units of the area consist of rocks the following rocks from bottom to top: Adigrat – Lower sandstone, Hamanlie limestone and Amba Aradom – Upper sandstone (Tadesse and Workineh 2009). The thickness of these deposits ranges from less than ten meters in Jigjiga area to more than 2000 m in the Sinclair oil company wells in Warder zone both in Galadi and in Gunburo wells and other oil and gas wells in Korahe (Shilabo, El Habred, Calub, and Magan oil wells) and other oil wells in Afder Zone (Bodle and Hilo Quran oil wells).

a. Js. Lower (Adigrat) Sandstone Formation

Adigrat sandstone is the oldest sedimentary unit of the area and has a limited out crop distribution lying uncomfortably on the high grade Precambrian basement.

Adigrat sandstone is a non-fossil bearing sedimentary unit composed of conglomeratic sandstone, coarse to medium grained sandstone and mudstone beds, with rare development of fine sandstone. While coarser sediments are characterized by thick beds, fine sediments commonly show thin bedding and lamination. Cross bedding is also a common structure developed in the sandstones. The sandstone is friable. Red color dominants in the sediments with light grey beds to a lesser extent. The sandstone is also found with violet, yellow, grayish white and reddish brown colors (WWDSE, 2013)

Lithologically, the unit is divided into the lower part consisting of medium to coarse-grained sandstone with minor beds and lenses of conglomeratic sandstone, pebbly sandstone and conglomerate, and the upper part which is comprised of fine to medium grained sandstone interbeded with layers of siltstone, marl, mudstone and shale. The boundary between the lower and upper part is gradational. Drilling data, the Sinclair XEF-1 drilled 24 m of Adigrat composed of 12 m of sandstone, 9 m of shale, and 3 m of basal conglomerate. Oil test well drilled in Bodle Afder Zone, the largest thickness of 253 m of Adigrat Sandstone was encountered (WWDSE 2013)

b. Hamanlie Formation

This formation presents the first marine sediments formed by the first flooding of the sea in the area. The type section for this formation is near the village of Hananley in Somali region and there it is described as white to buff, well-bedded, mainly oolitic and fossiliferous limestone. The lower part is Callovian and the upper is Oxfordian in age; total thickness is 210 m.

In Somali Region of Ethiopia the Hamanlie outcrops in Jigjiga zone along Jerar and Fafan streams and Filtu district of Liban Zone. Drilling data for oil wells in Warder Zone by Sinclair Oil Company have penetrated a limestone-dolomite-anhydrite facies as much as 1,067 m thick in one well, the 1 Galadi. Other oil wells also revealed existence of huge thickness of Hamanlie Limestone Formation. On the basis of foraminiferal evidence, Quinqueloculina inconstans, Epistomina mosquensi, Cristellaria contrails, Lentlcullnapolonlca, the Hamanlie includes the Callovian Stage of Ae Jurassic, whereas the lower limit varies because the Jurassic seas reached different parts of East Africa at different times, but it may include Toarcian Stage deposits in some areas. The formation has upper and middle member.

The Lower Hamanlie: The lower limestone represents the majority of sedimentary rocks of the area. It is observed commonly overlying the lower sandstone but it is common that the lower limestone rests directly on the basement. Its contact with the overlying upper limestone is gradational which is marked by a planar smooth and corrosional hard ground surface and mud cracks. It is distinguished from the upper limestone by its relatively steep slope topography and well-developed drainage pattern. The color of the lower limestone is usually grayish yellow.

The upper Hamanlie: The upper limestone represents the stratigraphic upper most part of the carbonate sequence of the area. The limestone outcrops form flat-topped ridges and are characterized by karastic topography with well-developed sinkholes and caverns. Bedding ranges from massive to very thick with a common development of stylolites along the bedding plane.

Layers of limestone are light gray, light brownish gray, dark gray and creamy in color. The thickness of the unit varies from 0 to 85 m at Burka. Lithologically, it is composed of dominant micritic limestone with subordinate Dolomite, cherty limestone, black limestone and clastic sediment.

c. Uarandab Formation

The type section for this formation is near the village of Warandab in Somali region, where it is composed of 55 m of gray, brown, and greenish gypsum-bearing shale intercalated with gray argillaceous limestone in the middle part, and similar shale in the lower 15 m. Fossils are common with abundant Belemnites and many ammonites. This formation outcrops in large area of Fik zone such as Sagag and Gasangas areas. The formation also is present in most of the oil wells in Somali Region of Ethiopia and there it is mostly shale with a maximum thickness of 300 m.

d. Gabredarre Formation

The type section for this formation is near the Town of Kabredarre in Korahe Zone and there it consists of flaggy limestone, fossiferous in the upper 40 m, underlain by 20 m of thin-bedded alternating Oolitic and marly limestone with gypsum bearing shale, overlying 30 m of earthy ocher-colored limestone, and finally 60 m of gypsum. Below the gypsum are 130 of finely crystalline, yellowish, partly oolitic limestone grading downward into 40 m of yellowish and gray marl containing flattened ammonite impressions. Most of the oil wells in Ethiopia were drilled through the Gabredarre, and a maximum thickness was present in the Gumburo oil well 629 m where the Gabredarre is a limestone with shale members.

e. Main Gypsum or Korahe Formation

Near the end of Jurassic time the sea began to withdraw from East Africa, probably as a result of epeirogenic movement, and it left behind a large evaporate trough. In Somalia and southern Ethiopia this phase is represented by the formation known as the "Main Gypsum" or Korahe Formation.

In outcrop the Early Cretaceous is represented by the Main Gypsum and the type section is near Gabredarre town. This formation consists of 200 m of gypsum with calcareous, marly, and shaly intercalations. The age of the Main Gypsum at the type locality is determined by the ages of the rocks beneath and above it and is placed between Portlandian and Barremian Stages. However, local limestone and shaly zones have revealed an Early Cretaceous fauna consisting of Orbitolina discoidea and Choffatella decipiens. The Main Gypsum merges by intercalation with the overlying Mustahil limestone formation, but thickens from its outcrop in Somali Region toward the east and southeast of Gode and Afder Zone at the expense of the underlying Gabredarre.

f. Km- Mustahil Formation

The type section for this formation is near the town of Mustahil town, and consists of alternating white to yellow limestone, marly limestone and marl, light-colored marl and clay, lenticular rudist reefs, and at the top, gypsum. The Mustahil ranges in age from Barremian into Cenomanian. It merges by intercalation with the overlying Ferfer Gypsum and the underlying Main Gypsum; consequently its thickness is varied but is estimated to be about 200 m.

g. Kg- Ferfer Gypsum Formation

The type section for this formation is at the town of Ferfer near the Somali border. It is very similar to the Main Gypsum, but no fossils have been found in it. However, it overlies and is overlain by Limestones of Cenomanian age and is intercalated with both units. At the type locality the Ferfer is approximately 200 m thick.

h. Kb- Beletwein Formation

The type section for this formation is near the major town of Beletwein in southern Somalia. It is composed of 145 m of mainly limestone. The formation consists of, in descending order, 35 m of alternating white and yellowish bearing limestone, shale, and sandstone with some gypsum beds passing upward into the Jessoma sandstone; 25 m of similar limestone with some shale; 15 m of siliceous limestone; 20 m of alternating brown, calcareous, locally quartzitic sandstone and arenaceous limestone; and 28 m of pseudo nodular Limestone with abundant mollusks and echinoids with two Orbitolina zones at the top; 11 m of compact fine-grained whitish limestone in beds 0.2 to 1.0 m thick; 3.5 m of brown calcareous sandstone abundantly fossiferous; and at the base 7.5 m of alternating gypsum and cream to buff fossiliferous limestone. The lower part of the formation is late Cenomanian and the upper part is early Turonian.

3.1.2.4 Neogene sediments

a. Kj- Jessoma Formation

The type section for this formation is near the village of Yessoma in southern Somalia. The Jessoma is composed of red, brown, purple, and yellow; loosely cemented to quartzitic; fine to very coarse-grained sandstone with local gypsiferous beds at the base. Cross-bedding is prevalent. It is unfossiliferous but, from the ages of the rocks beneath and above, it is believed to include deposits of the Turonian and most of the Senonian. Its thickness at the type section is about 350 to 400 m. Jessoma Sandstone formation outcrops in area east of Jigjiga all the way to Warder Zone.

According to SHAAC (2009) the following Jessoma thicknesses were encountered in Sinclair Oil wells in Somali Regional State:

• 430 m of Jessoma sandstone were found in the XF-5 well located close Gorgor village of Gashamo district.

• 396 m of Jessoma in XE-5 located close to Daratole district.

• 374 m of Jessoma was found in XEF-1 oil well located close to Koratunje village in Warder District.

Based on the above illustration, the thickness of Jessoma sandstone increases from east to west and northwest.

b. Ea- Auradu Formation

Paleocene is represented by the Auradu limestone, and the type section is in northern Somalia in the Nugal Valley where the Auradu attains a thickness of up to 550 m. It is a finely crystalline, compact, hard, usually tan to light-brown limestone with local thin gray shales. It contains shallow-water Foraminifera such as Lockhartias, Sakesarias, Alveolinas, and Nummulites.

The age of the Auradu limestone in outcrop includes the Paleocene and the Ypresian and part of the Cuisian Stage of lower Eocene as indicated by the presence of Lockhartia tipperi, Nummulites somaliensis, and Daviesina danieli.

In Somali Region of Ethiopia, the Auradu limestone outcrops eastern part of Warder Zone and the Sinclair wells in Warder Zone, has penetrated a maximum thickness of 399 m of Auradu limestone was found in the XE-3A well located Close to Bokh town.

3.1.2.5 Upper Oligocene-Quaternary Qb-Volcanic Flows

Finally, the lithostratigraphic sequences outcropping in the region are those of Upper Oligocene-Quaternary. Undifferentiated volcanic rocks are outcropping in Shinile zone. The basalt flows have been dated as Oligocene to Miocene (Mohr 1963), although basalt flows in the great rift valleys have been dated as Late Cretaceous into Oligocene (Swartz and Arden 1960). According to the previous study, the thickness of the volcanic flows in Shinile zone is 50-200 m.

a. Qa and Qc (Alluvial and Colluvial Deposit)

Alluvial and colluvial deposits are found along the structural valleys and in the dry streambeds. Alluvial deposit in the dry stream courses yields water for domestic use. The alluvial deposits can yield good quality and quantity of water that can be used both for domestic and livestock use. All the hand-dug wells in the region are located within this unit.

3.2 Geology of the study area

Field visit to the study area and observations was mainly done along road cuts and quarry sites to have a quick look of various Lithological units such as Precambrian basement rocks, Mesozoic to Neogene sedimentary rock successions, limited Neogene volcanic rocks and superficial deposits; as well as primary and tectonic geologic structures so as to characterize and assess geological conditions for groundwater potential assessment of the study area.

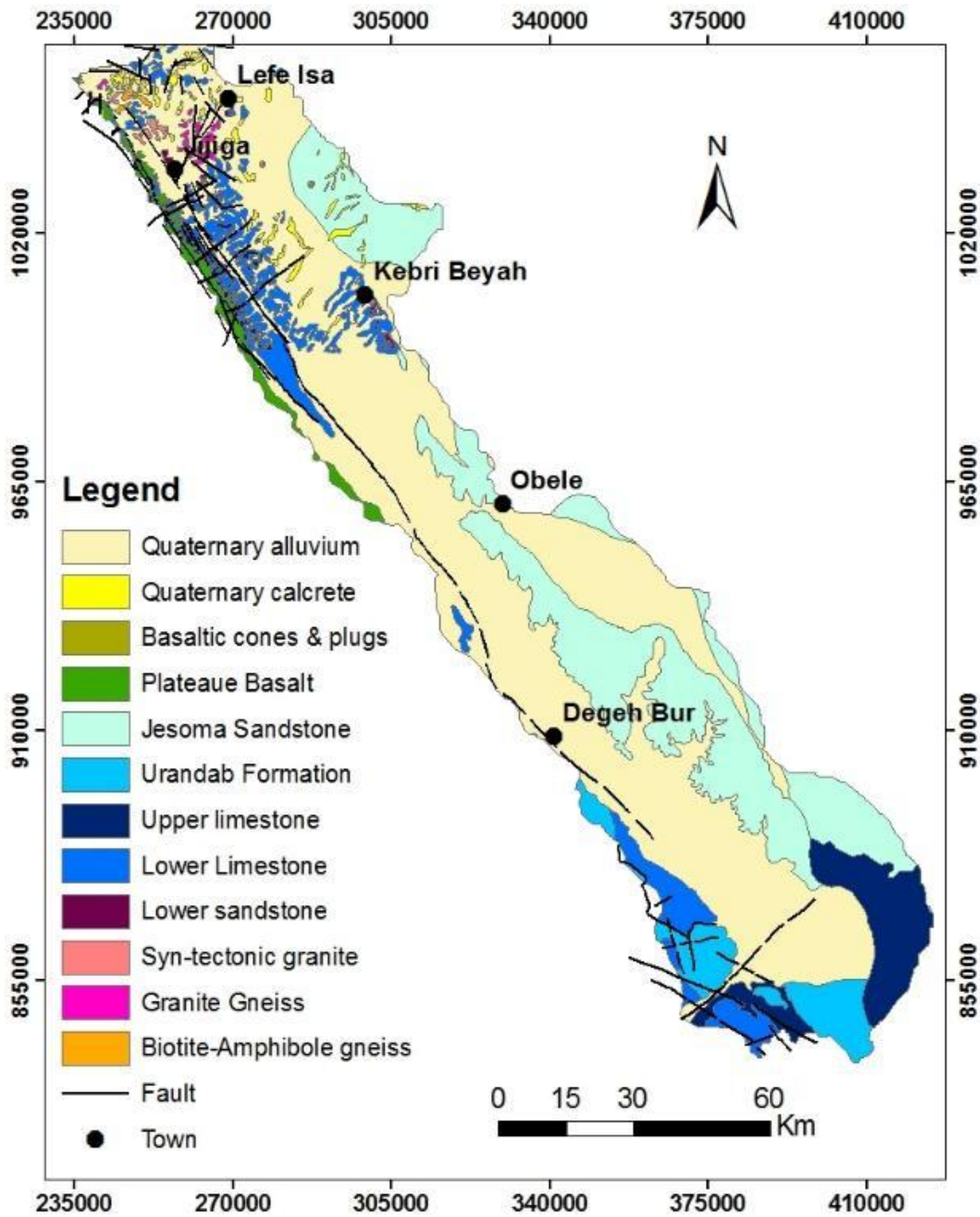


Figure 3.1 Geological map of study area

3.2.1 Lithology and Stratigraphy

3.2.1.1 Precambrian Basement Rocks

The Precambrian basement rocks are exposed in the northeast to northwest of Jigjiga town. The basement rocks exposed in the area include granodiorites with associated gabbroic bodies, granitic gneisses, granodiorites and different generations of granites. The map units including the minor lithologic components to occur in the area are briefly described as follows.

Figure 3.2: Highly fractured basement rock found to occur at the eastern foothill of Karamara mountain range

3.2.1.2 Mesozoic sedimentary succession

The Mesozoic sedimentary rock successions unconformable overlie the Precambrian basement rocks in the northwestern part of the study area in the valley of Jerer. These rocks comprise mainly the Lower Sandstone and Hamanlie Limestone. The younger successions, mainly Urandab and Gabredarre formations, are found to occur on flanks of Karamara mountain range and further downstream on ridges separating tributary rivers entering Jerer and in Fafem valley as well.

a. Adigrat Sandstone

This sandstone unit is mainly exposed in the northwestern part of the study area in upper part of Jerer River valley and at the foot of Karamara mountain range. This sandstone formation is the oldest Mesozoic sedimentary succession in the study area and is found to occur unconformably overlying the Precambrian basement rocks. It is generally massive with inter-layering of horizontally bedded shale and mudstone particularly as observed at the foothill of Ilaalami Xiqo (UTM coordinates 218254 m E and 1031413 m N).

The lithological contact between the Lower/Adigrat sandstone and the underlying Precambrian high-grade gneissic and plutonic basement rocks wherever exposed is marked by unconformable relationship. At lithologic contact zones the underlying basement rocks are represented by deeply weathered, decomposed and friable basement rock materials. On the contrary the lithological contact between the Adigrat and overlying limestone is gradational as marked by gradation from sandstone – calcareous sandstone – sandy limestone – limestone; such relationship is observed not far from Jigjiga at Sheik Ali Gure area. This actually signify changes of sedimentary depositional environment, i.e. gradual deepening of the basin.

Variegated color (yellow, reddish brown, buff, whitish) Adigrat sandstone intercalated with mudstone and siltstone (Fig.3.3) is exposed at Sheik Ali Gure area south of Jigjiga town. The mudstones at places appear as lenticular (pinch and swell) due to sedimentation loading; and mudstone blobs and Fe-oxide rich layers are also not uncommon. The sandstone is arkosic with feldspars being kaolinized. The sandstone grades upward to calcareous sandstone and contains traces of fossils in siltstone and mudstone layers.

The coarse-grained and conglomeratic sandstone exposed in Jerer valley about a kilometer to the west of Degahbour town, under the bridge across Jerer River and extend for a couple of kilometers downstream following both banks of Jerer river, is considered as Adigrat or Lower sandstone as it is overlain by Hamanlie limestone (intercalation of micritic and dolomitic limestone with marly limestone) to the west of Jerer valley.

Figure 3.3: Poorly consolidated and unsorted Adigrat sandstone formation consisting of mudstone and siltstone, Sheik Ali Gure area .S. Jigjiga

b. Hamanlie Limestone

In the study area Hamanlie formation is found to occur at its type locality; i.e. between lower reaches of Fafem and Jerer Rivers; around Karamara mountain range and in upper Jerer valley. As observed in the Karamara mountain range, upper Jerer valley south of Jigjiga town the Hamanlie formation conformably overlies the Adigrat/Lower sandstone formation. The nature of the lithological contact between Hamanlie and Adigrat formation is gradational from sandstone – calcareous sandstone/fine sandstone or siltstone – shale and to sandy limestone – fossiliferous limestone (Fig.3.4). The thickness of the Hamanlie limestone is thin at places, particularly in the upper reaches of Jerer river where interplay of tectonic upliftment, mass-wasting, weathering and erosional activities removed the overlying succession and upper portion of the unit. Even at places the Mesozoic sedimentary succession is uplifted and completely weathered and eroded to expose the Precambrian basement rocks. However, where overlain by the Urandab formation the thickness of Hamanlie is estimated to be more than 250 – 300 m.

Figure 3.4 Hamanlie limestone containing abundant macro-fossils exposed about 5 km south of Jigjiga to the east of Jerer River.

c. Urandab Limestone

This unit is widely exposed in the study area and is mainly composed of intercalations of gray shale consisting abundant macro-fossils (Fig 3.6.) gypsiferous and marly limestones. On outcrop scale the unit shows deep weathering which produce soft and easily collapsible rock materials. The unit conformably overlies the Hamanlie limestone formation.

Outcrops of shale, mudstone, micritic limestone (very thin) and gypsiferous layers are observed at Sandihile locality to the right side of Sasabane stream about 22 km from Degahbur town.

It is overlain by Gabridehar formation which is not mapped in the study area

Figure 3.5 (a) Shale, mudstone and gypsiferous limestone; (b) exposure of macro-fossils in Urandab unit, mainly mudstone

3.2.1.3 Neogene Volcanic and Sedimentary Rocks

The Neogene volcanic and sedimentary rocks in the study area are represented mainly by basaltic rocks exposed along the prominent Karamara mountain range and Jessoma sandstone underlying the flat-lying plain areas situated to the east of the Jerer valley.

i. Karamara volcanic basalt rocks

Karamara basaltic volcanic rock occupies the top part of the Karamara mountain range which occurs between the upper to middle reaches of the Fafem and Jerer rivers. The linearly arranged outcrops of Karamara basalt trends in NW – SE direction paralleling the Marda fault zone. It is presumed to be channeled and erupted through the Marda faults capping the Mesozoic sedimentary succession. The Karamara basalt is generally aphanitic in texture exhibiting crude/broad and less developed columnar joints. The joints range from about less than 10 cm to about 30 – 40 cm and the rock is commonly used as quarry sites for construction materials.

At places the spheroidally weathered aphanitic basaltic outcrop is found to occur at lower elevation suggesting flow of basaltic lava on irregular surface paleogeography. Inter-layering and intermingling of basalt and sandstone where the Harer – Jigjiga highway crosses the Karamara mountain range.

ii. Jessoma Sandstone

The Jessoma sandstone unit is dominant rock unit found to occur in the study area. This sandstone map unit underlies the eastern-half and southeastern parts of the study area particularly east of the Jerer River valley (see Fig.3.8). The unit is mainly drained by left side ephemeral tributaries of lower-reach of Jerer and streams of the Ogaden Basin.

Jessoma sandstone is characterized by variegated sandstone layers intercalated with frequent layers of shale and claystone as observed in the northeastern.

Figure 3.6: Jessoma Sandstone as exposed at a quarry site, Haroressa area

3.2.1.4 Superficial Deposits

a. Eluvial Deposits

Calcrete or carbonate concretions reaching up to 4-5 m in thickness are encountered covering the Jessoma Sandstone in northeastern part of the study area. These superficial deposits are formed as results of fluctuating groundwater level and evaporation in largely arid to semi-arid climatic conditions prevailing in the study area. The presence of relatively impervious calcrete/caliche or hardpan deposits may reduce or prevent recharge of groundwater.

b. Alluvial Deposits

Considerable alluvial deposits, which range from silty clay overbank floodplain sediments and fine-coarse sand channel deposits. The thicknesses of the alluvial deposits vary from place to place. Results of previous and current well drilling in the valley indicated the maximum thicknesses of the alluvial deposits range from ~40 m to ~70 m. As the major source of the alluvial deposits are the basement rocks in the upper Jerer, the size distributions of the alluvial sediments gradually decrease downstream suggesting dominance of silty clay or clayey silt in middle and lower valley.

3.3 Geologic structures of the study area

3.3.1 General

In the study area a number of mapping units categorized into Precambrian basement, Mesozoic sedimentary succession, and Neogene sedimentary & volcanic rocks subject to diverse geological and structural evolution are documented and shown in the geological map of the study area (Fig 3.1). The road cuts, quarry sites and river/stream banks present fresh rock exposures where meso scale structures could be observed.

From geology point of view groundwater potential assessment is mainly based on two important properties of rocks, namely porous media and fractured rocks. As such geologic structures particularly faults/fractures are considered significant for groundwater potential study and are interpreted from large scale satellite imagery and verified in the field at selected localities.

Some of the major structures observed in the Precambrian crystalline basements, Mesozoic sedimentary strata, and Neogene sedimentary/volcanic, e.g. Jessoma sandstone and Karamara basalts as well as other volcanic rocks, are briefly described as follows.

3.3.2 Precambrian Basement Structures

Strongly deformed and sheared Precambrian basement rocks showing strong alignment of structural fabrics are observed and underlying the Adigrat sandstone on eastern flank of the Karamara Mountain range.

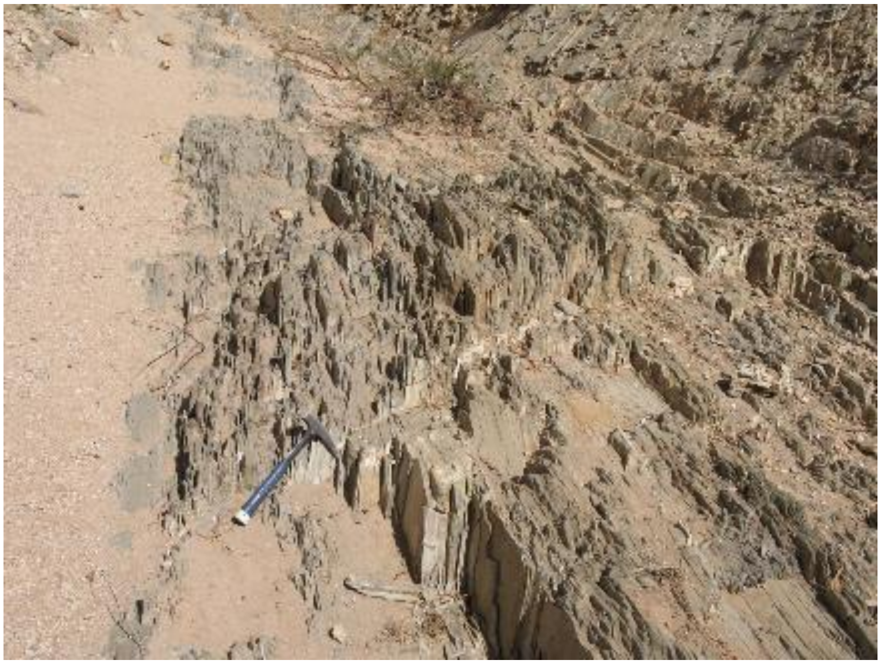


Figure 3.7 Precambrian basement rocks immediately underlie the Mesozoic sedimentary succession

Generally as the basement rocks experienced ductile deformation at great depth the fresh rock outcrops exhibit tight shear zones without open fractures. On the contrary, the open fractures are recognized in the basement rocks towards the top parts which were affected by surface weathering actions and/or where affected by Paleozoic – Mesozoic and Neogene rift tectonics.

3.3.3 Structures in Mesozoic Sedimentary Rocks

At the lithologic contact between the lower sandstone and the overlying Hamanlie Limestone Formation frequent intercalations or lamination of fine-sandstone, siltstone, shale and marly limestone are encountered during the field visit at the foot of Karamara mountain range and south to southeast of Jigjiga Town.

The Mesozoic sedimentary rocks exhibit horizontal bedding and laminations often intercepted by joints and fractures (e.g. Fig.10). Such vertical to sub-vertical fractures/joints are commonly observed in the Mesozoic sedimentary succession.

Figure 3.9 Fractured and horizontally bedded oolitic/pisolitic limestone exposed at Sasabane area nearby Hamanlie type locality

The thicknesses of the Mesozoic sedimentary strata increase downstream towards the confluence of Fafem and Jerer Rivers at Birkod area. However, Adigrat sandstone is exposed south of Degahbour to the west of Jerer River valley it is suggested that upliftment occurred in the area.

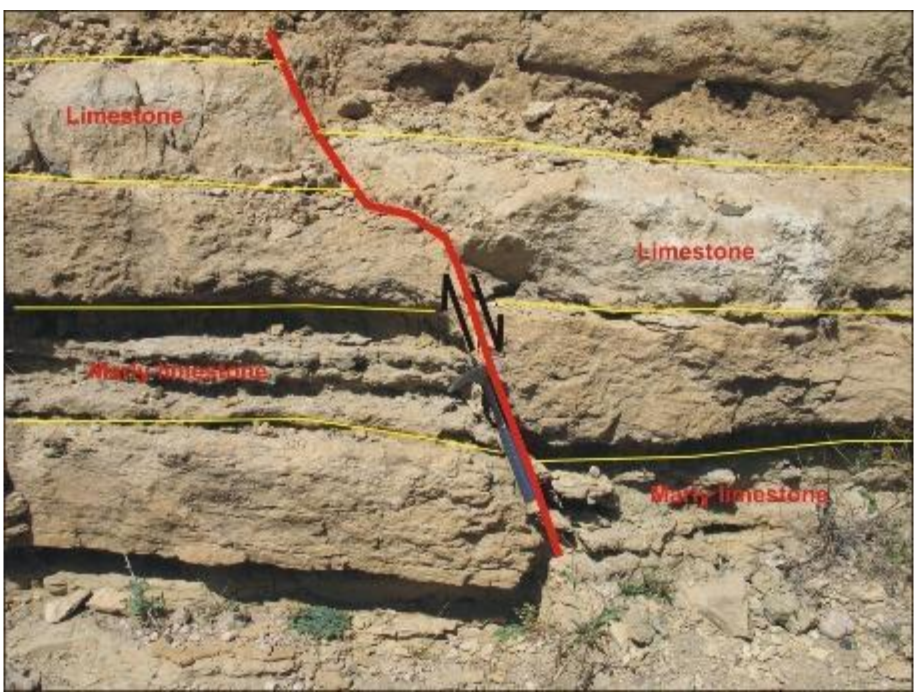


Figure 3.11. Normal fault as observed in the Mesozoic sedimentary rocks, at the foot of Karamara range in the Harer – Jigjiga road cut.

The Mesozoic sedimentary strata exhibit high density of lineaments indicating occurrence of frequent jointing and fracturing as well as faulting particularly related to Marda Fault Zone. The interplay of these structures is important in the control of recharge and flows of groundwater.

Density analysis of the lineaments indicates occurrence of large concentration of fractures/faults in the Mesozoic rocks particularly found to occur between Fafem and Jerer Rivers paralleling the Karamara mountain range. This area is expected to have extremely high recharge to groundwater as a result of the high density of fractures and faults. These fault/fractures extend as far as Jerer Valley and create potential channels to transmit or conduct groundwater.

3.3.4 Structures in Neogene Sedimentary and Volcanic Rocks

Neogene sedimentary (Jessoma sandstone) and volcanic rocks underlie large part of the groundwater potential assessment study area and occupy almost the entire area to the east of Jerer River and top part of the Karamara mountain range.

Lineament analysis of the areas underlain by Jessoma sandstone and Neogene volcanic rocks exhibit less fracture density as compared to areas underlain by Precambrian basement rocks and Mesozoic sedimentary strata. However, this doesn't necessarily imply that the rocks are less fractured or affected by tectonic movement. Area underlain by Jessoma sandstone as well as Adigrat sandstone and Hamanlie limestone (exposed north to southeast of Jigjiga) are often covered by calcrete and elluvial deposits (Fig.) which obscure the occurrence of faults/fractures. At places hardpans are well formed and such features may hinder recharge of groundwater.

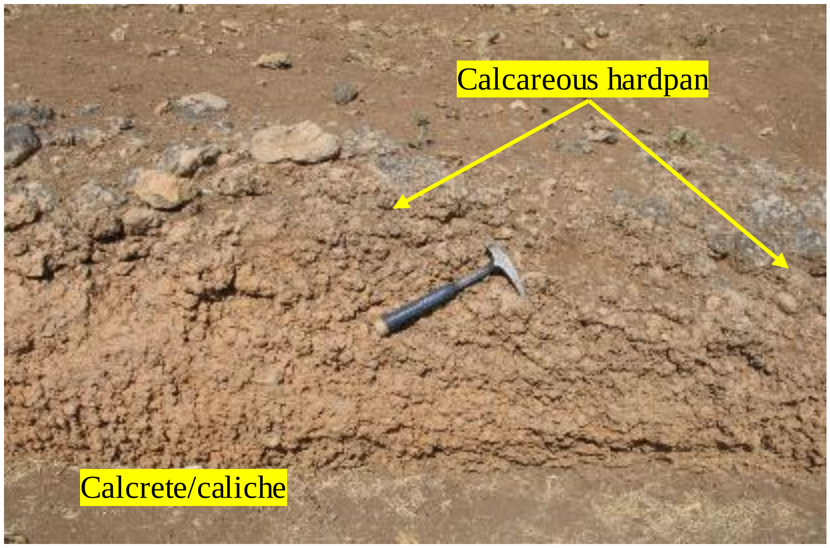


Figure 3.9 Hard pan and caliche/calcrete occurring ubiquitously covering the Jessoma sandstone

Intercalation of sandstone and basaltic rocks is observed in Karamara mountain range in a cut of Jigjiga – Harer road and quarry sites. These assemblages seem to have been created by intrusion of basaltic lava as dykes and sills. However, the presences of basaltic boulders in the sandstone suggest syn-depositional volcanism or reworking and intermingling during volcanism.

CHAPTER 4: HYDROMETEOROLOGICAL ANALYSIS

4.1 General

Hydrometeorology is the study of the two fundamental phases in the processes of hydrological cycle (precipitation and evaporation) within the atmosphere and at the earth's surface or atmosphere interface (Shaw 1988).

In this chapter, since the data of the study area both in space and time is very limited, efforts were made to present the general overview of the hydrometeorology and surface water resources. Hydrometerological data is used mainly to understand the role of the various climatic and hydrological factors in recharging the groundwater systems.

There is little number of meteorological stations in the area. Based on these scarce and incomplete climatic records, the hydrometeorology of the Jerer valley is characterized. The meteorological stations are placed in few urban centers. Monthly river discharge data was not obtained from the Ministry of Water Resources. Only two years of incomplete daily data of upper catchment was obtained from some other literatures. Since the obtained data displays large variations in discharge it was disqualified and calculation of the groundwater recharge was done based on the ungauged river.

In general meteorological data like precipitation, temperature, wind speed, evaporation, sunshine hours and relative humidity are key instrumental parameters to the study of groundwater recharge, runoff and evapotranspiration. Hence proper organization and analysis of such data is critically important for water resource investigation.

Table 4.1: Inventory of meteorological data types

No	Station	Temperature	Rel. Hum	Sun hrs	Wind speed	Precipitation
1	Chinacsan					2004-2014
2	Degahbour	1990-2014	2010-2014	2011-2013	1991-2005	1990-2014
3	Harshin	1990-2013				1990-2013
4	Jigjiga	1990-2014	1999-2014	1999-2014	2000-2012	1990-2014
5	Kebribeyah	2011-2014				2011-2014
6	Kebridehar	1990-2014	2010-2014	2011-2014	1992-2002	1990-2014
7	Hadow					2001-2011
8	Lafa Ise	2009-2013				1990-2013

4.2 Measurement of Precipitation

Precipitation is expressed in terms of the depth to which rainfall water would stand on an area if all the rain were collected on it. Thus 1 cm of rainfall over a catchment area 1 km^2 represents a volume of water equal to 10^4 m^3 (Subramanya, 2013). In order to observe the variation in rainfall within the study area, rainfall data was collected from seven measuring stations namely; Chinacsan, Jigjiga, Hadew, Kebribeyah, Lefe Ise, Obele and Degahbour. The rainfall measured by rain gauge, represents the depth of rainfall that has been occurred at a particular point: not the areal rainfall. For determining the mean areal precipitation of a given watershed, the rainfall data of various rain gauge stations are collected and analyzed. The mean areal precipitation is required for computing the runoff of catchment area.

Generally, the authenticity of rainfall data for computing the mean areal rainfall depends on the following points.

1. Areal distance between rain gauge stations and center of the representative area
2. Topographical characteristics of the area
3. Size of the watershed
4. Characteristics of the storm pattern and
5. Nature of the rainfall

To convert the point rainfall values at various stations into an average value over a catchment the following three methods are in use:

I. Arithmetical mean method

II. Thiessen polygon method

III. Isohyetal method

However, for this specific research only the arithmetic and thiessen polygon methods have been used to compare with.

I. Arithmetic mean method is used commonly when large number of rain gauges is uniformly distributed in catchment; rainfall does not differ very much among the rainfall of various rain gauge stations and the topography is nearly flat. The mean precipitation depth is the averaged value of the stations. The arithmetic mean is simply the statistical averaging of the series/stations.

The arithmetic mean method is given by:

$$P_{mean} = \sum_{i=1}^{n} Pi/n \text{ .... Equation 1}$$

Where:

P_{mean} = the mean value of Precipitation (mm),

n = the number of rain gauges in the meteorological stations,

P_i = the amount of precipitation (mm).

Table 4.2 Arithmetic mean of areal depth of precipitation

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual (mm)
Jigjiga	13.44	18.57	43.92	100.81	80.43	38.13	65.01	81.02	85.79	44.3	16.86	8.5	**596.78**
Obele	7.21	2.03	29.5	73.25	67.68	23.3	4.9	3.29	49.3	67.18	15.86	6.5	**350.00**
Jinacksan	15.22	5.99	75.97	123.21	47.55	36.36	85.44	109.49	78.83	37.2	30.49	1.17	**646.92**
Kebribeyah	18.68	20.9	45.33	79.67	87.73	29.2	39.9	90.33	83.94	75.5	47.4	11.32	**629.90**
Aware	7.21	2.03	29.5	73.25	67.68	23.3	4.9	3.29	49.3	67.18	15.86	6.5	**350.00**
Birqod	7.21	2.03	29.5	73.25	67.68	23.3	4.9	3.29	49.3	67.18	15.86	6.5	**350.00**
Hadew	3.58	4.17	26.1	82.54	96.76	67.8	58.62	83.68	63.35	44.67	14.6	7.08	**552.95**
Degahbur	3.21	2.03	17.7	73.25	67.68	17.16	2.9	5.29	39.7	65.7	16.88	9.5	**321.00**
Lafa Ise	13.22	23.86	55.14	101.77	96.99	64.28	129.93	147.22	81.14	31.07	12.09	12.53	**769.24**
Average	**9.89**	**9.07**	**39.18**	**86.78**	**75.58**	**35.87**	**44.06**	**58.54**	**64.52**	**55.55**	**20.66**	**7.73**	**507.42**

Therefore, as per the above table, the annual average areal depth of precipitation is found to be **507.42** mm using the arithmetic mean method.

For long years mean precipitation trend of the three main meteorological stations located inside the boundary of the study area shows bimodal type of rain.

II. Thiessen polygon method is used when a few rain-gauges are located in and around the catchment. The first step in the Thiessen polygon method is to connect all the rain gauge by straight lines so that no lines form an angle greater than 90 degrees. Next, perpendicular bisectors of the first line were constructed. The bisector should intersect within the triangular areas. The area of each polygon within the catchment is divided by the total area and expressed as ratio. The area ratio multiplied with the rainfall amount for each polygon gives an estimation of the rainfall over the watershed. This method has been applied for all sub-basins delineated in the study area. As per the Thiessen polygon method, the areal precipitation expressed as:

$$P_{mean} = \sum_{i=1}^{n} P_i * A_i / A \quad \text{......Equation 2}$$

Where: P_{mean} = areal precipitation over the sub-basin (mm);

P_i = precipitation depth in each station (mm);

A_i = area of each polygon (km^2);

A = total watershed area of sub-basin (km^2).

According to the Thiessen polygon method, the mean areal rainfall of the study area is **446.27** mm.

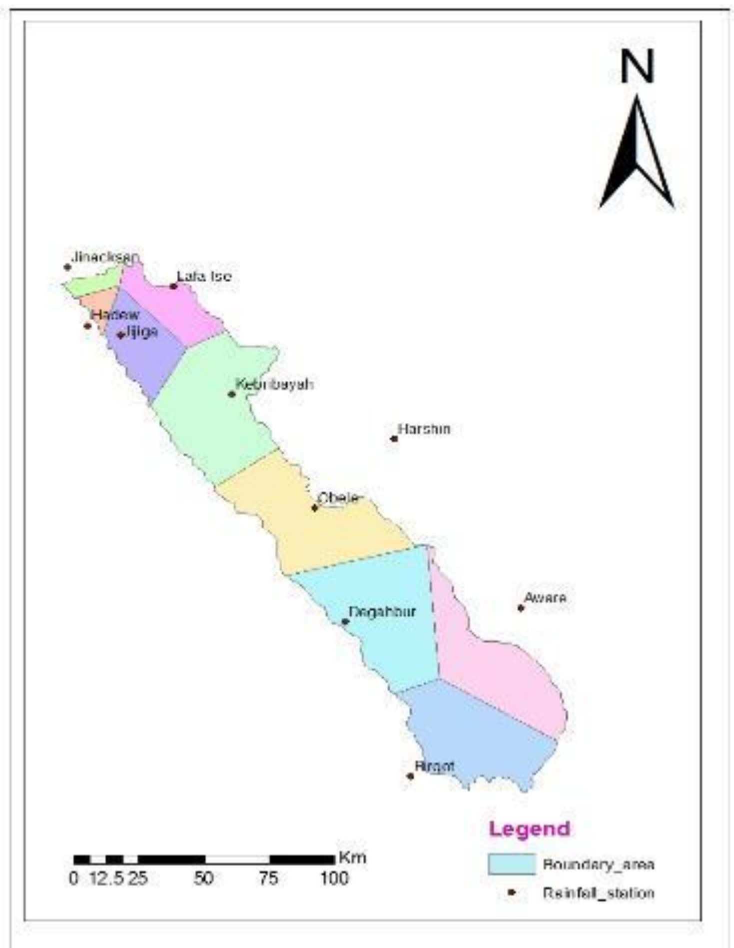


Figure 4.1 Thiessen Polygon of the study area and Locations of meteorological stations

Table 4.3 calculation of Thiessen polygon of the study area

Station	Rainfall (mm) Pi	Area (km2) A	Polygon Area (Ai)	Pi*Ai
Jigjiga	596.8	787	7.28	4344.70
Kebribeyah	629.9	1975.68	18.27	11508.27
Chinaksan	646	157.84	1.46	943.16
Hadew	637.8	150.64	1.39	886.54
Obele	350	1833.4	16.95	5932.50
Degahbur	321	2042.32	18.88	6060.48
Aware	350	1576.02	14.57	5099.50
Birqot	350	1665.1	15.4	5390.00
Lafa Ise	769.24	627.06	5.8	4461.59
	4650.74	**10816**	**100**	44626.75
Average areal precipitation (mm)		**446.27**		

4.2.1 Relation between altitude and precipitation

Generally, it is known that there is a correlation between annual rainfall and altitude (Table 4.4) and scatter diagram does show some correlation in the study area. The variation of period of the data and quality meteorology of data collection has an effect on the correlation. The relation between mean annual rainfall Y (mm) and elevation of the stations X (m) is **Y= 0.3736X-53.073 and R2 = 0.8797**

Table 4.4: Relation between altitude and precipitation

No	Name	Altitude(m)	Precipitation (mm/year)	Duration
1	Chinacsan	2007	646.9	2004-2014
2	Degahbour	1070	321	1990-2014
3	Harshin	1441	553	1990-2013
4	Jigjiga	1775	596.7	1990-2014
5	Kebribeyah	1753	629.90	2011-2014
6	Hadow	1807	552.8	2001-2011

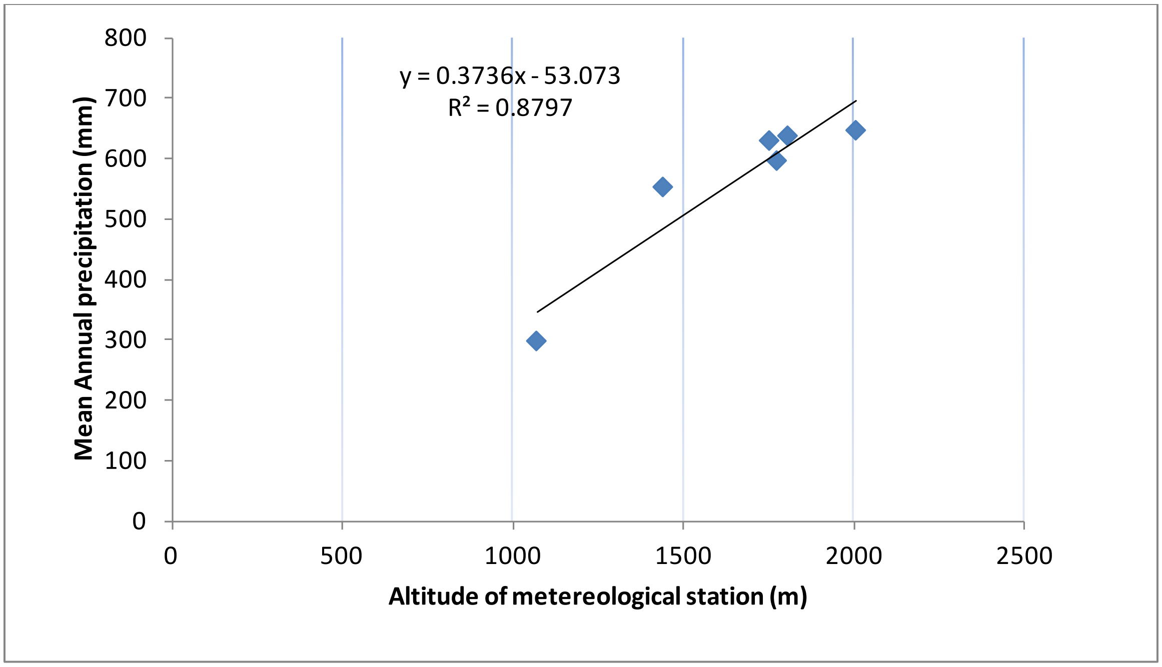


Figure 4.2: variation of precipitation with altitude

4.3 Evapotranspiration

Evapotranspiration (*ET*) is the loss of water to the atmosphere by the combined processes of evaporation from the soil and plant surface and transpiration from plants. Estimation of evapotranspiration is one of the major hydrological components for determining the water budget and is becoming indispensable for the calculation of a reliable recharge and evaporation rate for the groundwater flow analysis. Therefore, reliable and consistent estimate of evapotranspiration is of great importance for the management of water resources efficiently.

There are two types of evapotranspiration: Potential evapotranspiration (PET): the evapotranspiration from a vegetal cover if sufficient water supplied to obtain optimum growth or the maximum amount of vapor which might be transferred under the existing meteorological conditions (water is not the limiting factor). Actual evapotranspiration (AET): the evapotranspiration from a vegetal cover under the natural or given conditions of supply of moisture or the actual amount of vapor which might be transferred to the atmosphere, depends also on the availability of water to meet the atmospheric demand.

4.3.1 Estimation of PET

Estimating PET, involving equations ranging from the most complex energy balance method requiring detailed climatologically data (Allen 1989) to simpler method requiring less data

(Hargreaves 1982; Samani 1985). Among them, the FAO-56 based on the Penman-Monteith (PM) method (Allen et al. 1998) is currently used and is considered to be a standard method.

There are a few formulas which are more common than others. In this study will we just write about the Penman-Monteith formula because it's the most known and most used formula when it's about calculating evapotranspiration. The origin of the equation is the Penman equation and later Monteith developed the formula even more.

The method is of quite good accuracy and is usually used for calculations of evapotranspiration from farmlands. The good accuracy is due to all the parameters of the equation but still it isn't perfect. For instance, the r_s value is a constant depending on what kind of vegetation the area holds. If the equation is used over a large area with different kind of vegetation you have to estimate a value for r_s. The estimation gets even more non-accurate if the area contains spots without vegetation. (Ward 1999)

4.3.1.1 Reference Crop PET

The monthly values for the reference crop evapotranspiration (PET), as determined with the FAO Penman-Monteith method (Allen et al. 1998).

The most known formula for evapotranspiration is the Penman-Monteith formula,

$$E_T = \frac{\Delta R_n + (e_a - e_d)^* \frac{\rho^* c_p}{r_a}}{\lambda(\Delta + \gamma^*(1 + \frac{r_s}{r_a}))}$$

Where R_n = net radiation (W/m2)

ρ = density of air

c_p = specific heat of air

r_s = net resistance to diffusion through the surfaces of the leaves and soil (s/m)

r_a = net resistance to diffusion through the air from surfaces to height of

Measuring instruments (s/m).

γ = hygrometric constant

$\Delta = de/dT$

e_a = saturated vapour pressure at air temperature

e_d = mean vapour pressure

The reference evapotranspiration is a climatic index integrating the effect of air temperature, humidity, wind speed and solar radiation was calculated from two stations within the boundary of the study area; one is in the upper catchment and the other is in the lower; namely Jigjiga, and Degahbour. It expresses the evaporating power of the atmosphere. PET values in the two stations are very close with each other. However it is small in November through January in both stations. In Degahbour station the minimum PET of 88.8 mm/month was calculated in November while the maximum of 138.8 mm/month was recorded in March. The Jigjiga station the minimum PET of 98.89 mm/month was calculated in December and slightly rises through August 128.03 mm/month.

Hence as calculated by FAO Penman-Monteith method the annual reference Crop Evapotranspiration of Jigjiga and Degahbour are **1393.45** mm/year and **1417.86** mm/year respectively, while the average of the study area is **1405.6 mm/day**. The estimation of potential evapotranspiration of the Jerer valley indicates that it is much larger than the mean annual rainfall of the sub basin.

4.3.1.2 Thornthwaite Method

The Thornthwaite method is considered to be a popular method since it only requires monthly average air temperature and has been developed based on observations in limited climatic range (Tenalem et.al. 1998) .The method uses the following formula:

$$PET_m = 16\, N_m \left(\frac{10\, \bar{T}_m}{I} \right)^a mm \qquad (4.2.8)$$

where T_m- is the monthly mean temperature ^{0}c and N_m is the monthly adjustment factor related to hours of day light and m_c… is the months 1,2,3,4, …12

I –the heat index for the year, it is given by

$$I = \sum i_m = \sum \left(\frac{\bar{T}_m}{5} \right)^{1.5} \quad \text{for m=1…12} \qquad (4.2.9)$$

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

Table 4.5 Annual PET calculated by Thornthwaite method

Months	Jan	Feb	Mar		May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	PET mm/year
T_m (^{0}C)	20.98	21.73	22.53	22.88	22.94	22.51	21.68	21.83	22.37	21.62	21.23	20.86	
N	11.8	11.9	12	12.2	12.3	12.4	12.3	12.3	12.1	12	11.9	11.8	
N_m	0.97	0.98	1	1.03	1.05	1.06	1.05	1.04	1.02	0.99	0.97	0.96	
i_m	8.59	9.06	9.56	9.7	9.82	9.55	9.02	9.12	9.46	8.99	8.99	8.52	
I	110.38												
a	2.43												
	73.87	**81.30**	**90.60**	**96.84**	**99.37**	**95.82**	**86.59**	**87.25**	**90.87**	**81.16**	**76.08**	**72.17**	**1031.90**

Since the PET calculated by the Penman-Monteith cropwat is very much greater than the annual precipitation the average of the two methods, thus; Penman and Thornthwaite will be considered as the area PET (1405.6+1031.9)/2= 1,218.75 mm/year

4.3.2 Estimation of Actual Evapotranspiration (AET)

The mean annual actual evapotranspiration (AET) of the study area is computed using the formula of Turc, Langbein and Wundit, which is on the basis of data from mean annual precipitation in mm and mean annual temperature in ˚C.

AET is used to describe the amount of evapotranspiration that occurs under field condition when there is often not sufficient water available from soil moisture (Fitter 1996).

Turc (1954, 1955) is a widely used empirical formula to estimate the Annual values of AET for catchment areas which could be applied in both humid and arid climate either hot or cold.

$$\overline{E} = \frac{\overline{P}}{\sqrt{0.9 + \frac{\overline{P}^2}{[L(t)]^2}}}$$

$$L(t) = 300 + 25t + 0.05t^3$$

Where P is the mean annual precipitation (mm)

$L = 300+25T+0.05T^3$ (mm)

T= the mean air temperature (˚C) of the area

In this method, these results demonstrated that precipitation and Temperature could be the dominant factors in evapotranspiration (Shaw 1988)

For this computation, an average values of mean annual rainfall (P) and Temperature values (T˚) have been considered for the entire Area, so that mean Annual Rainfall amount for the area is **507.42** mm/year as obtained by the arithmetic mean of all stations located in and around the area. And similarly an average or mean value of Temperature (21.9 ˚C) is computed and assumed by a similar approach for the entire area. Based on this the annual actual evapotranspiration is given as follows: AET = **498.40 mm**

4.4 Groundwater recharge estimation

Recharge is the natural or intentional infiltration (percolation) of surface water into the groundwater system (Han 2010). The main mode of recharge of the study area is downward flow of water through the saturated zone reaching the water table. The main sources of recharge that are assumed are rainfall and seepage from the intermittent rivers.

Lack of proper estimation of groundwater is the main reason why groundwater exploitation and management have serious problems compared to surface water in the country. For proper estimation of recharge time series data of rainfall, runoff, evaporation are required. The first groundwater resource assessment was attempted over the whole Shebelle basin by WAPCOS 1990. However, the sub-surface drainage and recharge approach are very crude approximation. Base flow separation method may not give good result for the Ogaden part of the basin since the interaction of surface and groundwater is complex.

In the estimation of the groundwater recharge of Jerer river by different methods, the main limitation is that there is no time series water level monitoring data at any part of the sub basin to apply water level fluctuation method (recharge area approach) for recharge estimation.

Therefore, the recharge estimation methods applied for this study are as follows.

4.4.1 Rainfall Infiltration method

For area where adequate data is not available, recharge is estimated based on the rainfall infiltration factor method. The criteria recommended for the area on consideration of slope of the study area, land use/land cover and soil conditions is given below. And the geology of the project area is classified with geological material classification according to infiltration capacity of the rocks type for the estimation of groundwater recharge is shown (figure 4.1)

Norms:	**Recommended Infiltration values (WWDSE 2003)**
Recharge from Rainfall	
1. Alluvium	6%
2. Hard rocks	
- Granite – gneissic terrain	5%
- Basalt rocks	6%
- Sandstones and siltstones	5%
- Limestone	6%
- Gypsum beds	3%
- Shales/siltstone	2%

4.4.1.1 Delineation of Unit of Assessment in Sub–Basin

Since most of the basin area is occupied by hard rocks, the unit of assessment is taken as sub-basin or a catchment. Firstly out of the total geographic area of the unit, hilly areas (slope greater than 20%) are identified and deleted as these are not likely to contribute to groundwater recharge. However, the local topographic and geomorphological structures such as valleys, alluvial fans, plateaus and occurring within 20% slope zone are considered for recharge computation. With this regard, slopes of 100% basalts formations, 10% of the limestones, 5% of the sandstones and 2% of the Uarandab formation were found to be greater than 20% and hence not consider during calculation. The recharge form rainfall is given by;

Rrf = f x A x Rainfall

Where,

F = rainfall infiltration factor as estimated and assigned above

A = effective area of computation of recharge.

Hence according to the study area geological map the area is dominated by Alluvium, Limestone and sandstone. Previous calculations showed the annual areal depth of precipitation as being **507.42** mm/year.

Table 4.6 Calculation of recharge based on Ranifall Infiltration Factor

Litholgy	**area_Km^2**	**%**	**Infiltration coefficient**	**Annual Recharge (mm)**	**Estimated head rise after rains(m)**	**rainfall(mm)**
Alluvium	6095	56.9	0.06	15.22	0.5	507.42
Basement	63	0.6	0.05	12.69	0.5	507.42
Limestone	1328.4	13.8	0.06	14.22	0.5	507.42
Urandab	451	4.3	0.04	10.15	0.5	507.42
Sandstone	2302.8	22.6	0.05	12.68	0.5	507.42
	10240.2	98.2		**12.992**		
slope<20%						

According to (JICA, 2012) It is difficult to make absolute evaluation for the results of groundwater recharge values in Somali Region. As the sample of Africa area, the groundwater recharge values were estimated using the chloride mass balance (CMB) technique range from 15mm to 54mm in the area of average annual precipitation of 434mm (Bridget R Scanlon, et al, 2006).

Hence, based on the above findings by JICA and CMB technique, the estimated recharge value of the study area which lies in the above range seems well-matched.

CHAPTER 5 HYDROGEOLOGY

5.1 General

Hydrogeology can be defined as the study of ground water with particular emphasis given to its chemistry, mode of circulation and relation to geology environment (Davis & DeWiest, 1996). The occurrence of groundwater is mainly influenced by lithology, geological structures, and geomorphology and climate conditions. Lithology, geological structures and geomorphologic setting of the area strongly influence the quantity, quality and movement of groundwater. Since the climate condition throughout the area seems uniform, it has the same effect through the entire area.

The subsurface geological formations may be considered as "ware house" for storing water that comes from sources located on the land surface. Besides the origin, movement and chemical constitution of groundwater is controlled by the type of lithology, distribution, thickness and structure of hydrogeological units through which it moves. Man, through socioeconomic activities have also potential power to alter the natural groundwater flow systems and its quality Moreover, the stresses due to tectonics and weathering conditions govern the hydrogeochemical characteristics of earth materials. Therefore, acquiring knowledge about the existing aquifer materials, their spatial distribution and their hydraulic properties is a necessity.

The nature and distribution of aquifers, aquitards and aquicludes in geological system are controlled by lithology, stratigraphy, and structure of geologic deposits and formations.

5.2 Regional Hydrogeology

Tesfaye Chernet (1988) listed out 23 stratigraphic units in Somali region. Groundwater could occur in one or more aquifers of these units. Regionally, the aquifer types are: alluvial/colluvial sediments, fractured consolidated rocks such as metamorphic rocks, limestone, volcanic rocks, and sandstone and karastic limestone.

He has generally classified and presented the recharge condition to groundwater from rainfall on a map with scale 1: 2,000,000. The mean annual recharge from rainfall to groundwater estimation indicates that the region's recharge condition to groundwater falls under region 3 and 4. Recharge region 3 (which covers some part of Shinile zone) is characterized by mean annual recharge amount ranges between 50-150mm/yr whereas region 4 (which covers the Ogaden and

Shebelle basins) the recharge is less than 50mm/yr. Moreover, in region 3 the direct recharge from rainfall is moderate the recharge from runoff/localized along stream is moderate to high. The direct recharge from rainfall in region 4 is low but the recharge from runoff /localized along stream is low or moderate.

The important hydrostratigraphic units in the region are:

- Alluvial sediments with localized along stream recharge
- Fractured consolidated rocks
- Limestone with karst in nature

5.3. Hydrogeology of the study area

5.3.1 Characterization of aquifer systems and units

5.3.1.1 Aquifer Systems

Major Aquifer system classifications have been made from the hydrogeological patterns of the area for the depth of groundwater level in wells and aquifer units in relation to the prevailing hydrochemistry of the groundwater. This is based on the observation and analysis of all the compiled well log data and pumping test data for the existing wells in the study area.

The rocks and deposits forming the hydrogeological framework for a groundwater flow system are termed hydrogeological units. A hydrogeological unit has a considerable lateral extent and has reasonably distinct hydrologic properties because of its physical (geological and structural) characteristics. An aquifer is a geologic unit that can store and transmit water at rates fast enough to supply reasonable amounts to wells (Fetter 2001, p. 95). The water yielding materials in the Jerer valley consist primarily of unconsolidated alluvial deposits, consolidated (bedrock) carbonate rocks and sandstones that underlie the unconsolidated alluvium or are exposed directly at the surface may be a source of water if the consolidated rocks are sufficiently fractured or have solution openings (Gachet 2013).

Depth classification of the aquifers was done by the Ministry of Water Resources in 2013. Below is the proposed classification of aquifers in Ethiopia – made to make a distinction between the different shallow aquifers.

Table 5.1 Depth classification of aquifers (MWIE 2010)

Proposed name	Depth (meter)
Very shallow	0-30
Shallow	30-100
Deep	100-250
Very deep	>250

a. **Very shallow (**0-30m**) -shallow aquifer system (**30-100m**)**

This aquifer system extends throughout the Jerer valley in the dry stream courses and in the natural depressions. The aquifer unit consists of sand, gravel with some clay and in most cases it is found in a semi confined nature below a sandy clay layers and sometimes found in un confined. This situation is observed in the different shallow wells and open dug wells drilled along the river banks like the shallow wells in the northern Jigjiga town, and Degahbour town wells where a shallow sand and gravel aquifer system are encountered at a depth of around 30-90 meters. The alluvial deposits hold shallow waters which are being exploited by shallow hand dug wells with total depths ranging between 10 and 32 m and a static water level of around 8–30 m. Hand dug wells are dug along dry stream beds where thick sand is accumulated along the banks of Jerer stream and its tributaries. The alluvial deposits can yield good quality and quantity of water that can be used both for domestic and livestock. Majority of hand-dug wells in the study area are located within this aquifer.

In addition to the river sediments, the shallow aquifer system exists also within the weathered basement. Such weathered basement aquifers can reach a thickness of 40 m maximum with good yields if the nature of the basement is acidic (rich in quartz) and less productive if the basement is basic. Nevertheless, such aquifers are marginal and can only be used to supply fresh drinking water for small communities (Gachet 2013). Furthermore, shallow aquifer was encountered in the fractured quaternary volcanic basalts in the northern part of the study area and as was observed in the Degahbour borehole lithology 58-62m.

As observed from the lithology of southern Jigjiga well field Adigrat sandstone aquifer which is the main water bearing strata was encountered at a depth ranging 36-99m and the water table is 50-80m.

b. Deep Aquifer system (100-250 m**)-to Very deep** (>250 m**)**

Most boreholes in the study area tap water from deep aquifer system i.e. carbonate rocks and sandstones. The primary two deep aquifers of the study area are: Hamalie limestone and Adigrat sandstone. Both aquifers have high-quality aquifer due to fracture and karstification respectively.

There exists a big variation in the depth of occurrence in this aquifer system on the study area along the northwest- Southeast direction. As below cross section (from Gachet 2013) shows that these aquifers are shallow in the northwest of the study area around Jigjiga since the basement which acts as bottom barrier for the groundwater above it is close to the surface while the thickness and depth of these aquifers increases further into south, for example Limestone is very thin layer 38-56 m in southern Jigjiga well field, while it is about 90-180 m in Birkod, the southern tip of the study area. In the same way the groundwater level slightly declines as you move to south (fig 5.1). Adigrat sandstone aquifer was reached at 350 m in the new borehole drilled recently at Ararso by IRC and water struck at 270m while the SWL is 100. The BH has a yield (Q) of 15 l/s. This shows that most deep aquifers drilled in the Hamanlie and Adigrat formations are either confined or semi-confined immediately after Jigjiga upto the confluence of Jerer with Fafan in the downstream of the study area. The reason why boreholes in these formations are confined is that they are overlain by impermeable Uarandab formation which composes intercalations of gray shale, gypsiferous and marly limestones

c. Aquitards

Both basement and the Uarandab shale formations play the role of an Aquitards, with the assumption that the Karamara range basalts offer a tight waterproof wall all along Jerer river course, one can expect artesian water from the Hamanlie and Adigrat formations around a maximum depth of 400 m, starting from Obole well, 110 km south of Jigjiga; if the wells are cemented through the Uarandab formations, freshwater from the Hamanlie and Adigrat aquifers would be protected from the Gypsum pollution of the Uarandab seal as you can see from the cross section (5.1). Urandab formation thickens as you move towards southeast of the study area.

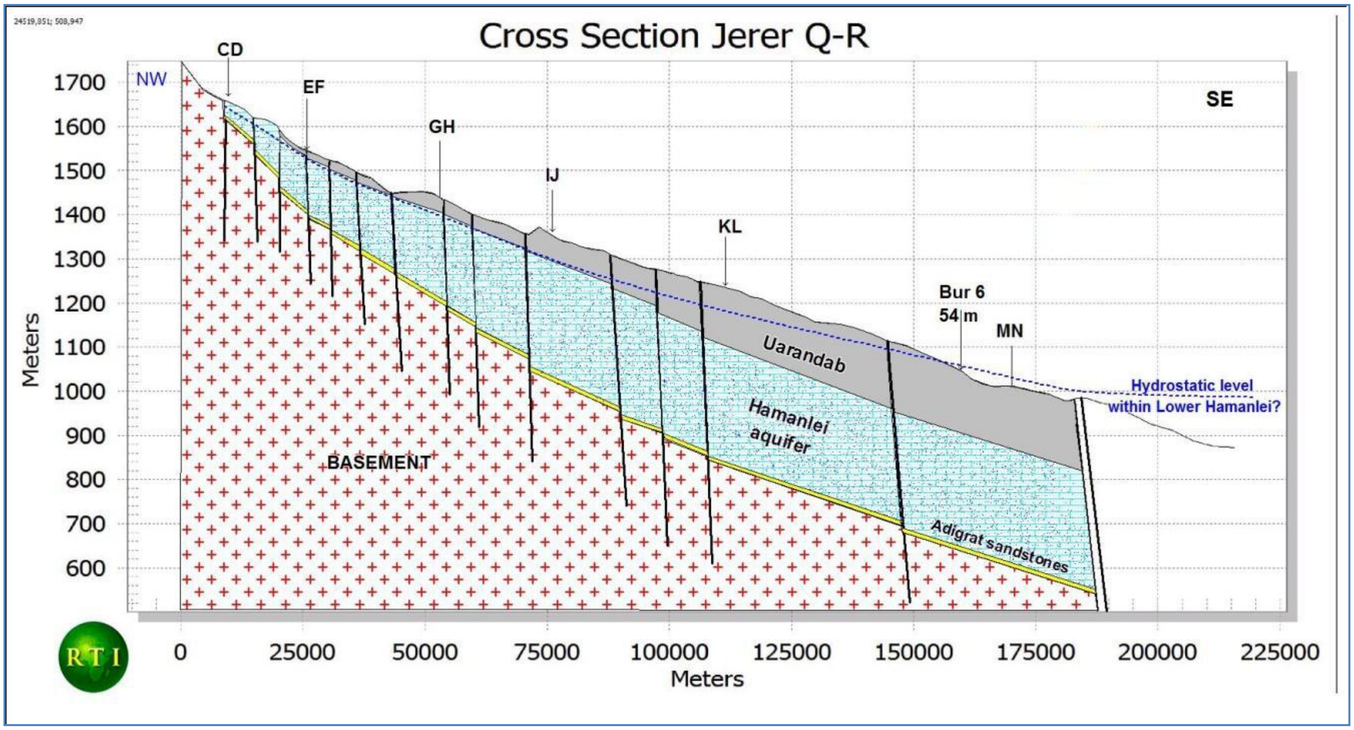


Figure 5.1 Cross section of Jerer valley (Q-R) from Jigjiga to Birkod, the southeastern end (Source RTI)

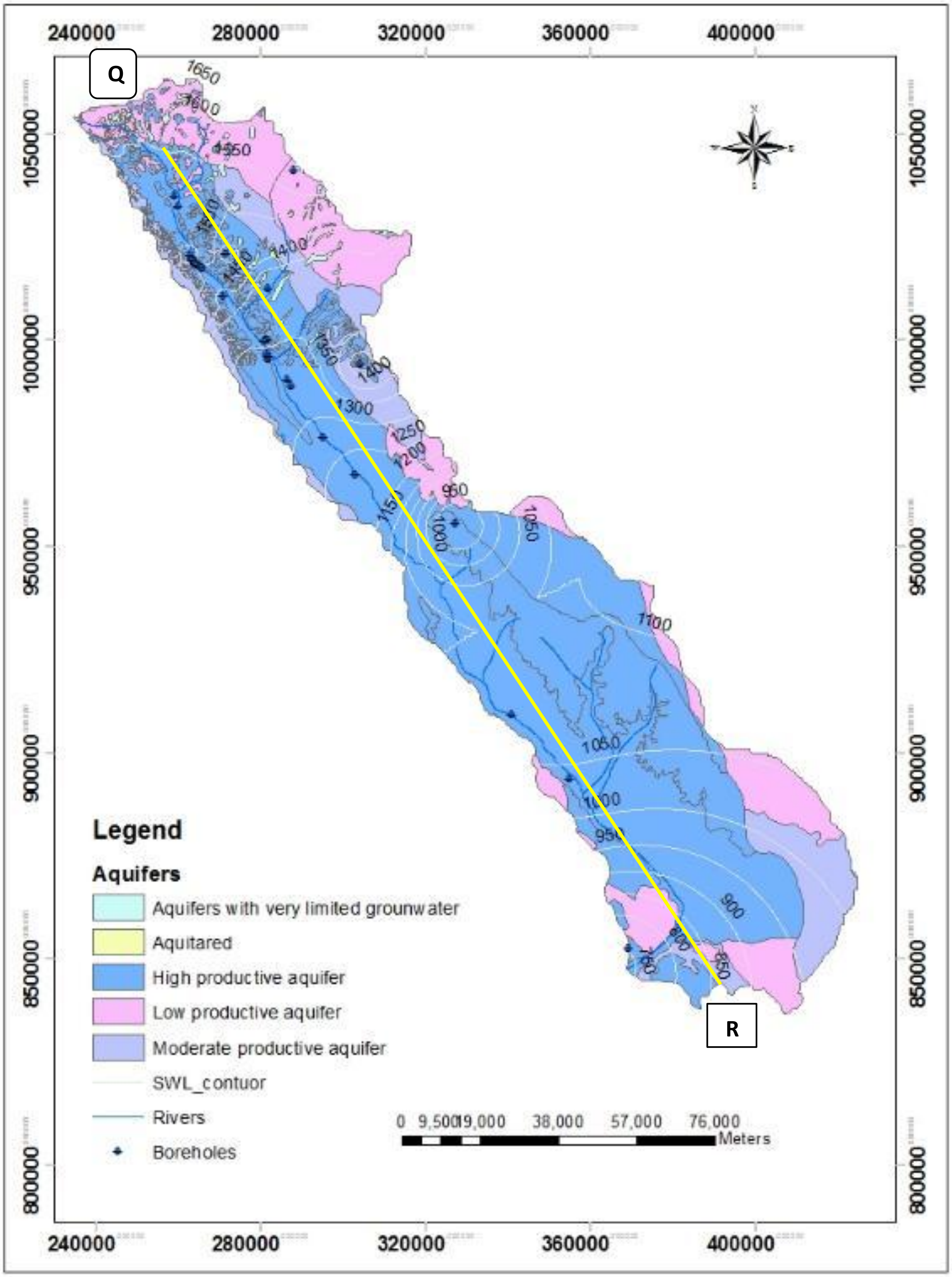


Figure 5.3 Hydrogeological Map of the study area

5.3.1.2 Characterization of aquifer units

The qualitative division of lithological units is based on the hydrogeological characteristics of various rock types using water point inventory data. The lithological units were divided into groups with dominant porous and fissured permeability and impermeable rocks. This division served for definition of the basin's aquifer/aquitard system. Since the quantitative data such as transmissivity, permeability, aquifer thickness and yield are not adequate or evenly distributed enough to make a detailed quantitative potential classification; analogy was used for characterization of rocks without the adequate number of water points. Hence, the hydrogeological characterization of the study area reveals the following aquifer/aquitard system:

I. High productive aquifers

The high productive aquifers are represented in the study area by the Adigrat (Lower) sandstone, Hamanlie limestone and quaternary deposits and expressed in the hydrogeological map in blue color.

- **Adigrat sandstone (lower sandstone)**

Adigrat sandstone is an important water source and as it extends beneath the lowlands without facies change it remains the most important potential aquifer of the whole region. Its thickness varies between 30-50 meters in the north and exceeds 150 meters in the southeast of Ogaden. This formation displays relatively high porosity and permeability, especially near the surface where it has been leached (Hadwin et al. 1973). Based on the lithology of the oil wells in Ogaden, the average expected thickness is 200 m, but in the Jerer valley, outcropping formations reach an average of 25 to 70 m only with an estimated porosity of 14% with well sorted quartz grains in the sandstones. This means that if well exposed to rainfalls, Adigrat sandstone block of $1km^2$, with a cumulated storage unit of 10 m (less than 50% of the lithological column) and a porosity of 14% can store 1.4 million m3 of water, or a volume of 1.4 m^3/m^2 (Gachet 2013).

This capacity can be increased if the Adigrat formations are well exposed to fractures which improve the recharge process and enlarge rock porosity and conductivity, which is the case in the Marda shear fault system environment (study area).

In any case, the recharge capacity is linked to rainfalls quantities, but the cumulative process working years after years is most likely creating huge opportunities downstream.

All the boreholes drilled in the southern Jigjiga have apparently targeted the Adigrat sandstones and weathered basement aquifers on the left bank of the Jerer river, at depths ranging from 115 to 128 m, reaching the static water level at a depth of 68 m. The yields range from 4 to 20 l/sec as shown below (table 5.2)

Table 5.1 Characteristics of wells drilled in Adigrat sandstone in Jigjiga well field

S/No	ID	Depth (m)	SWL (m)	Pump position (m)	T (M^2/day)	Q (l/s)	Maximum expected draw down (m)
1	BH1	128	47.47	109-115	5.8	5.43	88
2	BH2	127	65.94	110-116	16	7.02	98
3	BH3	133	73.9	113-119	91	21.96	88.9
4	BH4	123	70.79	105-111	73	17.57	100.79
5	BH5	127	68.3	108-114	97	22.91	83.3
6	BH6	115	64.16	97-105	97	24	70
7	BH8	127	67.72	110-116	28	11.94	82.72

- **Hamanlie Limestone formation**

The Hamanlie formation previously known as Hamanlie series is used for the fossiliferous limestone of Jurassic age of southeastern Ethiopia and the Ogaden region. The rocks in this series are predominantly limestone and dolomite having gradational contact with the Adi grat sandstone and with the overlaying Uarandab formation. Abundant fresh water has been met in many boreholes in outcrop areas (SHAAC 2010).

The limestone of upper and lower units of the Hamanlie formation represents major water bearing formation of the area. This formation represents highly productive fissured jointed and karstic aquifer in the area. In some places it is intercalated with beds of calcareous sandstones, siltstone and gypsum.

In the Mesozoic sedimentary units the water is accumulated in its weathered, fractured horizons and holes of solution cavities, caverns, fissures and sometimes in caves i.e. wide holes in which water flows very long distances with very high discharge like an underground river.

The limestone outcrops are clearly seen in big gorges, river valleys and sometimes ridges. The development of karst, the dominant phenomena in Hamanlie limestone, plays a significant role in groundwater flow. The deep groundwater level in Hamanlie limestone is most probably due to the lack of shale and mudstone intercalation that leads to deep vertical percolation of infiltrated groundwater.

According to the small amount of borehole data collected from the study area the depths of wells vary from 30 to 300 m, the static groundwater level varies from 30 to 100 m, transmissivity varies from 5–20 m2/day and yield varies from 2 to 6 l/s.

Boreholes drilled in this formation have good yield as in the case of well field which supplies water to the Kebribeyah town and Garbile borehole, 45km south of Jigjiga. The depth of this well is 200 m and reached the basement at a depth of 183m and confirms a 75 m thrust of the basement between the East side and the West side of the Jerer river. The static water level is 89.6 m and an aquifer thickness of 90 m, pumping tests have revealed that with a pumping rate of 4 lit/sec, the maximum draw down attained was 10.6 m and 94% of the water level was recovered in the first minute after the shutdown of the pump. The basement within the graben is overlaid by 37m of Adigrat sandstones and by only 130 m of Hamanlie limestone and 20 m of alluvial deposits.

According to the contractor SRS WWCE, the aquifer is highly fractured with development of good fissural and karstic permeability suitable for groundwater storage. Karstification of the limestone and fracturing are ideally in favor of direct infiltration by precipitations and run off in the rainy season.

Table 5.3 Characteristics of wells drilled in Hamanlie in Kaho well field Kebribeyah

BH ID	Depth (m)	SWL (m)	SCREEN		Q (l/s)	T (m2/d)	Specific capacity l/s/M
			start (m)	End (m)			
EB1	150.0	85.9	120.0	150.0	2.64	8.32	0.94
EB2	176.5	85.9	135.0	177.5	1.78	6.5	0.71
PB1	168.5	85.0	135.0	165.0	4.7	4.85	0.11
PB2	205.0	84.0	135.0	189.0	5.4	7.27	0.15
PB3	267.0	77.4	150.0	267.0	5.5	16.25	0.48

- **Alluvial deposits**

The alluvial deposits generally formed from fine to silty clay deposits derived from limestone and basement rocks crop out. They range in thickness from a few meters to a maximum of 36 m in the wells located south of Jigjiga town. These are thin blankets with soils derived from in situ alteration of underlying rocks. Furthermore colluvial deposits, alluvial fans characterized by heterogeneous grain size and irregularly distributed talus debris and alteration cover beds exist in some areas especially north and south west of Jigjiga. The alluvial deposits hold shallow waters which are being exploited by shallow hand dug wells with total depths ranging between 10 and 32 m and a static water level of around 10–30 m (Kebede 2013).

Usually, the layer of alluvial sediments along rivers Erer, Hamaresa/Gobele, Dakata, Fafem and Jerer with aquifer thickness of about 20 m has transmissivity ranging from 5m^2/day to 300 m^2/day (GSE 2010). These aquifers can be easily developed by shallow drilling. Where the thickness of alluvial deposits is insufficient for drilling the groundwater can be developed by shallow dug wells.

II. Moderate productive aquifers

Moderate productive formations are represented by the volcanic rocks and Jessoma sandstone and expressed in the hydrogeological map as light blue color.

- Volcanic rock (Basalt)

The basalt is exposed in the northern part of the study area and around Degahbour area. It is predominantly vesicular and is well fractured, columnar, jointed and weathered. The degree of weathering may be superficial or continue to certain depths. The upper basalt is also affected by E-W or NE running faults. Fractures play very important role in the movement and drainage of groundwater. They are fragmented and form boulders and therefore, can easily infiltrate water if there is adequate precipitation. From field observation, boreholes are found in this unit along fractured or deeply weathered zones. Boreholes drilled in Degahbour (Towlane) have shown a shallow aquifer of weathered Basalt with a yield of 5 l/s and Birkod areas have yield 3 l/s. The thickness of this aquifer varies from 28 m - 60 m.

- Jessoma sandstone

The Jessoma sandstone is variegated quartzose sandstone partly terrestrial and poorly cemented. It is categorized as extensive aquifer with intergranular permeability and moderate productivity. In these rocks, the depth to groundwater is quite high (100 to 300m and more). Because of unfavorable climatic conditions in the Ogaden area, the groundwater potential is very low. The discharge in some wells is about 0.6l/s (Alemayehu 2006).

III. Low Productive Aquifer

- **Basement rocks**

The basement rocks are classified as low productive fissured aquifer which occupies an area at the bottom of deep valleys along the Jerer in the northeast part of the study area.

In the Precambrian basement rocks the groundwater is accumulated or stored in the fracture openings, weathered parts, fractures and joints of the hard rock which may be closed at depth hindering deeper groundwater circulation and storage. Therefore, because of limited fracturing and jointing, small extent and impermeable nature of the rock, they have very little prospect of having sufficient water storage to be good regional aquifers. In the study area the Precambrian basement rocks are mostly found at depth overlain by Adigrat sandstone and Hamanlie limestone. The alluvial deposits associated with granite are believed to be good aquifers that store and transmit sufficient water. Boreholes drilled in the northern Jigjiga tap water from this aquifer. The depth in general is about 30m

5.4 Aquifer zones (Groundwater zones)

The zonation of groundwater aquifers in the Jerer valley is made based on available pumping test data, amount of recharge, topography and Lithological logs.

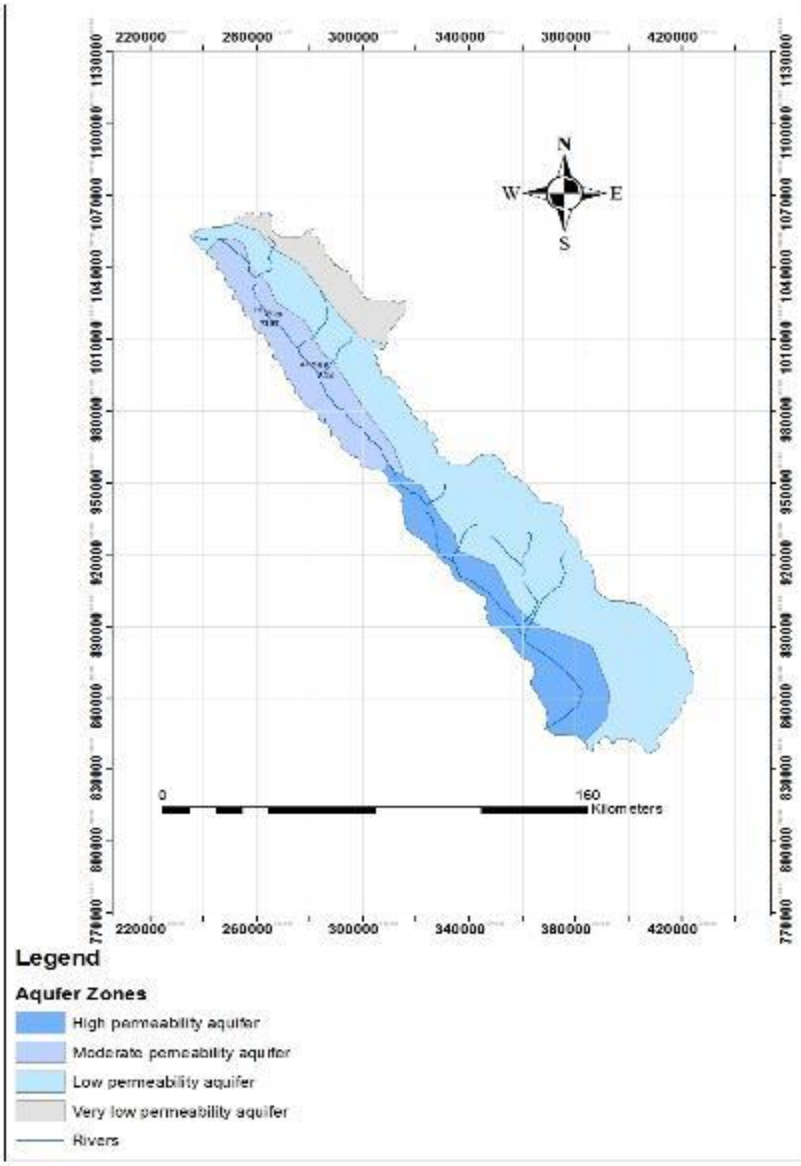


Figure 5.3 Map showing aquifer zones

Zone 1 High permeability zone

Based on the pumping test data Transmissivity value of this zone is greater than 97m^2/day and the elevation is 700-1000 m.a.s.l. Since this zone is the confluence of Jerer and Fafan it has very thick alluvial deposits covering large area. Hence it probably has highest river bank storage. The main aquifer layers are alluvial deposits underlain by karstified limestone. The zone is normally recharged by river wadis in addition to the direct recharge from precipitation. Boreholes drilled in this zone have a yield ranging 6-20 l/s.

Zone 2 Moderate Permeability zone

Based on the available pumping test data this has a transmissivity value ranging 70m2/day -97 m2/day. Borehole yield in this zone ranges 3-6 l/s. The topography of this zone ranges 1000-1500 m.a.s.l is little bit higher than zone 1. The recharge mechanism is direct recharge and floods from Jerer river.

Zone 3 Low permeability zone

Transmissivity ranges between 1-70m2/day and yield range 1-3 l/s. The zone is characterized by higher elevation and compacted lithology. As this zone is away from the Jerer stream the recharge mechanism is only from direct precipitation, as the river is in lower elevation all precipitation runs off towards the river.

Zone 4 Very low permeability zone

Transmissivity < 1m2/day the recharge is only from precipitation and the geology of the area is dominated by unfractured basement rocks. The elevation of this zone ranges 1700-1800 m.a.s.l. Boreholes drilled in this zone showed a very low yield of < 1 l/s.

5.5 Groundwater Recharge and Discharge

5.5.1 Groundwater Recharge

Like in the other areas, the groundwater recharge is mainly from precipitation depending on its intensity and annual distribution, topographical gradient of the area, lithological composition of aquifers and their tectonic disturbance. The groundwater of the higher areas generally gets recharged from direct precipitation. There is also a seasonal but significant amount of recharge to localized aquifers from most of the Tributaries as well as the main streams after the Kiremt rains when the level of stream is above the groundwater level. Aquifers along the river are recharged by the surface water of streams as the flow of the stream is controlled by structures. This type of recharge is important in the downstream lowland where evapotranspiration is higher and precipitation is lower than in the highland. This type of bank infiltration is very important for local alluvial aquifers and where most of the water well sites are located.

As rainfall is less than 500 mm over large area of the study area, direct recharge is clearly inadequate; vertical recharge that occurs is concentrated along the major valleys, especially in their superficial deposits and in fault gouge in valleys that are structurally controlled. In the mountains and foothills, erosion is so deep that recharged water soon finds its way towards valley axes, to become stream or subsurface wadi gravel flow (Hadwin et al. 1979)

Some boreholes in the cretaceous and Neogene rocks have taped fresh or slightly saline aquifers, many of these showing declining yields. On the evidence likely seems that the discharge from these boreholes exceeds recharge and the consequential decline is likely to continue even at modest pumping rates. Horizontal recharge provides the most dependable groundwater resources. Highland rain infiltrates vertically and laterally into the exposed karstified limestone and sandstone of the lower parts of the succession, and moves southeastwards beneath the younger gypsiferous formations. Karst is a unique hydrogeological terrain in which the surface water and ground water regimes are highly interconnected and often constitute a single, dynamic flow system (White 1993). The presence of karst usually is indicated by the occurrence of distinctive physiographic features that develop as a result of the dissolution of soluble bedrock such as limestone or dolostone (Field, 2002).

The most efficient sub watershed is the upper Jerer, which is dominated by Adigrat sandstone and Hamanlie limestone. According to the studies conducted by the RTI these two units can harvest drain and store 2 billion m3/year or at least 50% of the 4.1 billion m3 harvested on the complete Jerer watershed.

In such a favorable geologic and structural context, most of the rainfalls quantities on the highlands, upstream the Jerer watershed, are immediately swallowed by fractures and absorbed horizontally and vertically by the Hamanlie limestone and lower sandstone formations and conveyed underground, limiting the Evapotraspiration subtraction.

Such a scenario repeated for million years can contribute to the storage of very important freshwater quantities available downstream, within the main Adigrat and Hamanlie aquifers. As a result, the Jerer River hardly flows even during the rainy season because most of its water is quickly captured by fractures and absorbed by karsted limestones of the Hamanlie formation.

The Jerer River have average slopes of 3.3 to 3.8% thus indicating that this river basin have potential for the recharge and storage of groundwater along its length.

Figure 5.4 Jerer dry river bed during rainy season, downstream the Kaho wells (RTI report)

Recharge of the Jerer area was also recently determined by Addis Ababa University Department of Earth Science Isotope Hydrology Laboratory using stable Oxygen isotopes(Tritium) of water samples collected from three USAID/IRC drilled wells at Jerer valley (Ararso, Garawo, and Degahbour). Although it is difficult to use one sample to interpret sources of recharge, the oxygen-18 value of the Ararso sample was compared to local meteoric water lines to provide additional insight. Many factors can affect the isotopic composition of a sample and this interpretation is made with the assumption that no fractionation has occurred since recharge. The oxygen-18 value of 2.1 percent suggests a mixing of waters of different origins. While the isotopic signature resembles the meteoric water line representing monsoonal precipitation originating in the South Indian Ocean, its relatively heavy signature probably suggests a mixture with a second source of water. This second source of water resembles precipitation that originated in a wetter, cooler climate, possibly in the past (at least 10,000 years before present).

The most likely explanation is a mixture of older water and water more recently recharged. These data indicated that there is detectable tritium, indicating that some portion of groundwater was recharged within the last 50 to 60 years (possibly decayed bomb-pulse tritium from the 1950s to 1960s).

A possible interpretation of these analytical results is that the water reflects a local, recently (50-60 years) recharged source of water. Another interpretation is that a sample is a mixture of regional and local water sources in a regional aquifer containing older water. If any water was recharged to the regional aquifer through the limestone, the presence of younger water would be expected due to short residence time in the carbonate-rock aquifer.

Ararso and Degahbour wells data (with higher TU activities) suggest that they are drilled within the regional aquifer structure, which probably receives more direct recharge from precipitation.

5.5.2 Groundwater Discharge

A discharge zone or area can be defined as that portion of the drainage basin in which the net saturated flow of the groundwater is directed toward the water table. In this area there is a component to the direction of groundwater flow near the surface that is upward (Cheery 1979).

In the study area in general topographic and structure controls play a major role for the occurrence of groundwater discharge zone in various ways in the area. As topographic highs like the mountain range in the northwest of the study area are the recharge zone, the topographic lows or the valley bottom of the study area such as the southeastern part of the area near Birkod is considered to be a groundwater discharge zone.

5.6 Groundwater Flow

The regional groundwater flow direction of the area seems to follow the surface water flow and is highly dependent on the geomorphology and structures. Groundwater-level altitudes in the Jerer valley (study area) are lower to the south, which may suggest a general south to southeast groundwater-flow direction trending down the valleys. Because of the geologic and structural complexity in this area, sparse measurements, and potential error in determination of the land-surface altitude, there is a large degree of uncertainty as to whether all of these groundwater levels represent a single surface. For example, laterally discontinuous and fractured basalt underlies the Karamara Range. Differences in the water table on either side of the Range may suggest no lateral flow through the basaltic dike (Gachet 2013)

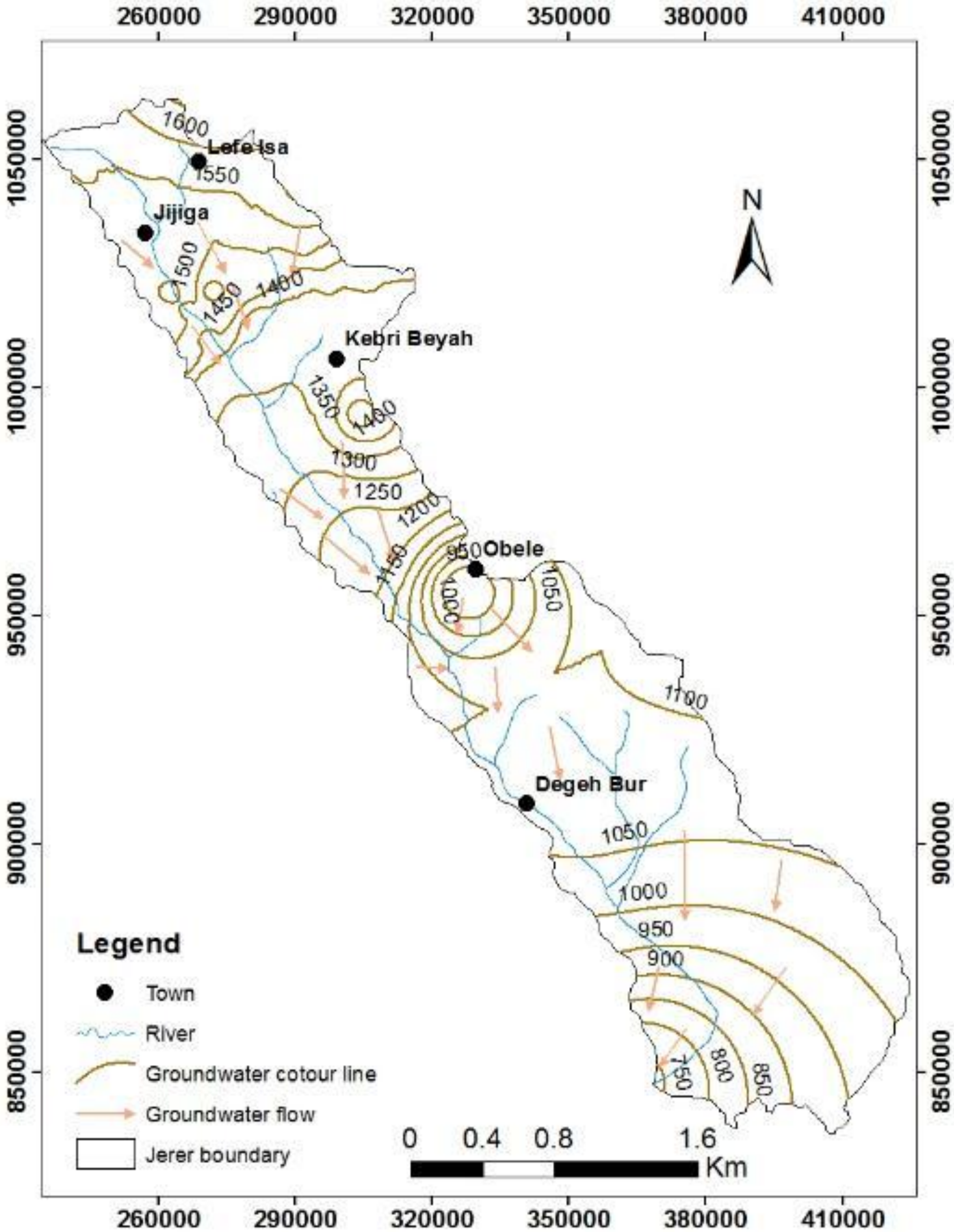


Figure 5.6 water level contour lines and general groundwater flow

5.5.1 Description of the hydrogeological framework

Most groundwater recharge probably originates from precipitation onto the northern metamorphic highlands (northern Jigjiga). It then runs off on the relatively impermeable metamorphic rocks and enters surface exposures of the Adigrat and Hamanlie Formations. Similarly, runoff from the relatively impermeable volcanic rocks of the Karamara Range also recharges the primary Adigrat and Hamanlie Formation aquifers.

Groundwater flow in the valley is to the south through the alluvial deposits, the Hamanlie Limestone and Adigrat Sandstone. The rocks of the Karamara Ranges seem relatively impermeable in the north and less so to the south. The Karamara range forms a barrier, effectively blocking east to west flow, although some flow occurs to the west between the southern parts of the valleys. Apart from evaporative losses, at least some stream flow in the river appears to recharge to groundwater as discharge decreases downstream to the south.

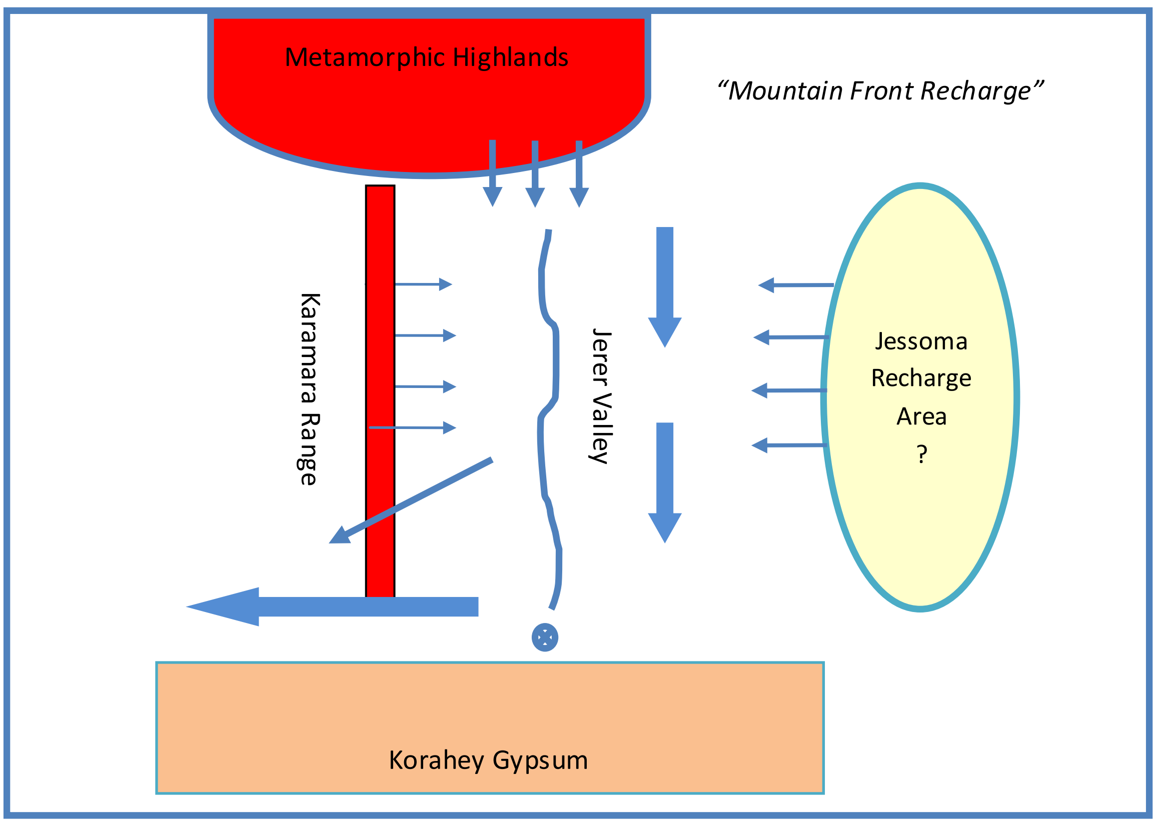


Figure 5.7 schematic diagram. Thick arrows represent general groundwater flow direction. Thin arrows represent components of groundwater recharge .Width of arrows represent general amount of flow(Diagram modified from Gachet 2013)

Eastern exposures of the Jessoma Formation probably receive some mountain front recharge as runoff enters the groundwater system from the sandstone to the west. Water also directly infiltrates into the sandstone body itself, but this recharge probably does not flow into the Hamanlie and Adigrat Formation aquifers because of a possible basal clay layer. If this clay is present, the Jessoma Formation may act as “stand-alone” aquifer. If there is hydraulic connection with the primary Adigrat Formation and Hamanlie Formation aquifers and no clay layer, then water from the Jessoma Formation also is a source of recharge to the primary aquifers to the west (Gachet 2013).

CHAPTER 6: HYDROGEOCHEMISTRY

6.1 General

For the purpose of the hydrochemical characterization of the groundwater and explanation of the major geologic controls on the hydrochemical variations and concentrations, a water quality analysis has been done on water samples collected from 49 water points in the study area. This water quality analysis in general includes water samples taken from 29 deep and shallow wells including wells from the northern highland or recharge zone ranging in depth from 30 to 250 meters, water samples taken from 20 hand dug wells. In addition to the laboratory chemical Analysis of the above samples. Insitu field measurements of water quality parameters like pH, water temperature and TDS has been performed to observe the behavior of the physical and hydrochemical behavior of some parameters at the time of sampling.

6.2 Groundwater Sampling

In this chapter an attempt is made to provide the hydro geochemical characteristics of the area from the point of view of the water quality for domestic uses. As an objective of this section, the physiochemical analysis, which is considered as hydrochemical data is resulted from different water sources like boreholes and hand dug wells. These determine of ground water flow along the river basin. In its approach as ground water moves from place to place, the chemistry of water changes due to, displacement and replacement reaction between ions, duration and interaction between rock and water. The groundwater quality analysis was conducted on the different geological formation of the study area. The analysis is crucial for the recommendation of water quality of the study area for human consumption comparing to WHO standard. A total of forty nine (49) water samples from boreholes and dug wells were collected. Most of the sample data used in this study collected from SWWDSE, SHAAC consultancy Co. and regional water bureau. To fulfill the gap, water samples were taken from three bore holes inside Jigjiga town. Measure of Electrical Conductivity (EC) and PH were made during the field.

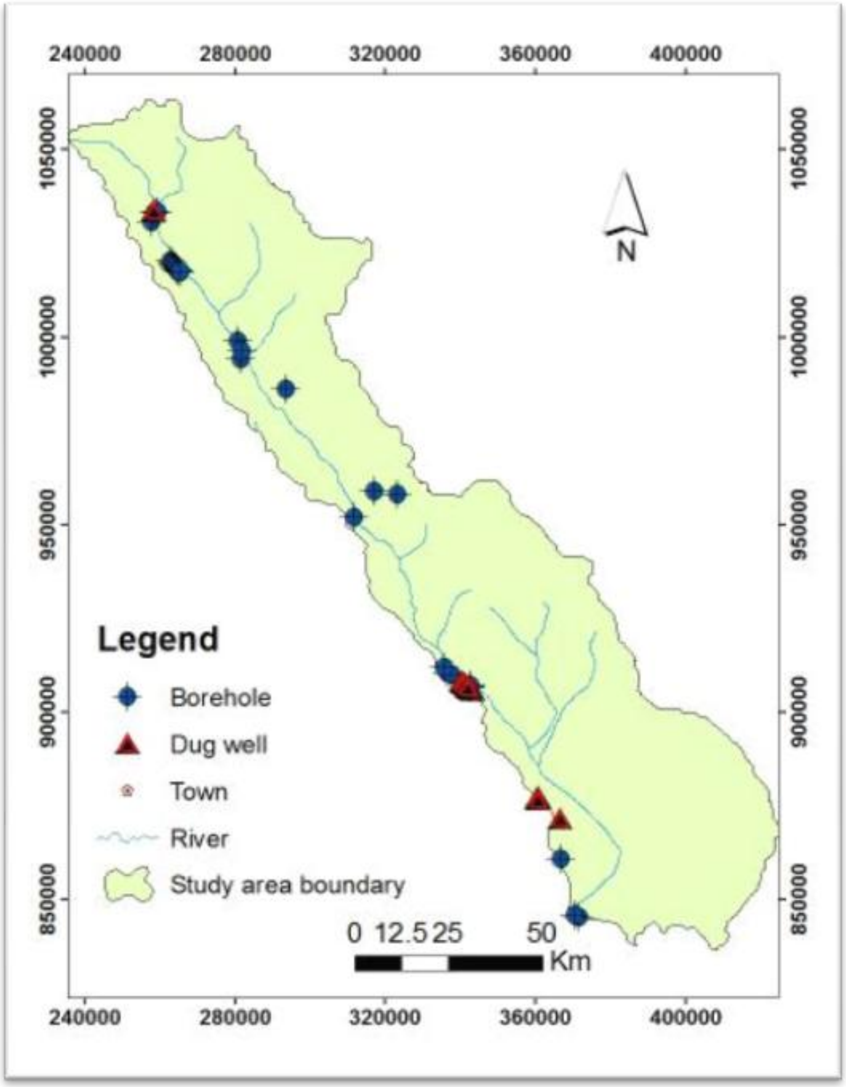


Figure 6.1 Water sampling points

The main hydrochemistry of natural water characteristics of the study area can be expressed by some physical parameter like pH, TDS, conductivity and major constituents (HCO3, SO4, Cl, Na, Ca and Mg) and secondary constituents (K, F, NO3, and CO3) have been used.

6.3 Physical Parameters

6.3.1 Hydrogen Ion Activity (pH)

According to Hem (1992) Hydrogen ion of natural waters mainly fall between 6 to 8.5 and it is controlled by interrelated chemical reactions that produce or consume hydrogen ions. The dissociation equilibrium for water is always applicable to any aqueous solution, but many other equilibrium and many non equilibrium reactions that occur in natural water among solute, solid and gaseous, or other liquid species also involve hydrogen ion. Field pH values generally are higher or lower than laboratory pH values by as much as ± 1pH unit or more (Pyne et al. 1995).

Field values are commonly lower than laboratory values because collection, transport, or storage causes a release of dissolved carbon dioxide from the water into the head space of the sample and a release to the atmosphere when the sample is opened.

In the field, pH measurements were made of each sampling point since this parameter may immediately change with time. Almost all samples regardless of their source displayed a pH value ranging 6.96-8.38 and hence the samples were found to be within the WHO and Ethiopian Water standard guideline (6.5-8.5)

Table 6.1 Table showing minimum and maximum pH

Sources	Minimum pH	Maximum pH	Average
BH	6.96	8.38	7.46
HDW	7.02	8.07	7.50

The above table shows that water in the study area have a good quality regarding the pH value for the sampled water points. All samples are within the WHO limit.

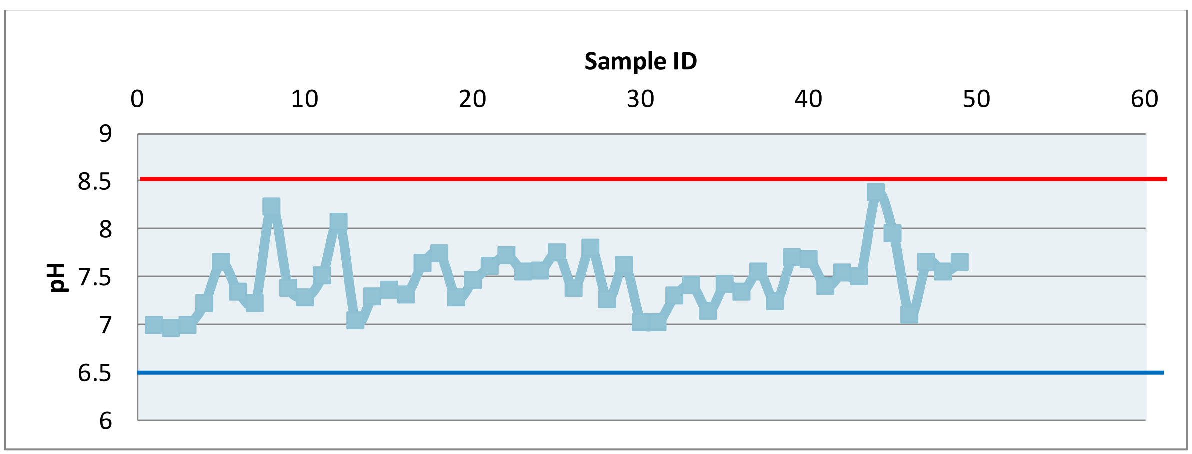


Fig 6.2 Showing pH in the WHO limit (6.5-8.5)

6.3.2 Electrical Conductance (EC) and TDS

Conductivity or specific conductance is a measure of the ability of water to conduct an electric current. It is sensitive to variations in dissolved solids mostly mineral salts. The degrees to which these dissociate into ions, the amount of electrical charge on each ion, ion mobility and the temperature of the solution all have an influence on conductivity.

Conductivity is expressed in (µS/cm) at a specified temperature, usually 25 ^{0}C and for given water body is related to the concentrations of total dissolved solids (TDS) and major ions.

In general, the larger the value of specific conductance the greater the concentration of dissolved solids in the water sample. Total dissolved solids, TDS (in mg/l) may be obtained by multiplying the conductance by a factor (A) which is commonly between 0.55 and 0.75. This can be expressed as TDS = EA (where E is conductivity in µs/cm and TDS is total dissolved solids in mg/l.

The conductivity of most freshwaters ranges from 10 to 1,000 µS/cm but may exceed 1000 µS/cm, especially in polluted waters, or those receiving large quantities of land run-off. It is usually measured in situ with a conductivity meter, and may be continuously measured and recorded.

In the study area, samples from boreholes EC values range from 720 µs/cm to 4,890 µs/cm and the overall average EC values of bore holes in the study area is about 1752 µs/cm. The minimum EC was observed at Tawlane BH near Degahbour in the Middle Jerer while the highest was observed in Jigjiga town borehole (J17).

The highest EC value in hand dug wells is measured at Jigjiga town (3270 µS/cm) and the lowest is measured from hand dug well in Horwarable village (728 µS/cm) near Degahbour.

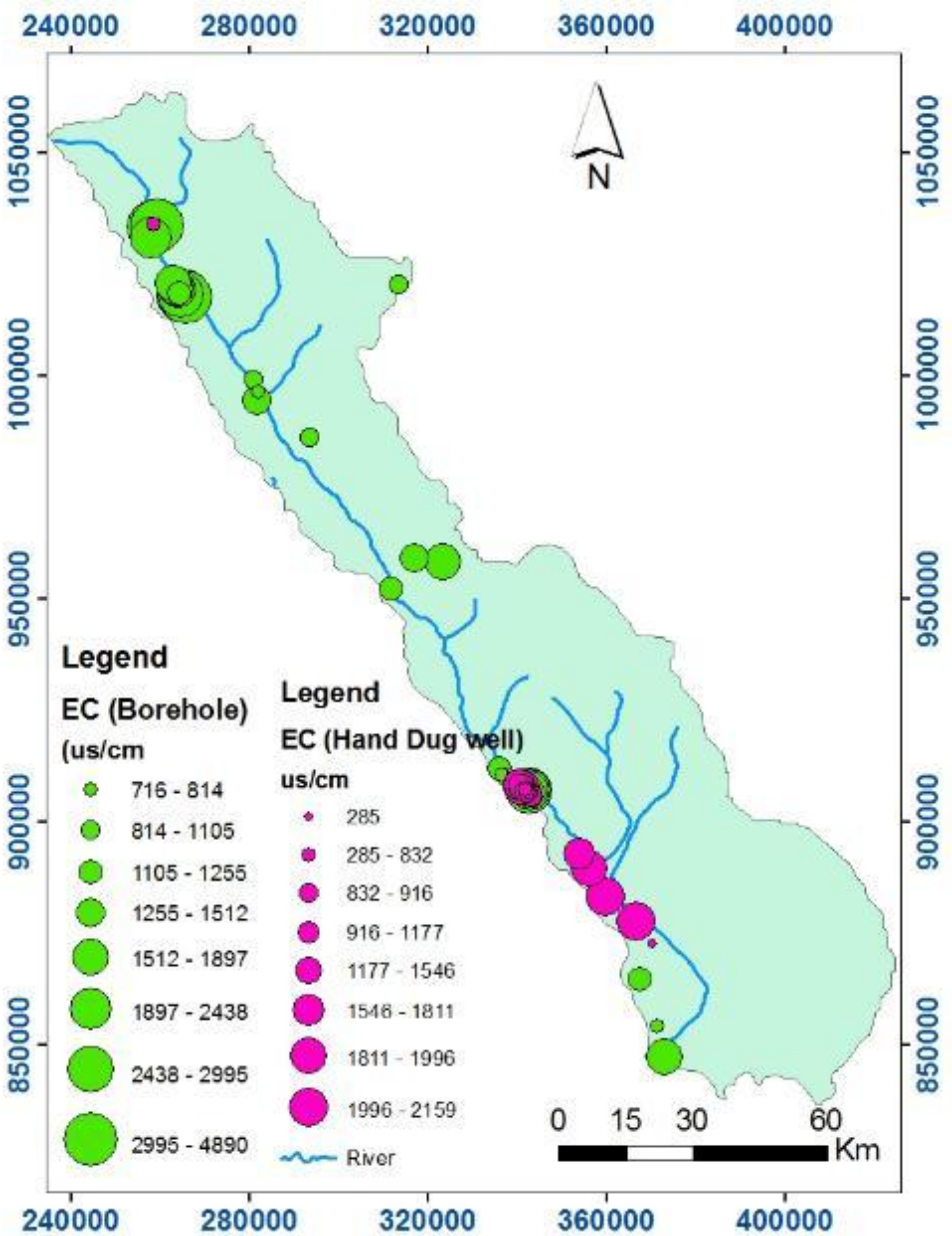
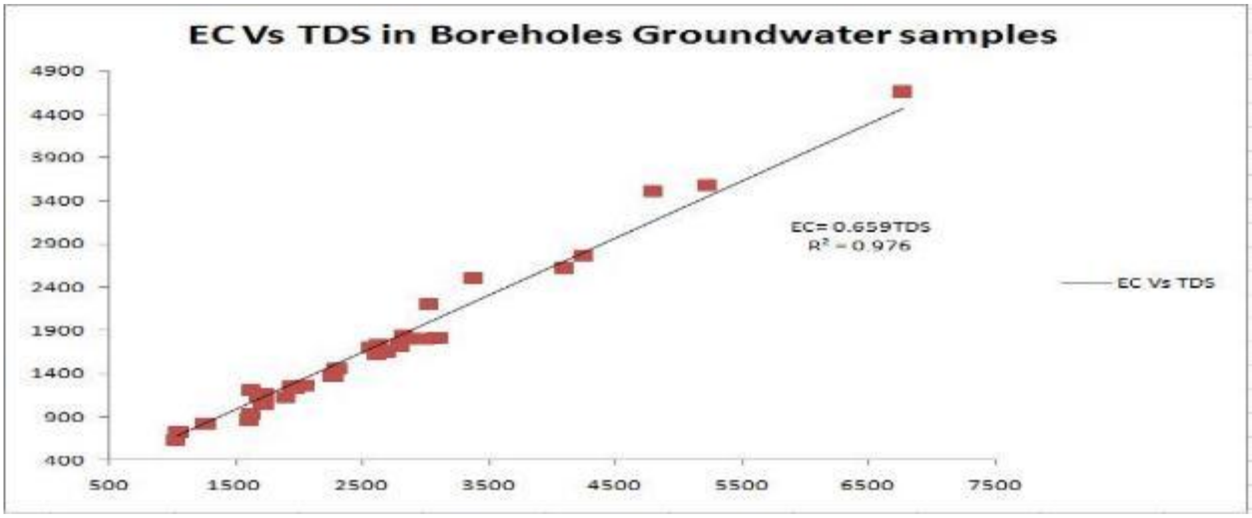


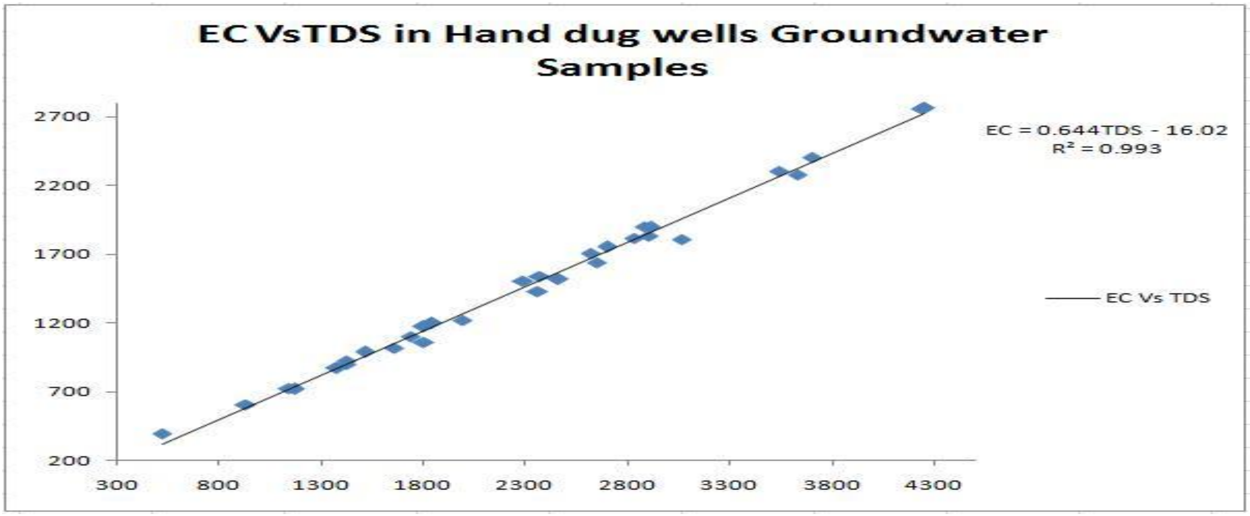
Figure 6.3 EC distribution map

The TDS conditions of the boreholes display values ranging between 4505mg/l in Horwarable of Degahbour woreda in the middle Jerer while the minimum TDS of 761mg/l is observed in the discharge zone of Birkod Town. The mean TDS of borehole and HWD are 1968 and 1930 mg/l respectively which is by far greater than the WHO standard of 1000 mg/l. Hence more than 80% of the samples collected from the boreholes and 84% of the samples collected from HDWs have not complied with the WHO and Ethiopian standards. The samples that complied with the WHO standard are Tawlane and Birqod. In Jigjiga area (the upper Jerer) the quality of groundwater contained in the limestone and sandstone is quite variable, showing TDS content from 856 to 2,700 mg/l in boreholes located in Jigjiga plain.

Generally evaporates layers within the Limestone Group, causes splitting, stagnation and salinization of the underground water elsewhere in the Sedimentary basin aquifers in SE Ethiopia (Kebede 2013).



(a)



(b)

Figure 6.4 Relationship between EC (μs/cm) and TDS (mg/l) (a) BHs (b) HDWs

Based on the above figure, the Electrical Conductivity (EC) increases with the increase of Total Dissolved Solids (TDS). Hence, the electrical Conductivity of Groundwater both the deep and the shallow wells tend to have very high values and this is due to the high concentration of dissolved salts. According to (WWDSE, 2003) It was concluded that the general trend in increase of TDS is from the northwest to southeast within the Shebelle basin.

Table 6.3 Classification of water based on TDS (Freeze & Jerry 1979)

Class	**TDS (mg/l)**
Fresh Water	0-1000
Brackish water	1000-10,000
Saline water	10,000-100,000
Brine water	More than 100,000

Fresh water is water that contains less than 1,000 mg/l of dissolved solids; generally, more than 500 mg/l of dissolved solids undesirable for drinking and many industrial uses. Hence great majority of the samples in the study fall under brackish water.

6.3.2.1 Sources of Salinity

All groundwater contains salts in solution. The type of salts depends on the geological environment, the source of the groundwater, and its movement. The weathering of primary minerals is the direct source of salts in groundwater. Bicarbonate (HCO3) is usually the primary anion in groundwater and forms as a result of the solution of carbon dioxide in water. Carbon dioxide is a particularly active weathering agent for such source rocks as limestone and dolomite.

Sodium in water originates from the weathering of feldspars (albite), clay minerals, and the solution of evaporites (halite and mirabilite). Evaporites are also the major natural source of chloride in groundwater, while sulphate originates from the oxidation of sulphide ores or the solution of gypsum and anhydrite. Such primary minerals as amphiboles (hornblende), apatite, fluorite, and mica are the sources of fluoride in groundwater.

Groundwater quality is also related to the relief of the area. Fresh groundwater usually occurs in topographic highs which, if composed of permeable materials, are areas of recharge. On its way to topographic lows (areas of discharge), the groundwater becomes mineralized through the solution of minerals and ion exchange. Groundwater salinity varies with the texture of sediments, the solubility of minerals, and the contact time. Groundwater salinity tends to be highest where the movement of the groundwater is least, so salinity usually increases with depth. Irrigation also acts as a source of salts in groundwater. It not only adds salts to the soil, but also dissolves salts in the root zone. Water that has passed through the root zone of irrigated land usually contains salt concentrations several times higher than that of the originally applied irrigation water. Evapotraspiration tends to concentrate the salinity of groundwater. Highly saline groundwater can therefore be found in arid regions with poor natural drainage and consequently a shallow water table

Highest TDS aquifers were mapped in northern highland of Jigjiga which is the recharge area. This is attributed to the fact that both boreholes in the recharge area that have highest TDS and EC values are located inside Jigjiga town and they polluted J 17 which has EC of 4890 µS/cm has also the highest NO_3 value of 219.57 mg/l the same is the J 18 with 3960 µS/cm it has NO_3 value of 160 mg/l. Regarding the HDWs JV001 located inside Jigjiga town has EC 3270 µS/cm and NO_3 value of 188.30 mg/l. In addition to the pollution other causes of higher TDS and EC in the recharge area can be irrigation and agricultural activities. Since agricultural activities are more common in the recharge area than discharge.

6.3.3 Hardness

Hardness is the chemical property of water suggesting the presence of Ca^{+2} and Mg^{+2} which principally cause the water to be hard. Calcium and Magnesium enter the water via the action of carbonic acid. As water and carbon dioxide react, carbonic acid is produced and dissolves calcium and magnesium from carbonate rocks (e.g. Limestone, Dolomite),What constitutes "hard water" has been variously described. A generally accepted classification for hardness as mg/l of $CaCO_3$ according to Dufer and Becker (1964) cited in Tamiru and Tenalem (2001) hardness range in milligram per liter (mg/l) is given by:

0 to 60 = Soft

61 to 120 = moderately hard.

121 to 180 = Hard

>181 = Very Hard.

From Different water samples analyzed, the water qualities of all samples tend to be very hard for both groundwater and hand dug wells. The minimum hardness encountered in the study area is 300 mg/l of $CaCO_3$ while the maximum is 2500 mg/l for all samples. Most likely, geology of the area which is dominated by Carbonate rocks (Limestone, Dolomite and intercalation of Gypsum) is responsible for the hardness of the water.

Hardness levels above 500mg/l are not desirable for domestic use. Samples of the study area have more Ca^{++}, thus hardness of water is one factor of water quality. In general, it is relatively high for borehole and small for spring water. Those water samples rich in calcium are categorized as hard water calcium is imparted by leaching of calcium rich rocks (basic rocks), acidic rocks dominated by Na characterized by water low hardness.

6.4 Cations and Anions

6.4.1 Sodium Ion (Na^+)

Sodium is one of the major cations characterized ion exchange chemical reaction during evolution process by Ca and Mg. Cations exchange is a reaction in which the calcium and magnesium in the water are exchanged for sodium that is adsorbed to aquifer solids such as clay minerals, resulting in higher sodium concentrations (Hem, 1985). The generalized reactions are as follow (Hem, 1985)

Na2X + Ca2+ = Ca X + 2Na+

Na2 X + Mg2+ = Mg X + 2Na+, Where X = aquifer solid

The WHO guideline value for sodium in drinking water is 200 mg/l. Many surface waters have below 50 mg/l. However, ground water concentrations frequently exceed 50 mg/l; Sodium is commonly measured where the water is to be used for drinking or agricultural purposes, particularly for irrigation.

The sodium concentration of boreholes in almost 50% water samples in the study area is below the maximum desirable and permissible level of the standards. High Na concentration above the limit was only observed in samples collected from Jigjiga and Degahbour. The high concentration of sodium of these boreholes is associated with the weathering of basalt rocks.

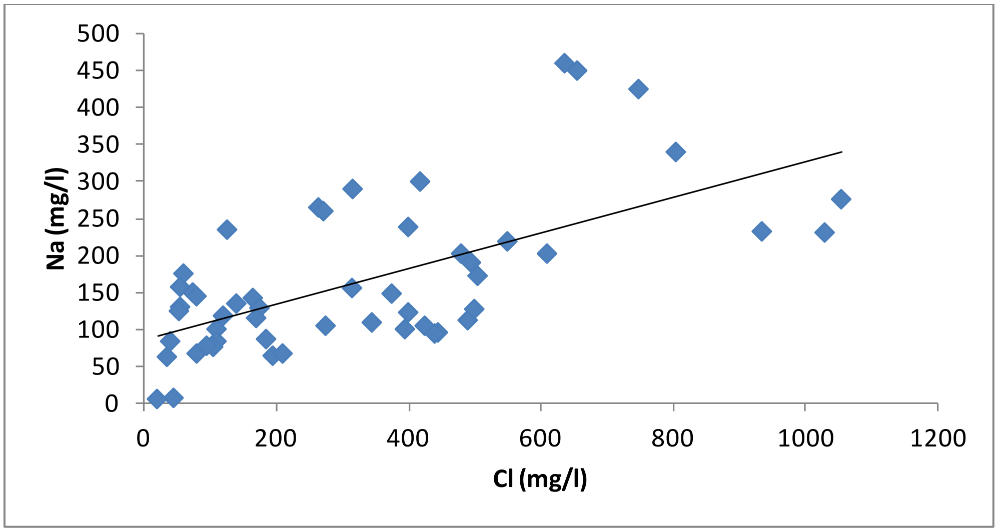


Figure 6.5 Relation between Na and Cl

6.4.2 Calcium & Magnesium (Ca^{2+} & Mg^{2+})

Out of the major cations that constitute the ground water chemistry in the study area, Calcium (Ca^{+2}) and Magnesium (Mg^{2+}) are the most dominant cations where Ca^{2+} in particular shows a significant variations spatially through the study area. The calcium concentration which ranges in the area between a minimum values of 71 mg/l in the upper valley and maximum values of 837-1240 mg/l in the southeastern lowland of Degahbour (Middle Jerer) which in general shows increasing trend toward the downstream. Therefore from the samples analyzed in the study area Ca^{2+} and Mg^{2+} in general show a negative relationship.

Calcium Ca^{2+} is dissolved in water as it passes over and through limestone deposits which the main aquifer formation in the study area. Magnesium is dissolved as water passes over and through dolomite and other magnesium bearing formations. Because groundwater is in contact with these geologic formations for a longer period of time than surface water, groundwater is usually harder than surface water.

The decrease in the concentration of calcium is possibly related to its precipitation along flow path which relatively gives lower concentration in the valley formations in comparison to the higher Sodium concentration.

6.4.3 Potassium Ion (K^+)

The principal potassium minerals of silicate rocks are the feldspars orthoclase and microcline (KAlSiO8), the micas and the feldspathoid leucite (KAlSi2O6). In dilute natural water in which the sum of sodium and potassium is less than 10 mg/l, it is not unusual for the potassium concentration to equal or even exceed the sodium concentration. According to (Hem 1985) Potassium is slightly less common than sodium in igneous rock but more abundant in all the sedimentary rocks. In the ocean the concentration of potassium, though substantial, is far less than that of sodium. The study area all 49 samples collected from different sources show that the concentration of Na^+ (mg/l) is by far greater than concentration of K^+ (mg/l).

6.4.4 Bicarbonate ions (HCO_3^{2-})

The presence of carbonates and bicarbonate influences the hardness and alkalinity of water. The weathering of rocks contributes carbonate and bicarbonate salts. The relative amounts of carbonates, bicarbonate and carbonic acid in pure water are related to the pH. As a result of the weathering process, bicarbonate was the dominant anion in most samples but however, as shown below (fig 6.6) it is evolved into Chloride. In study area, the maximum bicarbonate ion concentration is 553 mg/l in Southern Jigjiga well field (JJ BH 05) and the minimum is observed in Baka (BH SB002) in the discharge area

6.4.5 Sulfate ion ($SO4^{2-}$)

Sulfate concentrations are associated with type of Lithology and pollution from surface water. There are high concentrations of sulfate at wells which emerged at the contact between limestone, shale and gypsum intercalation. This is due to the high sulfate dissolving from gypsum. In the study area, wells have the highest sulfate ion concentration is in Boreholes 680 mg/l at JJ BH 08/07 and HDWs 762 mg/l at JV001, both in Jigjiga. Water containing about 500 mg/l of sulfate tastes bitter; water containing about 1000 mg/l may be cathartic (Todd 1980).

6.4.6. Chloride (Cl^-)

Chloride is known by its conservative nature in the chemical evolution process and good indicator of the relative age of ground water compare to other major ions .The high chloride concentration is associated with type of Lithology and pollution from surface water. High chloride concentrations in groundwater show contamination from pit Latrines, waste disposals.

For WHO, maximum acceptable level of chloride is 250 mg/l and that of Ethiopian drinking water standard is 533 mg/l. In the investigated area, the chloride concentration for almost all samples taken from groundwater is under range of the limit of the standard, chloride ion ranging from 40 mg/l to 1055 mg/l in BHs, 20mg/l to 550 mg/l in HDWs. Out of 29 BH samples only 8 samples are above the permissible limit. While HDW are all below the limit.

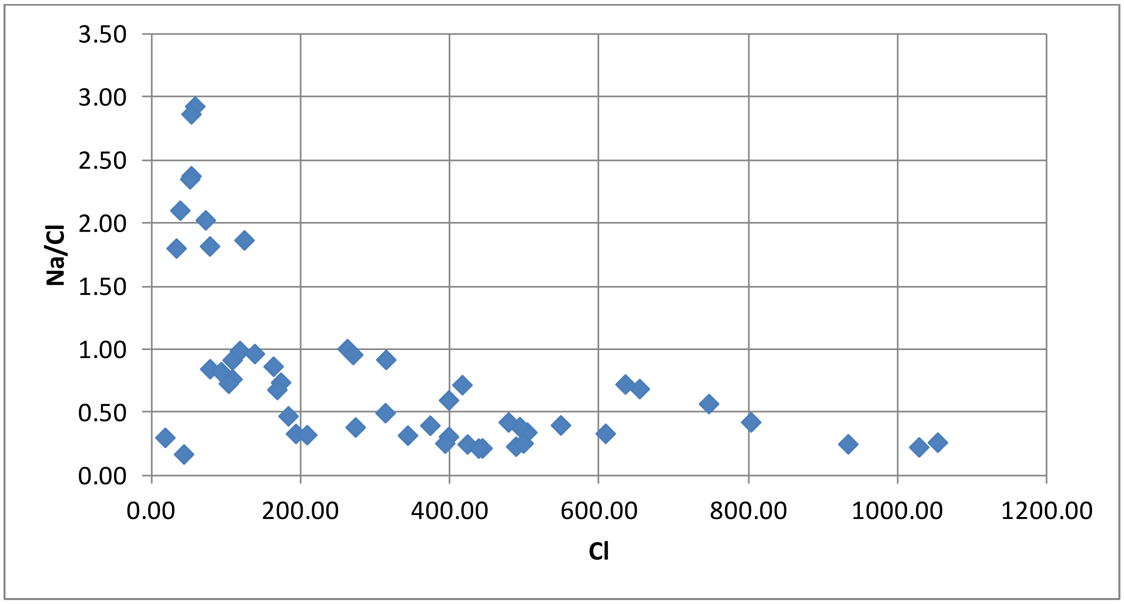


Figure 6.7 relationship between Na/Cl and Cl

6.4.7. Fluoride Ion (F^-)

WHO standard for fluoride is 1.5 mg/l and that of Ethiopian drinking water standard is 3.0 mg/l (JICA, 2013). Small amounts of fluoride, between 0.6 and 1.0 mg/l, are necessary for controlling dental caries; excessive amounts provoke caries and stain the tooth enamel from yellow to black brown, If the fluoride is in excess of 1.5 mg/I dental mottling and severe osteoporosis, due to incorrect absorption of calcium, may occur, Skeletal flurosis occurs mainly if fluoride intake is in excess of 3 mg/I for several years, Severity of symptoms are also due to various other factors such as nutritional deficiencies as well as to the chemical composition of the water. Higher concentrations of fluoride in drinking water are also linked with cancer (Smedley 1992). The permissible limit of F depends on temperature; a higher intake of fluoride can be permissible in colder climates (Hamill and Bell 1986).

Based on the Laboratory analysis results of Fluoride, the maximum concentration of 1.84 mg/l was found in Birkod BH2 (JV040).

6.4.8. Nitrate (NO_3)

Nitrate is commonly used as a quality indicator of potential contamination of groundwater. The content of nitrates is not related to the rock composition (type) but it reflects pollution of groundwater by human and/or animal waste. The background content of nitrates in groundwater is about 5 to 10 mg/l depending on the relevant land cover. High nitrate concentration levels indicate contamination from municipal wastes. Extremely high NO3 pollution was encountered in Jigjiga town water supply BHs such 220 mg/l in J17 and 161 mg/l in J18. Regarding HDWs very high NO3 pollution was encountered in JV001 HDW located inside Jigjiga town. As the WHO recommended maximum limit for drinking water is 10mg/l NO_3- Water with higher concentration of represents a significant health risk to infants (Blue baby disease).

6.5. Water Types

Water Types classification of the samples collected from all sources is made to observe the major water groups, their relationship and evolution along the flow path by using a graphical method. The piper diagram is the most widely used graphical form. The diagram displays the relative concentration of the major cations and anions on two separate trillinear plots, together with a central diamond plot where the points from the two trillinear plots are projected.

The ion concentration in most of the water samples is dependent on elevation, lithology, structures and climatic conditions. Lithology of the area has a significant effect on the concentration of chloride, sulfate and sodium. The presence of high Concentration of chloride, sulfate and sodium shows a complex process of rock-water interaction and ion exchange. The predominant water types in Ethiopia based on the dominant anions which are bicarbonate, sulfate, and chloride types (Tesfaye 1993).

In general, the classification of water samples of the area based on the Aquachem software analysis is made as follows based on the Aquachem software analysis.

6.5.1.1 Boreholes water types

Table 6.4 water types in BH

S/N	Water type	No of Samples	% of Samples
1	Ca-Na-Mg-SO4-Cl	2	6.89
3	Ca-Mg-Cl	5	17.24

4	Ca-Na-Mg-HCO3	1	3.44
5	Ca-Mg-Na-Cl	5	17.24
6	Ca-Mg-Na-HCO3-SO4	1	3.44
7	Ca-Na-Mg-SO4-HCO3	1	3.44
8	Ca-Na-Mg-HCO3-SO4	1	3.44
10	Mg-Ca-Cl	1	3.44
11	Mg-Ca-HCO3	1	3.44
12	Mg-Ca-SO4-HCO3	1	3.44
13	Mg-Ca-Na-SO3-HCO3	1	3.44
14	Na-Ca-Mg-HCO3-SO4-Cl	1	3.44
15	Na-Ca-Mg-HCO3-Cl-SO4	1	3.44
16	Na-Ca-Mg-CO3-SO4-Cl	1	3.44
17	Na-Ca-HCO3-Cl-SO4	1	3.44
18	Na-Mg-HCO3-SO3-Cl	1	3.44
19	Mg-Ca-Na-SO4-HCO3	1	3.44
Total		29	100

6.5.1.2 HDW water types

Table 6.5 Water types in HDW

S/N	Water type	No of Samples	% of Samples
1	Ca-Mg-SO4	3	15
3	Ca-Mg-Cl	**6**	30
4	Ca-Mg-Na-Cl	2	10
5	Ca-Mg-Na-SO4-HCO3	1	5
6	Ca-Mg-HCO3	1	5
7	Na-Mg-Ca-SO4-Cl	1	5
Total		20	100

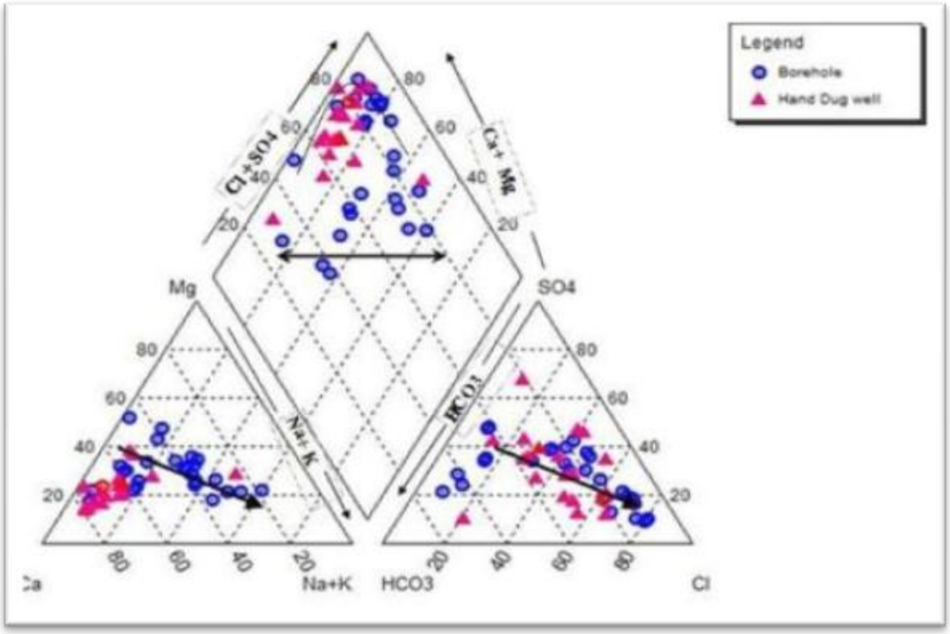


Figure 6.7 Piper diagram of all water samples showing the path of evolution and some mixture

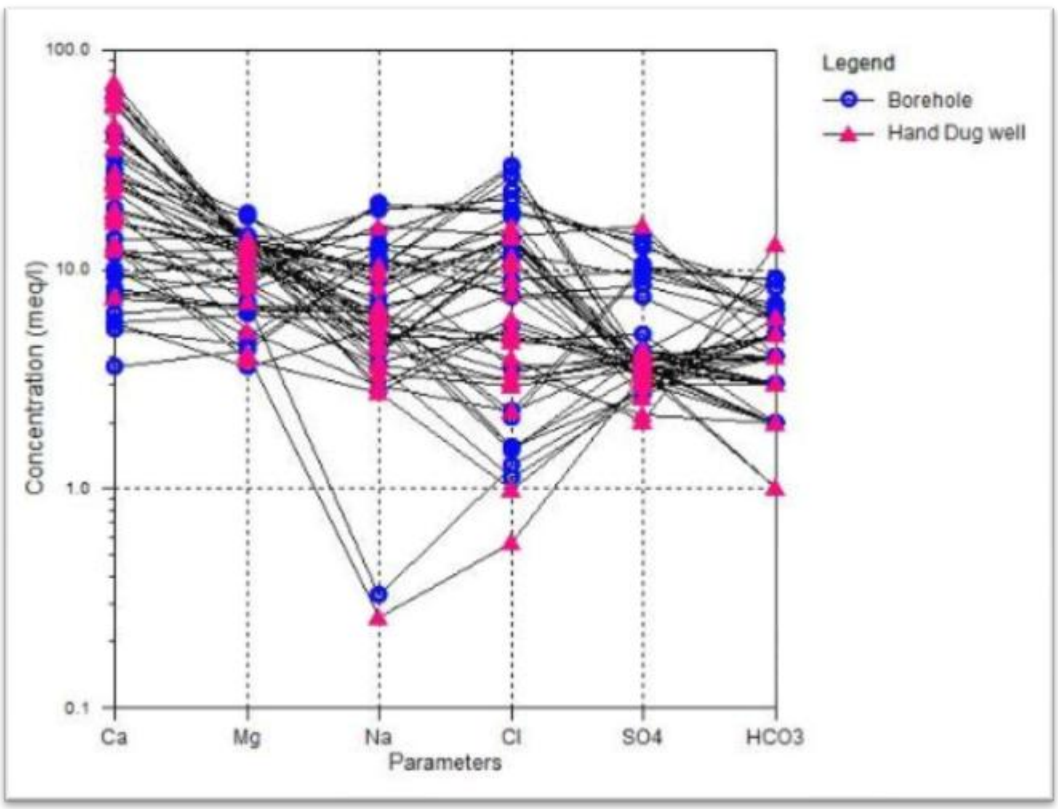


Figure 6.8 Scholler diagram shows Ca & Cl as dominant ions (cations and anions)

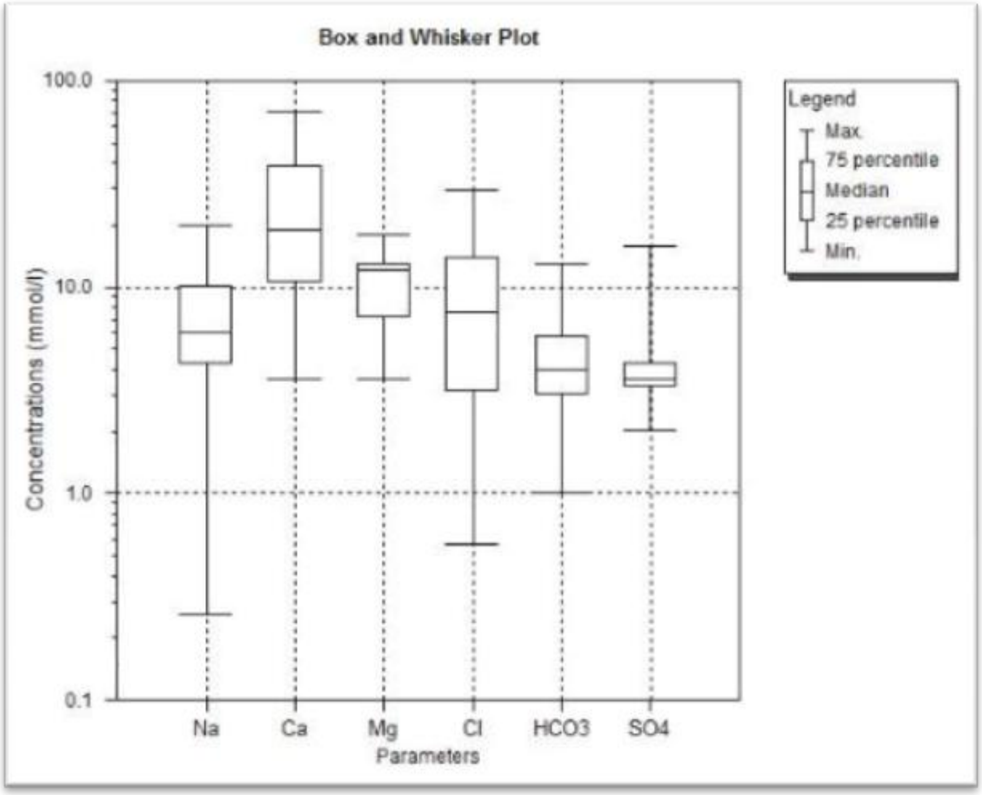


Figure 6.9 Box and Whisker diagram for groundwater

6.5.2 Geochemical Evolution

The geochemical data of dissolved major and minor constituents in the groundwater samples indicates the main processes responsible for the geochemical evolution are: (2) Minerals weathering process and (1) dissolution of carbonate minerals characterized by high loadings of Ca, and Mg.

The Ca-SO_4 or Ca-Na-SO_4 water is not the end member of groundwater geochemical evolution because the end member of geochemical evolution is Na-Cl water type. The main cause of geochemical evolution in the study area is dissolution of carbonate and sulfate minerals in the watershed of Jerer river valley and leaching of evaporate within the series layers the valley alluvial aquifer matrices.

By using Piper Diagrams for both water sources the pattern indicated that the predominant water type for all sources (BHs and HDWs) is Ca-Mg-HCO3-Cl type of Water. The water type shows some extent of anion evolution but the cations are in early stage of evolution. The path of evolution is as follows

Ca → Mg → Na

HCO_3 → HCO_3 + SO4 → SO_4+HCO_3 → SO_4 +Cl → Cl+SO_4 → Cl

In unconfined shallow aquifers water samples from downstream show both Cl^- type and HCO3 type which implies the presence of mixing of fresh water most likely due to recharge from the river and flooding. Direct recharge from precipitation has no significance as it is almost equal to the AET. Accordingly the groundwater chemistry shows significant variation throughout those aquifers. In addition the groundwater of the study area is also affected by climatic conditions. The hydrochemistry of shallow aquifers on the unconsolidated sediments are dominated by climatic effect while the deep fractured aquifers are dominated by lithologic effect. In the study area the chemical evolution show a major ion change process along flow path. From piper plot diagram the evolution sequence shows change is as follows.

CHAPTER 7 CONCLUSIONS AND RECOMMENDATIONS

7.1. Conclusions

In general from the hydrogeological viewpoint groundwater condition in Jerer sub-basin is characterized by the existence of both very shallow to very deep aquifer systems with porous, karstified, fractured and weathered aquifers of different rocks. The depth to water level in the valley increases southwards-southeastwards from only 6-10 m around Jigjiga to more than 250 m in the south.

On the basis of the prevailing hydrometeorolgic conditions in the study area, a direct recharge from local precipitation for the groundwater in the area is almost negligible where almost all the rain fall is lost by evaporation before joining the water table.

Based on the small amount of data collected during this research the Aquifer units in Hamanlie limestone and Adigrat sandstone shows better transmissivity values than other units in the sub-basin. Transmissivity values ranges from 6-97 m2 /d with yield 4-20 l/s in Adigrat sandstone, while Tansmissivity ranges 5–20 m2/day and yield varies from 2 to 6 l/s in Hamanlie limestone.

Accordingly, based on available pumping test data, amount of recharge, topography and lithological logs the study area aquifers were mapped into four aquifer zones; High permeability zone to very low permeability zone. The high permeability zone was mapped in the southern part of the study area where Jerer stream joins Fafan stream. The main aquifer layers in this zone are alluvial deposits underlain by karstified limestone. Since it is along the river, it is normally recharged by river wadis in addition to the direct recharge from precipitation. Boreholes drilled in this zone have a yield ranging 6-20 l/s.

Regarding the recharge mechanism of the study area horizontal recharge provides the most dependable groundwater resources. Highland rain infiltrates vertically and laterally into the exposed karstified limestone and sandstone of the lower parts of the succession and moves southeastwards beneath the younger gypsiferous formations. Most of the rainfalls quantities on the highlands, upstream the Jerer watershed, are immediately swallowed by fractures and absorbed horizontally and vertically by these two formations and conveyed underground, limiting the Evapotraspiration subtraction. However, recharge of the area estimated to be 13 mm/year.

The regional groundwater flow direction of the area seems to follow the surface water flow direction and highly dependent on the geomorphology and structures. Groundwater-level altitudes in the Jerer valley (study area) are lower to the south, which may suggest a general south to southeast groundwater-flow direction trending down the valleys.

From Different water samples analyzed, the water qualities of all samples tend to be very hard for both groundwater and hand dug wells. The minimum hardness encountered in the study area is 300 mg/l of $CaCO_3$ while the maximum is 2500 mg/l for all samples. Most likely, geology of the area which is dominated by Carbonate rocks (Limestone, Dolomite and intercalation of Gypsum) is responsible for the hardness of the water. The value of pH is in the WHO accepted range while the value of Fluorine is also in the accepted limit except one Birkod BH which was attributed to the Basalt formation seen in the well log. By using Piper Diagrams for both water sources the pattern indicated that the predominant water type for all sources (BHs and HDWs) is Ca-Mg-HCO3-Cl type of Water. The water type shows some extent of anion evolution but the cations are in early stage of evolution. The highest E.C was met at Jigjiga town BHs and HDW this was caused by pollution of water as evidenced by increased NO_3 contents.

7.2 Recommendations

- Detailed hydrogeological studies are recommended in the Jerer valley in order to identify the interaction between different aquifer units and the role of the Jessoma formation in recharging the underlain aquifers such as Hamanlie and Adigrat.
- In order to characterize the water sheds and sub-watersheds in Somali region appropriate amount of hydrometeorological stations and river flow gauges should be placed.
- As the amount of groundwater recharge in the middle and lower Jerer sub-basins and Lower Fafan is relatively small, artificial recharge, soil and water conservation and forestation must be maximized.
- To estimate the recharge of the area properly water level monitoring is required

- For conducting comprehensive study on the region's water resources, data management is highly recommended especially keeping the information related to ground and surface water.

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Declaration

I hereby certify that the thesis entitled ‘‘Characterization of Groundwater Systems and Aquifers in Jerer Valley, Somali Region, Eastern Ethiopia’’ has been carried out by me under the supervision of Prof. Tenalem Ayenew, department of Earth Science, Addis Ababa University during the year 2015, as partial fulfillment of the degree of M.Sc in Hydrogeology.

I further declare that this work has not been submitted to any other university for award and also that all sources of materials used during this thesis works have been properly acknowledged.

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Mohammed Mukhtar **June, 2015**

ANNEX 1 list of boreholes used for Hydrogeological characterization of the study area

S/N	Site	UTM_X	UTM_Y	Elevation	Depth	SWL	AWSL	Q l/s	Draw down	T
1	Adaley	270781	1010771	1508	230	81	1427			
2	Aranadka	304116	994222	1600	292	126	1474			
3	Bardahle	348439.5	892615.1	950	94		950			
4	Birkod	364780	847899	780	238	43	737	6		
5	Degahbur 6	341054	909374	1116	54	19	1097	3		
6	Durwale 1	287405	988876	1420	235	92	1328			
7	Farda	281572	1000278	1451	180	85	1366	2		
8	Gabagabo BH1	232747	1034009	1507	30	10	1497			
9	Garawo	345999.6	897893.42		210		0			
10	Garbahare	303132	967460	1305	298	99	1206	6		0
11	Harorays 5	290970	1043487	1810	282	204	1606	3		
12	Harre 2	281675	1012551	1560	259	207	1353			
13	Higlalay	340800	934529	1350	317					
14	Horakalifo	295065	976594	1334	212	70	1264			
15	Istanbuudh	298467	100141	1620	306		1620			
16	Jica 1	281111	1000180	1450	200	85	1365	7		
17	Jica 2	280743	1000004	1452	200	88	1364	5		
18	JJ BH 01	262832	1020610	1724	128	47.47	1596	5.43	88	5.8
19	JJ BH 02	263362	1019888	1668	127	65.94	1541	7.02	98	16
20	JJ BH 03	263561	1019447	1721	133	73.9	1588	21.96	88.9	91
21	JJ BH 04	263930	1019198	1712	123	70.79	1589	17.57	100.79	73
22	JJ BH 05	264215	1018494	1632	127	68.3	1505	22.91	83.3	97
23	JJ BH 06	264706	1018113	1616	115	64.16	1501	24	70	97
24	JJ BH 07	265188	1017812	1612	122	65.9	1490	ly		1.7
25	JJ BH 08	265599	1017638	1613	127	67.72	1486	11.94	82.72	28
26	JJ BH 09	266052	1017451	1600	128	68.4	1472	ly		3.8
27	JJ Korder	257679.3	1031248.1	1650	32	12	1639	11		

28	JJ Serp BH3	257679.4	1029752.5	1640	36	6	1634	2		
29	Lef Ise 6	278067	1064444	1722	137	70	1652			
30	Lef Ise 7	278962	1063258	1727	135		1727			
31	Lefe Ise 1	278580	1063706	1730	100		1730			
32	Lefe Ise 3	279198	1065797	1714	129		1714			
33	Magalo Ad	327424	955501	1150	440	250	900			
34	Obele	322457	943761	1200	322		1200			
35	Kaho EB1	281973	995591	1412	200	88	1324	2.64		8.32
36	Kaho EB2	281874	996159	1417	178	84	1333	1.78		6.5
37	Kaho PB1	281423	996766	1410	187	85	1325	4.7		4.85
38	PB2				205	84		5.4		7.27
39	PB3				267	77.4		5.5		16.25
40	Tuli Guled	253913	1063179	1900	91		1900			
41	Waaji 2	271575	1021032	1535	126	70	1409	3		
42	Xaaxi	286358	990509	1424	250	94	1330			
43	Xerageel 1	268106	1069008	1825	227		1825			
44	Xerageel 2	268351	1069234	1825	211	133	1692			

ANNEX 2 Hydro chemical data of water samples

Sample No	Source	CO3 mg/l	HCO3 mg/l	SO4 (ppm)	NO3 (ppm)	F (mg/l)	TDS(ppm)	pH	EC(ms/cm)	Cl (ppm)	Ca(ppm)	Mg(ppm)	Na(ppm)	K(ppm)
J6	BH	Nil	402.60	475.95	26.92	0.88	1725.00	6.99	2300.00	315.93	200.00	60.00	290.00	2.30
J17	BH	Nil	500.20	600.11	219.57	0.86	3667.50	6.96	4890.00	748.44	380.00	156.00	425.00	3.60
J18	BH	Nil	395.28	499.60	160.75	0.59	2970.00	6.99	3960.00	804.86	328.00	151.20	340.00	3.30
JV055	BH	120.02	183.02	175.70	0.13	1.20	1075.50	7.22	1434.00	195.00	849.60	156.35	64.53	11.93
SB007	BH	90.01	244.03	135.60	0.13	0.92	828.75	7.65	1105.00	45.00	125.80	85.60	7.56	0.01
SB035	BH	180.02	122.02	171.30	0.13	0.90	726.75	7.34	969.00	445.00	480.00	145.24	96.04	17.50
SB037	BH	360.05	122.02	147.50	0.15	0.90	607.50	7.22	810.00	490.00	275.20	173.49	112.55	18.29
SB044	BH	120.02	122.02	168.20	0.11	0.79	802.50	8.23	1070.00	505.00	248.00	128.10	172.58	17.50
JV005	BH	180.02	122.02	175.50	0.11	0.82	885.00	7.38	1180.00	500.00	544.00	171.75	127.56	7.95
JV039	BH	60.01	244.03	171.50	0.11	1.32	1020.00	7.28	1360.00	440.00	817.60	168.25	94.54	24.65
SB032	BH	60.01	122.02	172.20	0.15	1.44	1425.00	7.51	1900.00	395.00	1240.0	169.52	100.54	36.58

											0			
JV001	HDW		244.00	762.00	188.30	0.57	2452.50	8.07	3270.00	506.00	150.00	115.00	360.00	7.50
JV002	BH	120.02	305.04	183.70	0.13	1.17	2250.00	7.04	3000.00	1030.00	836.80	158.73	231.10	18.29
JV006	HDW	60.01	244.03	186.20	0.15	1.15	690.00	7.29	920.00	110.00	449.60	104.29	100.54	4.77
JV007	HDW	180.02	366.05	125.00	0.17	1.41	1162.50	7.36	1550.00	400.00	488.00	166.03	238.60	15.11
JV014	HDW	60.01	183.02	190.50	0.14	1.17	585.00	7.31	780.00	110.00	344.00	86.19	84.04	3.98
JV015	HDW	60.01	61.01	169.30	0.23	0.94	607.50	7.64	810.00	105.00	548.80	101.59	76.53	2.39
JV017	HDW	60.01	183.02	206.80	6.68	1.09	1500.00	7.74	2000.00	165.00	1422.40	153.65	142.56	10.34
JV018	HDW	60.01	244.03	202.30	0.08	1.17	1357.50	7.28	1810.00	120.00	1139.20	151.11	118.55	8.75
JV019	HDW	120.02	122.02	104.30	7.96	1.27	1567.50	7.46	2090.00	120.00	1300.80	152.22	118.55	10.34
JV025	BH	120.02	305.04	161.80	0.11	1.22	1132.50	7.61	1510.00	610.00	571.20	160.16	202.59	13.52
JV026	HDW	120.02	183.02	144.50	0.18	1.19	832.50	7.72	1110.00	35.00	246.40	46.83	63.03	5.57
JV027	HDW	60.01	183.02	195.30	0.04	1.09	840.00	7.55	1120.00	80.00	372.80	63.33	67.53	3.98
JV040	HDW	60.01	183.02	173.50	0.22	1.14	1110.75	7.56	1481.00	375.00	907.20	125.40	148.56	8.75
JV046	BH	120.02	305.04	163.00	0.20	1.10	540.00	7.75	720.00	55.00	115.20	75.56	130.56	7.95
JV049	BH	180.02	183.02	164.00	0.11	1.17	1365.00	7.38	1820.00	935.00	649.60	159.84	232.60	18.29
JV050	BH	180.02	427.06	130.70	0.13	1.30	765.00	7.80	1020.00	55.00	145.60	83.02	157.57	6.36
JV056	HDW	120.02	305.04	141.20	0.15	1.24	1260.00	7.26	1680.00	550.00	811.20	168.10	219.10	24.65
SB009	HDW	120.02	61.01	160.50	0.16	1.04	825.00	7.62	1100.00	20.00	260.80	50.00	6.00	2.39
SB010	HDW	120.02	122.02	157.50	0.31	1.00	1461.75	7.02	1949.00	495.00	1102.40	154.44	190.58	10.34
SB017	HDW	180.02	61.01	161.20	0.13	1.19	622.50	7.02	830.00	185.00	366.40	157.94	87.04	5.57
SB018	HDW	60.01	793.10	97.50	0.08	1.15	1620.00	7.30	2160.00	140.00	1235.20	149.52	135.06	7.95
SB024	BH	150.02	244.03	185.60	0.20	1.13	926.25	7.41	1235.00	126.00	235.00	151.50	235.00	19.23
SB028	HDW	540.07	183.02	173.20	0.12	1.12	546.00	7.14	728.00	210.00	326.40	146.19	67.53	3.98
SB030	BH	180.02	244.03	158.20	0.13	1.02	1830.00	7.42	2440.00	1055.00	792.00	174.13	276.12	22.27
SB034	HDW	60.01	305.04	148.00	0.14	1.37	1102.50	7.34	1470.00	315.00	715.20	165.56	156.07	13.52
SB040	HDW	60.01	305.04	148.80	0.24	1.14	847.50	7.55	1130.00	275.00	504.00	134.29	105.05	6.36
SB042	HDW	60.01	305.04	178.70	0.07	1.19	1605.00	7.24	2140.00	175.00	1297.60	150.79	129.06	8.75
JV028	BH	120.02	549.07	130.20	1.24	0.95	1102.50	7.70	1470.00	40.00	184.00	140.16	84.04	3.18
SB002	BH	180.02	122.02	242.00	0.08	1.20	937.50	7.68	1250.00	170.00	654.40	217.46	115.55	6.36
SB031	BH	180.02	244.03	198.40	0.44	1.84	1290.00	7.40	1720.00	480.00	516.80	211.90	202.59	7.16

JJ BH 01	BH	nill	546.60	476.60	1.53	1.24	1287.75	7.54	1717.00	74.10	157.30	78.20	150.00	3.70
JJ BH 02	BH	nill	546.60	489.60	1.63	1.30	1288.50	7.50	1718.00	79.80	162.60	80.96	145.00	3.70
JJ BH 03	BH	nill	241.60	357.50	1.48	0.82	1338.00	8.38	1784.00	264.10	71.40	51.98	265.00	4.10
JJ BH 04	BH	nill	358.70	402.60	4.10	1.37	1420.50	7.95	1894.00	271.70	106.40	55.20	260.00	4.10
JJ BH 05	BH	nill	553.90	201.30	25.90	0.85	941.25	7.10	1255.00	53.20	114.00	43.70	125.00	3.10
JJ BH 06	BH	nill	427.00	443.60	0.89	1.03	2122.50	7.65	2830.00	418.00	190.00	97.10	300.00	4.50
JJ BH 07	BH	nill	351.40	638.80	0.84	1.28	2767.50	7.55	3690.00	655.60	237.10	103.00	450.00	5.90
JJ BH 08	BH	nill	358.70	680.20	0.80	0.77	2767.50	7.65	3690.00	636.50	243.20	105.80	460.00	7.70

ANNEX 3 Well logs of boreholes drilled in Adigrat sandstone and Hamanlie limestone in southern Jigjiga

BH1 Stratigraphy

Top (m)	Bottom (m)	Stratigraphic Unit
0	36	Alluvial
36	84	Adigrat Sandstone
84	114	Weathered Basement
114	128	Fresh Basement

BH2 Stratigraphy

Top (m)	Bottom (m)	Stratigraphic Unit
0	38	Alluvial
38	56	Jurassic Limestone
56	80	Adigrat Sandstone
80	98	Weathered Basement
98	128	Fresh Basement

BH3 Stratigraphy

Top (m)	Bottom (m)	Stratigraphic Unit
0	36	Alluvial
36	99	Adigrat Sandstone
99	114	Weathered Basement
114	133	Fresh Basement

BH4 Stratigraphy

Top (m)	Bottom (m)	Stratigraphic Unit
0	36	Alluvial
36	84	Adigrat Sandstone
84	114	Weathered Basement
114	131	Fresh Basement

BH5 Stratigraphy

Top (m)	Bottom (m)	Stratigraphic Unit
0	38	Alluvial
38	56	Jurassic Limestone
56	80	Adigrat Sandstone
80	105	Weathered Basement
105	132	Fresh Basement

BH6 Stratigraphy

Top (m)	Bottom (m)	Stratigraphic Unit
0	38	Alluvial
38	63	Jurassic Limestone
63	82	Adigrat Sandstone
82	107	Weathered Basement
107	135	Fresh Basement

BH7 Stratigraphy

Top (m)	Bottom (m)	Stratigraphic Unit
0	36	Alluvial
36	84	Adigrat Sandstone
84	114	Weathered Basement
114	129	Fresh Basement

BH8 Stratigraphy

Top (m)	Bottom (m)	Stratigraphic Unit
Top	**Bottom**	**Unit**
0	38	Alluvial
38	63	Jurassic Limestone
63	82	Adigrat Sandstone
82	107	Weathered Basement
107	128	Fresh Basement

ANNEX 4. Hydro meteorological data

Rainfall

Station	East	North	Elevation	Jan	Feb	Mar	Apr	May	June	Jul	Aug	Sep	Oct	Nov	Dec
Jijiga	092000	0424700	1775	13.44	18.57	43.92	100.81	80.43	38.13	65.01	81.02	85.79	44.30	16.86	8.50
Degahbur	081300	0433300	1070	3.21	2.03	17.67	73.25	67.68	13.30	2.90	3.29	39.40	57.72	12.88	4.50
Jinacksan	93000	423600	2007	15.22	5.99	75.97	123.21	47.55	36.36	85.44	109.49	78.83	37.20	30.49	1.17
Kebribayah	090624	0431023	1753	8.68	0.00	5.33	39.67	67.73	26.20	19.90	73.33	64.00	25.50	37.40	2.10
Harshin	085442	0434400	1441	3.58	4.17	26.10	82.54	96.76	67.80	58.62	83.68	63.35	44.67	14.60	7.08
Lafa Ise	093000	0425400	1700	13.22	23.86	55.14	101.77	96.99	64.28	129.93	147.22	81.14	31.07	12.09	12.53
Hadew	93666	42666	1807	3.58	4.17	26.1	82.54	96.76	67.8	58.62	83.68	63.35	44.67	14.6	7.08

Temperature

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean
Jigjiga	18.38	19.58	20.63	21.29	21.63	21.79	21.34	21.56	21.59	19.77	18.35	17.66	20.30
Degahbour	23.58	24.67	25.66	25.81	25.23	24.57	23.98	24.73	25.81	24.75	24.13	23.73	24.72
Kebribeyah	19.34	20.29	21.15	21.62	21.58	20.75	19.35	19.20	20.15	20.37	20.33	19.45	20.30
Lefe Ise	22.61	22.38	22.68	22.78	23.32	22.93	22.03	21.83	21.95	21.60	22.12	22.63	22.40
	20.98	21.73	22.53	22.88	22.94	22.51	21.68	21.83	22.37	21.62	21.23	20.86	21.93

ANNEX 5. PET table calculated by Cropwat

Month	Min Temp °C	Max Temp °C	Humidity %	Wind km/d	Sun hrs	Rad $MJ/m^2/day$	Eto mm/d	Annual PET
January	15.4	31.8	57	2	10	22.4	3.76	116.56
February	16.2	33.1	57	2	10	23.7	4.16	116.48
March	17.6	33.7	56	2	9.8	24.5	4.48	138.88
April	19.1	32.5	74	2	8.7	22.9	4.54	136.2
May	19.2	31.2	71	1	8.7	22.3	4.32	133.92
June	19	30.1	72	3	8.4	21.4	4.09	122.7
July	18.9	29.1	75	3	5.7	17.5	3.42	106.02
August	19.4	30.1	73	3	7	19.9	3.85	119.35
September	19.6	32	70	2	8	21.6	4.22	126.6
October	18	31.5	64	2	6	17.9	3.44	106.64
November	16.8	31.5	67	2	5	15.4	2.96	88.8
December	16	31.5	63	3	8.2	19.4	3.41	105.71
								1417.86