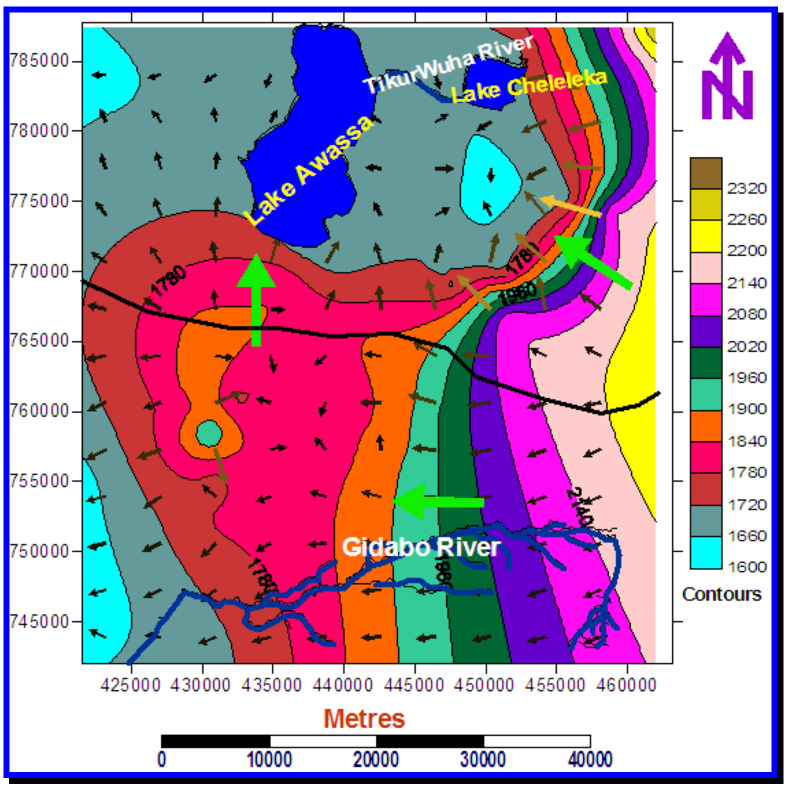
ADDIS ABEBA UNIVERSITY
SCHOOL OF GRADUATE STUDIES
DEPARTMENT OF EARTH SCIENCES

GROUNDWATER CIRCULATION AND HYDROCHEMISTRY OF THE CORRIDOR (UPPER GIDABO RIVER AND LAKE AWASSA CATCHMENTS), SIDAMA ZONE, SNNPRS



A thesis submitted to the School of Graduate Studies of Addis Ababa University in partial fulfillment of the requirements for Degree of Master of Science in Hydrogeology

BY: MULULGETA MUSSIE

JULY 2007

ADDIS ABABA

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BY: MULUGETA MUSSIE MEHARI
FACULTY OF NATURAL SCIENCES
DEPARTMENT OF EARTH SCIENCES
JULY 2007

Approved by board of examiners

Dr. Balemwal Atnafu
(Chairman, Department of Earth Sciences) ____________________________

Dr. Tamiru Alemayehu
(Supervisor) ____________________________

Dr. Seifu Kebede
(Internal Examiner) ____________________________

Ato Zenaw Tessema
(External Examiner) ____________________________

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ABSTRACT

The study corridor is found in Sidama zone, SNNPRS. It is situated in the Central sector of the MER system. The study area with 1582 km^2, comprises parts of the two adjacent catchments namely Lake Awassa and upper Gidabo River, which is delineated arbitrarily so as to determine whether there is groundwater circulation between them or not and quantifying the amounts. Recently, the Awassa lake level is continuously rising since some times and evacuate so many residences from the lake shore and damage properties. This rising of the lake level causes a major threat for the Awassa town and surrounding rural communities.

Integrated methodologies are used to find out the groundwater flow system and hydrochemistry of the corridor along with employing the appropriate software like Global Mapper, Surfer, ArcGIS, ArcView, and Aquachem that facilitate for analyses and interpretations of the data in order to get the output. The secondary date are collected from the concerning offices and some primary date are obtained during field work. Accordingly, groundwater flow system is considered as shallow and deep aquifer cases and the outputs indicate that there is the same flow trend within the two flow systems. Groundwater flows take place from south east towards north west and to the west; and there are also flows from central west (Yirba area) to the north (Lake Awassa) in the study corridor. The total groundwater flowing amount that outflow from upper Gidabo river catchmetnt is quantified to be 5.81MCM.

On the other hand, hydrochemical data analysis part also reveals: evolution of major ions, water types, potablity of water for human consumption, spatial distribution of some major ions including fluoride and direction of groundwater flow. For example, the water sample from hot spring and Lake Awassa is Na-HCO_3 type, which indicates the presence of evolution. Whereas cold springs mostly from highlands and the eastern rift escarpment has the water type of Na-Ca-HCO_3, shows minor evolution. The increasing trends of the phisico-chemical analyses indicate that there is groundwater outflow towards the lake region.

CHAPTER ONE
Introduction

1.1 General

Water is one of the most prominent components for life to exist on earth. Without it life is not possible. A person requires about 3 liters of potable water per day to maintain the essential fluids of the body (Fetter1994). Primitive people in arid lands exist with this amount as their total consumption. Water is also used for various purposes such as municipality, industrial, commercial, irrigation, and for energy production. Although many environmental factors determine the density and distribution of vegetation, one of the most important is the amount of precipitation.

In many regions groundwater and surface water resources are connected and most surface features (lakes, dams, wetlands, rivers) generally interact with groundwater.

The exploitation of, or quality of one resources, can therefore affect the other. In order to effectively manage water resources, it is vital to develop an understanding of the basic principles and relationships guiding groundwater and surface water interaction.

Stephenson (1971) has shown that the hydrologic regime of a lake is strongly influenced by the regional groundwater flow system in which it sits. Large, permanent lakes are almost always discharge areas for regional groundwater systems. The rate of groundwater inflow is controlled by watershed topography and the hydrogeologic environment. Small, permanent lakes in the upland portions for local flow systems, but there are geologic configurations that can cause such lakes to become sites of depression focused recharge.

Water level fluctuations can result from a wide variety of hydrologic phenomena, some natural and some induced by man. In many cases, there may be more than one mechanism operating simultaneously and if measurements are to be correctly interpreted, it is important that we understand the various phenomena. For example, Lake Awassa shows continuous lake level rise with remarkable increasing trend since some times. This causes the main problem for Awassa town as well as lake side rural dwellers. Hence, scientific researches should be conducted with different approaches in order to see and quantify the possible sources of the surplus water that are added to the lake region.

Accordingly, the study corridor comprises parts of the two adjacent catchments namely Upper Gidabo River and Lake Awassa, they were studied separately by different researchers in different times. On the other hand, this study is mainly focusing on the adjacent zone and trying to determine the groundwater circulation between the two catchments if there is any, through groundwater contour, hydrochemical trend approach and geological structures.

1.2 Previous Work

As long as the previous works are concerned, mostly, many researchers have done their works in Lake Awassa Catchment rather than the Upper Gidabo River Catchment with having different interests of the area such as hydrogeology, lake level rise, engineering geology, land degradation, groundwater modeling, groundwater recharge, etc, of the area.

The main works related to hydrogeology are: Former lake levels and climatic change in the Rift valley of southern Ethiopia (Grove et al., 1975). Geographical Society of Japan; The hydrogeology of MER conducted by Geological Survey of Ethiopia (GSE), (Tesfaye Cherinet, 1982); the study was conducted to prepare 1:250000 scale hydrogeological maps of the lake regions.

The hydrogeology of Awassa area (Dessie Nadew, 1997). The purpose of this work is to make a general study on the availability and the usability of the water resources in the Awassa basin; Engineering Geology of Awassa (Zemenu Geremew, 2000) This work is mostly done on the area of engineering geology and also touches the hydrogeology which related to lake water balance and water quality assessment; Pollutions on Awassa area (Elias Gugsa, 2004). Hydrogeology and Engineering of Lake Awassa is done by GSE (Zenaw Tessema and Taddese Dessie, 2003) with the main objective of investigating the problem of lake level rise and forward possible remedial measures through use of hydrochemical and isotope approach as well as catchment wise water balance, and detail geological mapping.

Conceptualization of groundwater flow system and aquifer characterization in Awassa Lake Catchment (Wondwosen Mekonnen, 2005). This work contains detail aquifer characteristics of the rock units, origins and interactions of groundwater and surface waters and the effects of neo-tectonism, which rely on geology, hydraulics data of wells, hydrochemical and isotopic data as well as hydro meteorological variables.

Assessment of the water balance of Lake Awassa catchments (Yemane Gebreegziabher, 2004). According to the water balance estimated using the spreadsheet model, hydrological components that plays an important role in the lake level fluctuations are known to be evaporation, rainfall, and surface runoff with 131,106, and 83Mm^3 long – term mean annual values respectively. Another component is groundwater. The attempt made to quantify groundwater component based on pizometric map using Darcy's equation indicate the importance of groundwater inflow in the lake water balance. Nevertheless, constant groundwater outflow from the lake estimated to be 43M m^3 per year in an important groundwater component which plays a role in the water balance and freshness of the lake Awassa.

Numerical Groundwater Flow Modeling of the Awassa Catchment (Nardos Tilahune, 2006).This work was done having the general objective to understand the regional groundwater flow systems and develop groundwater management schemes through simulation of regional ground water flow in the aquifer as single layer system under water table, steady state conditions; Groundwater Occurrence in Ethiopia (Tamiru Alemayehu, 2006). In this work it took into consideration different hydrogeological studies by the author, his colleagues and postgraduate students, and describes the existing groundwater potential together with the future possibilities for the exploration and development of groundwater in different parts of the country.

Hydrogeology of Upper Gidabo River Catchment (Kedir Yasin,2002); Hydrogeology of Yirgalem and Kilisa Sheets (Shiferaw Lulu and Abebe Gebere Hiwot, 2004). AG Consult, Consulting Hydro geologist and Engineers; Groundwater Resources study of Gidabo Basin (Yetnayet Nigussie, 1990). Generally the geology of the study area is studied as part of the Main Ethiopian Rift to mention some of the regional works: Mohr (1960) has described the volcanic sequences; Berhane Melaku *et al* (1979), and Kazmin and Seife Michael Berhe (1981) have made a geological map at a scale of 1:250,000 and 1:500,000 respectively; Giday WoldeGebriel *et al* (1990) give the stratigraphic framework and the volcano tectonic history of the central sector of the MER and Giday WoldeGebriel *et al* (1992) documented the source, distribution and age of major plio-pleistocene silicic tephras of the central sector of the MER.

1.3Present work

The present work comprises mainly upon the corridor that is found on the adjacent area from both catchments namely Lake Awassa and Upper Gidabo River that cover an area of 1582 sq km. From the previous work, it is understood that the groundwater as well as surface water resource evaluation assessment studies and or different scientific research works have been done in the area separately; having different intentions. Among the recent studies, two of them have indicated that there would have been the possibility of groundwater interaction between the catchments.

In this research, it is attempted mainly to identify and to confirm the existence of groundwater circulation and the major zone of interaction between the two adjacent catchments if there is any; quantifying the amount of water that flows to the lower catchment (Lake Awassa). And also to asses mainly the hydrochemical, and geological, hydrogeological, structural aspects of the study areas.

1.3.1 Objectives

General Objective

- It is to determine whether or not the groundwater flow takes place from the Upper Gidabo River watershed to the Lake Awassa catchments by using groundwater contours, hydrochemical trend analysis, and geological structural mapping.
- To study the hydrochemistry of the study area, especially focusing on the interaction zone, by using physico-chemical analysis of sampled water for safe and potable water utilization.

Specific Objectives

- ♣ to show interaction of groundwater between the two catchments if there is any.
- ♣ to determine the direction of groundwater flow.
- ♣ to show and map the controlling structures.

- ♣ to identify the main zone of interaction.
- ♣ to give possible suggestions for water resources utilization and environmental management measures.
- ♣ to prepare the hydrochemical maps (EC, TDS, and Major ions like Na, Cl and HCO_3) in order to recognize groundwater flow direction.
- ♣ to present geological, hydrogeological, hydrochmical, and structural findings of the corridor.

1.3.2 Methodology

The methodologies those are adopted to perform this work are described as follows.

- Literature review, surveying and studying of previous works from both catchments, especially in the corridor.
- Collection of data and previous works
- Preparing base map from topographic map at the scale of 1: 50000
- Conducting field work in order to observe and describe geology, hydrogeology, structures and morphology of the study corridor.
- Collecting and analyzing of the representative water samples from different water bodies to study the hydrochemistry of the study area.
- Performing the insitu test for the sensitive parameters like pH, TDS, EC, temperature. Water sampling tests were done in regional water bureau's laboratory.
- Carrying out the borehole inventory to record the water level of the wells so as to recognize groundwater flow direction along the corridor.
- Producing the structural map of the study area and determining whether the groundwater flow is controlled by structures or lithologies.
- Producing the hydrochemical maps such as EC, TDS, major ions, and groundwater contour lines that are used to observe groundwater circulation.
- Data interpretation based on field and previous works, laboratory results, and maps produced for different parameters.
- Different kinds of appropriate softwares (ERDAS, Arc view, Arc GIS, Global mapper, Surfer, Aquachem etc. were used extensively in this work.

CHAPTER TWO

GENERAL DESCRIPTION OF THE STUDY AREA

2.1 Location and Accessibility

The study corridor is found in Sidama zone, SNNPRS. It is located in the central sector of the MER system and bounded between 427000 to 462000 E and 743000 to 788000 N UTM location (8°20' to 38°39' E long and 6°43' to 7° 07' N lat) with total area of 1582Km² and perimeter 160.068Km (Figure 2.1). The study area comprises Awassa town, the capital of SNNPRS that is located at the distance of 270km from Addis Ababa.

As far as the accessibility of the roads in the study corridor is concerned, the main asphalt road from Addis Ababa to Moyale (Border town) crosses the entire length of the corridor. Generally the northern, central and southern parts of the study area are well accessed with gravel and dry weather roads. The western part of the area is mostly accessed with dry weather roads. However, the eastern plateau and escarpments are poorly accessed even in dry seasons.

2.2 Physiography and Drainage

The landscape of the study area is the result of volcano-tectonic and erosional processes. Generally as it is observed and noticed during field survey, and referred from the previous work that the landforms in the catchment can be broadly grouped into three: the plateau, the escarpment and the rift floor in which all the landforms showing a main feature of NNE-SSW alignment inline with the major tectonic line orientations. The maximum and minimum elevations in the study corridor are 3320 m.a.s.l. and 1680 m.a.s.l. on the eastern water divide(south east) and at Lake Awassa(rift floor) respectively. There is an elevation difference of over 1500 meter between the plateau (Pick Mountain) and the rift floor.

Lake Awassa is a caldera lake without surface outlet, formed by a volcano-tectonic depression. The eastern rim of the caldera is coincided with the eastern escarpment of the Main Ethiopian rift whose average throw is about 500m and its maximum elevation reaches 2700m.a.s.l.

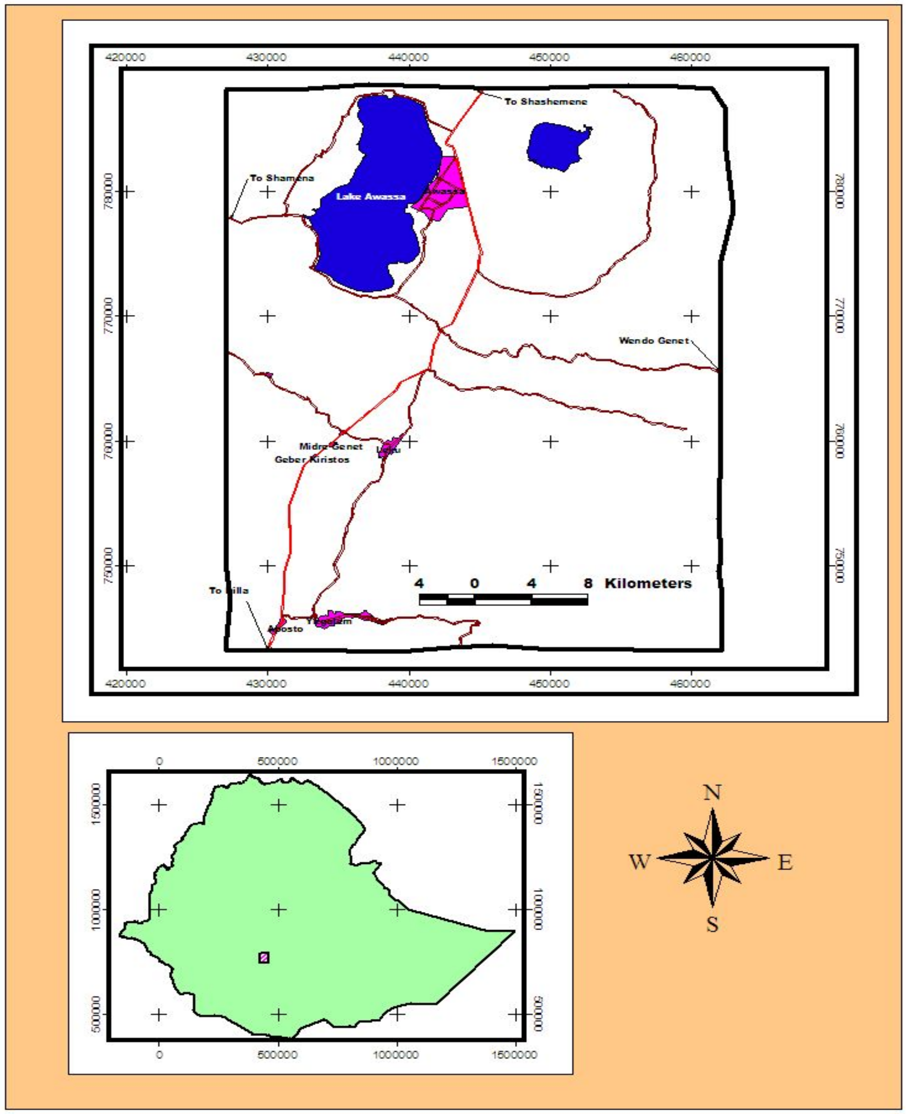


Figure 2.1 Location Map of the Study Corridor

The floor of the caldera is characterized by flat land containing Lake Awassa and some volcanic domes and cones.

The southern and western walls of the caldera form an arc, which is truncated by several NNE-SSW/N-S trending faults. These faults along with the caldera rims form local surface depressions with out surface connection with Lake Awassa such as Derba pond. The northern part is bounded by Corbetti caldera, which is a nested caldera within

Awassa caldera having elevated recent volcanic complexes such as Mt. Chebi and Urji with maximum elevation of 2200m.a.s.l. Water bodies, swampy areas and small volcanic hills characterize the floor of the depression, such as Lake Awassa, Shallo, and Mt. Tabor. (Wondwosen Mokonnen, 2005).

The rift floor is an undulating to rolling plain; the torrential streams rushing down the escarpment cut deeper into the rock formations of this region; thus the area is characterized by valley sides having relatively steep slopes and with convex summits.

The plateau occupies a narrow strip in the eastern part of the corridor forming a flat to undulating landscape that is slightly dissected with some depressions characterized by seasonal drainage deficiencies. The mountainous escarpment on the other hand is a highly dissected terrain with dense drainage system and torrential streams comprising the entire eastern escarpment. However, the south western part of the corridor is characterized by local horst and graben structures forming parallel wide valleys that are poorly drained and totally water logged during the rainy seasons.

The drainage pattern in the eastern part of the corridor is generally dendritic in which most of the streams originate from the eastern plateau and escarpment. The drainage is dense on the escarpment indicating the presence of impervious geological materials and occurrence of low infiltration triggering high runoff. On the other hand, the drainage pattern is sub parallel and sparse, and follows structural weakness zones in the central part of the corridor.

The major stream in the southern part of the corridor is Gidabo River. This river with having main tributaries like Kolla, Raro etc., drains to Lake Abaya that is found south west out of the corridor. There are also many small streams in this sub area which are tributaries of river Gidabo. On the other hand, Lake Awassa sub-basin is a volcano-tectonic depression (caldera), the drainage pattern becomes a radial type (Dessie Nadew, 1977). The only Perennial/significant River that drains from the eastern escarpment flowing westward, which replenishes Lake Awassa, is Tikur wuha with catchment area of 625km^2.

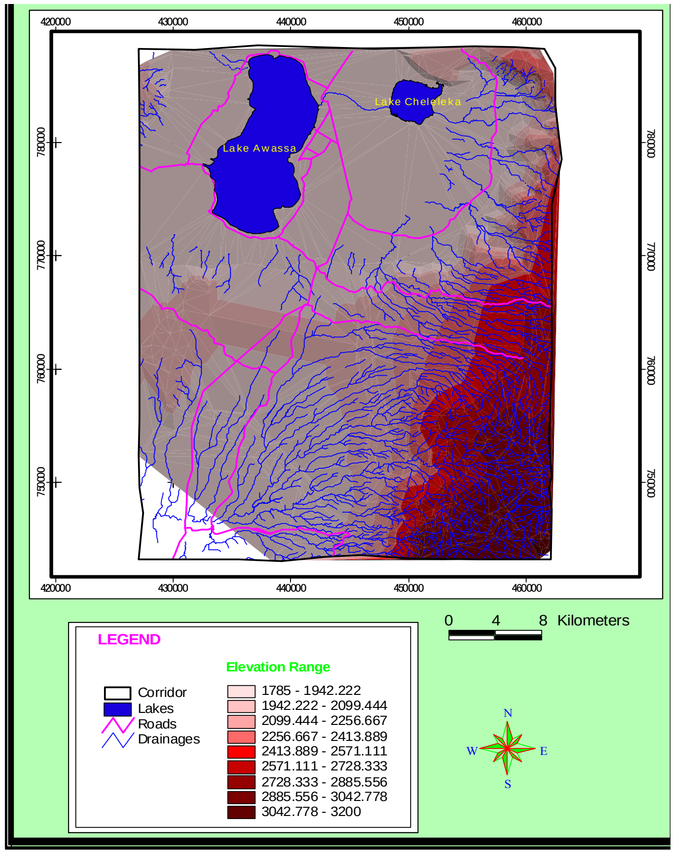


***Figure 2.**2 Physiography and Drainage Map*

2.3 Climate

Based on the annual and monthly mean of temperature and rainfall and also on seasonal changes of rainfall, type of natural vegetation associated and altitude the climate of the study area varies among temperate, subtropical tropical and tropical traditionally called "Dega" "Woina Dega" and "Kolla" respectively (National Atlas of Ethiopia, 1988). The mean annual rainfall of the southern part of the study corridor, around Yirgalem and high pick plateau areas, is 1379.22 mm and the mean monthly temperature varies between 17 ^{O}C and 20 ^{O}C that correspond to the months August and March respectively (Kedir Yasin, 2002).

On the other hand, the Awassa area has a sub-humid climate (FAO, 1984) and gets a mean annual rain fall of 1032mm over the entire northern part of the corridor. This sub area is characterized by an eight month long rainy season from March to October where the big rain (Kiremet) occurs from July to September with rain fall range from 70-140mm and the dry period is from November to February that gets less than 20mm rain fall.

The mean annual temperature at Awassa is 19.5^{0}C and the mean annual temperature ranges from 12-26^{0}C. Maximum temperature occurs in January, February and March that reaches around 29^{0}C where as minimum temperature occur during months of November and October which decreases up to 10^{0}C. Daily sunshine hours range between 4-9 hrs, where the minimum occurs during rainy seasons and the maximum during dry months. The mean monthly relative humidity at Awassa ranges between 54-76% which depends on the variation of dry and wet seasons (Wondowosen Mekonnen, 2005).

2.4 Soil and Land use / Land cover

The factors that control soil formation are climate, organisms, relief, parent material, time and vegetation. The processes of soil formation are those that modify the regolith and give it the acquired characteristic which distinguishes soil from the parent material. These processes are generally governed by climate/latitude (Bridges, 1978).

All types of chemical weathering operate most effectively in very warm and wet climate, for water is essential for most of the chemical reactions and rate of chemical reactions to increase with increasing temperature (Small, 1978). In humid tropical regions of the world (which is also characteristic of the studied area) ferallitization is a characteristic process of soil formation. This process involves the relative accumulation of the oxides of iron and aluminum with the loss of silica. The process of ferallitization is accompanied by a strong leaching of the soil, so the pH values are low. The resulting soil is freely drained and red in color (Bridges, 1978).

According to Kedir Yasin(2002), soils of the Southern part of the corridor namely Upper Gidabo sub-basin can be divided in to four textural classes: sandy loam (including the Red and Gray varieties), silty loam, clays and thin gravelly sand soils. While based on Wondosen Mekonnen (2005), in the Lake Awassa sub basin, soils on the rift floor are developed in recent alluvial deposits especially at the eastern part of this sub basin where as the rest of areas are associated with lacustrine sediments and volcanic material. Based on their dominant characteristics these soil types are classified in to four groups as mentioned above.

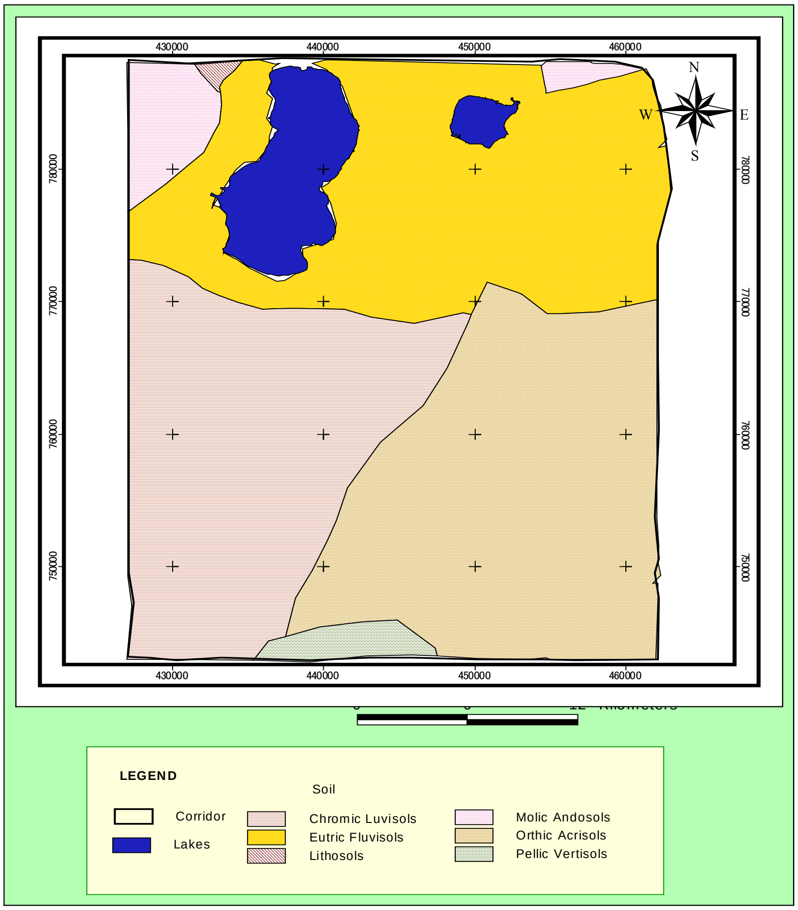


Figure 2.3 *Soil Map of the study Corridor modified after SNNPS, Bureau of Finance and Economy Development, regional atlas, 2005.*

Soil and land use/land cover map was prepared by Southern Bureau of Finance and Economy Development, Regional Atlas, (2006). Figure 2.3 shows a simplified soil map modified from this work. Based on this work the major soil units are cambisols, andosols, alisols and leptosols where they are classified based on the physical and chemical characteristics.

As far as land use is concerned, the main land use of the study corridor is rain fed agriculture with agro-forestry practices. Thus, on the northern part of the area at the rift floor, Awassa state and private small holding farms are occupying a considerable wide area surrounding the lake. Swampy areas are found in and around Lake Cheleleka and at some places in Boricha and Shebedino woredas. These places are used as a very important grazing land. Vegetation is greatly related to climate, altitude and soil type. The plateau area is covered with Juniper trees and bamboo in which the gentle valley slopes and wide valley bottoms are covered with cereal crops like barley and wheat.

Enset (false banana) and cereal crops are cultivated in almost all areas including the bowed slopes. In the lower parts of the escarpment especially below 2000 m.a.s.l coffee and horticultures dominate and the cereal crops changed to sorghum and maize. Accordingly, Figure 2.4 shows the modified land use map of the study corridor. In this map it is observed that the wide area of the southern and central part of the study corridor is intensively and moderately cultivated, respectively.

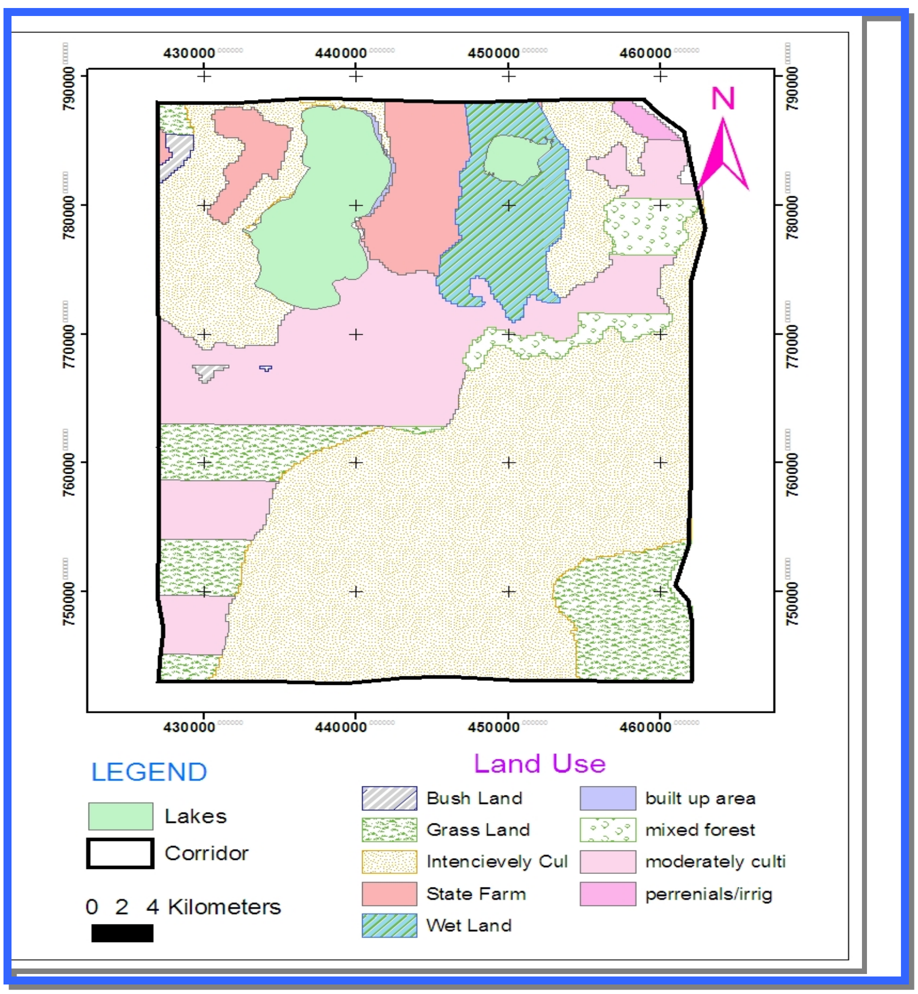


Figure 2.4 *Land uses Map modified after SNNP, BOFED, regional atlas, 2005.*

2.5 Population

Human

The total population, in the study area that comprises almost of four woredas namely Dale, Shebedino, Boricha and Awassa Zuria, was estimated based on regional Statistical Abstract (2005) prepared by Central Statistical Agency. Accordingly, the population size of the study corridor is about 1,508,728 as of July 30, 2005 projection.

2.6. Groundwater and surface water development

2.6.1 Public Consumption

Relatively groundwater is developed at the central part and along the Wondogenet ridge for drinking water supplies through drilling wells and capping high yield springs of the study corridor whereas the western margin and south eastern parts mainly the plateau areas are poorly developed. The rural people who are living in these areas are using water for their day to day activities and livestock from springs and surface water sources like rivers and streams and from dug wells. The hot thermal groundwaters and springs in Yirgalem (Gidabo), Wondogenet, Kidanemihret and Awassa (Gemeto) are often used for bathing, livestock watering and curative purposes.

Regarding to the water quality, at the vicinity of Lake Awassa, including itself, the fluoride concentration is beyond World Health Organization's (WHO's) guidelines, 2004 which is 1.5 mg/l. Therefore, the water from these areas is not potable.

Urban water supply System

The major towns in the study area are Awassa, Yirgalem, Leku and Yirba which have the water supplies from both surface and groundwater sources.

The surface water resources in the study area is already developed and used for Yirgalem and partly for Awassa towns from Gidabo and Kedo rivers respectively for water supply system. There are 3 to 5 boreholes with yields ranging 6-12 l/s that are developed at Gemeto well field to supply water for Awassa town. Loke spring, which was rehabilitated in 1981 E.C for the rural communities, has also been partly supplied to this town. The collective yields of the Loke spring and other springs, which are found at the vicinity of it, are about 25-30 l/s (report from Bureau of Water Resources Development, 1991 E.C).

As the population and business activity of the towns are growing at an alarming rate, obviously, more water will be needed in the future. This additional water demand can be supplied by either increasing the number of boreholes around the Gemeto well field and/or utilizing surface water resources of the study corridor based on detail hydrogeological studies.

The main potential source for Awassa in the future would be Gidabo River. (Shiferaw Lulu and Abebe G/Hiwot, 2004).

Newly drilled two productive boreholes intending to supply water for Yirgalem town has been abandoned due to its high iron content beyond WHO water quality standard. The water supply system of Yirba and Leku towns are from groundwater sources. There are two to three new boreholes drilled for each town. These can be sufficient for the current populations of the towns, but in the future the demand will increase; therefore, extra sources should be designed ahead of time.

Rural water supply Systems

The groundwater development for the rural areas especially in the central part of the study area, are mainly concentrated on shallow and hand dug wells. Mostly, peoples who are living in highlands (on plateau area) are using water for drinking and other activities from springs and streams respectively. As there is sufficient groundwater resource in the area, the rural water supply schemes would basically depend on groundwater resource like capping springs and constructing shallow wells.

2.6.2 Irrigation

Concerning the irrigation practice of the study corridor, few works have been observed and identified during field survey. As pre knowledge of the area and from previous work (AG Consultant, 2004), there are traditional extensive usage of the existing streams and rivers around Wondogenet area for cash crops including chats through small scale irrigation.

On the other hand, three schemes have been identified in the southern part of the study area. These are:

- Wamole irrigation scheme;
- Raro irrigation scheme; and
- Chancho-Dese irrigation scheme.

Wamole irrigation scheme

This is an existing scheme with a diversion weir across Wamole River. It is located 2 Km away from Leku town. Currently, the scheme is irrigating about 35 ha. However, the reconnaissance study by Co-SAERSAR (1998) indicated that the command area of the scheme 75 ha.

Raro Irrigation scheme

This is a scheme planned by Co-SAERSAR (1998) to irrigate about 100 ha by diverting Raro River, which is a tributary of Gidabo River. According to the report, the site is located between 6º 35’ N –6º 45’ N Latitude and 38º 20’ E – 38º 30’ E Longitude. The exact location of the proposed diversion point could not be identified. However, a suitable site occurs at 428300 E and 736800 N UTM and 1780m a.s.l.

Chancho-Dese irrigation scheme

This scheme has been established with financial assistance of Lutheran World Federation by constructing a diversion weir across Gidabo River at Chancho Kebele 425750 E and 743900 N UTM (see Figure 8.4). The scheme irrigates about 300 ha. (AG Consultant, 2004)

CHAPTER THREE
GEOLOGY

3.1. Regional Geology

The MER is the northern segment of the Great East African rift system running NNS-SSW direction, which is a fault bounded trough bordered by the plateaus in the east and west. It is the result of Cenozoic volcano-tectonic and sedimentation processes. It extends from Lake Abe, Afar-triple junction and dies out southward into Lake Turkana and Lake Stifane rifts south of Lake Chamo. It is about 80km wide and 700km long.

The MER is characterized by active extensional tectonics. Two main fault systems have been distinguished in the MER: a N 30 ^{O} E - N 40 ^{O} E trending fault which characterizes mainly the rift margins and a N-S to N 20 ^{O} E trending fault system, the Wonji Fault Belt (WFB), which exhibits a number of sigmoidal, overlapping right-stepping en-echelon fault zones obliquely cutting the rift floor (Boccaletti *et al*, 1998). Tertiary volcanic rocks dominate most of the geologic sections exposed along the rift margins.

The MER is divided geographically in to three sectors: Northern, Central and Southern. The central sector of the MER in which the study corridor is a part is more than 175 km long and 75 km wide extending from the north of Lake Ziway in the north to Lake Abaya in the south. The central sector of the MER is a symmetrical rift mostly characterized by well-defined synthetic rift margins having variable throw along the strike of boundary faults. The rift escarpment is subdued at places due to weathering and accumulation of pyroclastic falls along the margins.

The plateau areas overlooking the rifts probably originate during the Oligo-Miocene when an immense volume of Trap basalts and minor ignimbrites were out poured on top of an up-domed Mesozoic and Precambrian basements. Volcanism, plateau uplift and development of the Main Ethiopian Rift have been attributed to a mantle hot spot beneath the Ethiopian plateau (Ebinger *et al*, 1993).

Concerning the development of the MER different interpretations and dates have been given by different authors: pure tension (Di Paolla, 1972; Giday Woldegebreil et al., 1990: Ebinger et al., 1993; Chorowicz et al., 1994); transtention (Bocalleti et al., 1992); oblique rifting (Bonini et al., 1997); and extensional tectonics (Mohr 1967).The geological development of the study area, as it is the part of MER, is the result of the geological events that took place in the part of the eastern Africa and Ethiopia. In the part of the eastern Africa and Ethiopia following the regression of the Mesozoic Sea to the south-east a major uplift occurred, which is known as the Arabo-Ethiopian Swell resulting in upraised and up arched land mass fissuring of which under tension permitted the ascension of voluminous basaltic magma to form the Ethiopian flood basalt province (Mengesha Tefera et al., 1996).

Uplifting and fissuring under tension and volcanism was followed by rifting of the red sea at first which was then followed by rifting in the Afar depression and finally in the Main Ethiopian Rift. Migration of volcanism controlled by regional structural development has been documented within the tertiary flood basalt province in Ethiopia (Mengesha Tefera et al., 1996).

The earliest volcanic sequences mainly representing the Ethiopian Flood Basalt Province are found typically overlying the Precambrian, Paleozoic or Mesozoic sediments and also found inter-bedded with Cretaceous regressive sandstones along the southern and western margins of the Afar Depression (Mengesha Tefera et al., 1996).

The earliest flood basalts are known by the name as Ashangi Basalts (54 to 36 Ma), Jima Volcanics (42.7 to 30.5 Ma), Aiba Basalts (34 to 28 Ma), Arsi and Bale Basalts (Oligocene to Miocene), Mekonen Basalts (34.8 to 23.1), Alajae Formation (36 to 13 Ma), Tarmaber Gussa and Tarmaber-Megezez Formations (26 to 9 Ma). This flood basalt volcanism culminated by the formation of alkaline basaltic shield volcanoes such as Tarmaber Formation (Mengesha Tefera et al., 1996).

Jima volcanics are the earliest volcanics, which cover most part of the southern Ethiopia, are considered analogous with the main flood basalts volcanic sequences. It covers major part in the south and southwest Ethiopia in the areas extending between Hagre Selam and Mizan Teferi in the east to west direction being dissected by the rift and covered by silicic volcanics in the rift proper and in the north to south direction extends between Bedele and Jinka. This volcanics form a thick succession of basalt and felsic rocks with basalt dominating its lower part. Jima volcanics almost always rest on the Precambrian basement and Davidson (1983, in Mengesha Tefera et al., 1996) has reported age of 42.7 to 30.5 Ma and 29.7 Ma by Gidey Woldegebriel et al (1990).

The name Nazareth Series was given to a thick succession of welded ignimbrites with fiamme, pumice, ash and rhyolite flows and domes with rare intercalations of basalt which occur in the MER, rift margins and adjacent plateaus (Meyer et al., 1978 and Mengesha Tefera et al., 1996). These volcanics are considered to be products of eruptions mainly from marginal centres in the rift and an age range of 9 to 3 Ma has been given on the basis of Mio-Pliestocene lacustrine sediments of the Chorora Formation and some Absolute K/Ar age determinations (Morbedelli et al., 1973, Tiercelin et al., 1980; Kazmin and Seife Michael Berhe, 1978 and Mengesha Tefera et al., 1996).

Dino Formation belong to a rocks made up of green and grey ignimbrites with well developed fiamme and unwelded pyroclastics and water lain pyroclastics with occasional intercalated lacustrine beds and aphyric basalts which overlies the Nazareth series in the rift valley. This formation according to the geological map of Ethiopia (Mengesha Tefera et al., 1996) covers an extensive area within the MER in the area between Lake Abaya and Awash town. In Awash Gorge an ignimbrite member of Dino Formation was isotopically dated to be 1.5 Ma old (Kazmin and Seife Michael Berhe, 1978 in Mengesha Tefera et al., 1996).

In the course of the development of the rift system, a variety of continental sedimentary basins were developed, in the MER lacustrine sedimentation is wide spread during the pluvial period of quaternary resulting the present rift valley lakes where they are the remnants of one mega ancestral lake. The Pliocene age Awassa caldera is a result of this tectonic and geologic evolution and is by far the largest in the east African rift system, covering half the width of the rift floor, approximately 50x40 km (Gidey Woldegebriel, 1968). The caldera is composite, containing the younger 15km wide nested Corbetti caldera with in it in the northern margin. The main Awassa caldera is asymmetrically overlapped against the eastern rift escarpment causing this rift margin arcuate, while Corbetti is along the rift axis.

The oldest volcanic rocks, which are the plateau trap series are exposed on the western escarpment and consists of about 1000m of basaltic lava flows, with interbedded ignimbritic beds, overlaid by massive rhyolites and intervening tuffs and basalts (Di Paola, 1972; Merla et al., 1979; Gidey Woldegebriel et al., 1990). Radiometric age of the basalts range from 40-25Ma and the rhyolites 37-27Ma (Merla et al., 1979; Gidey Woldegebriel et al., 1990).

The eastern plateau is constituted by Pliocene to early Pleistocene (4.6-1.6Ma) shield volcanoes such as Chillalo, Kecha and Badda). It is characterized by trachayte with subordinate basalts and mugearites (Di Paola, 1972; Merla et al., 1979; Gidey Woldegebriel et al., 1990), Miocene phonolites.

Most parts of the floor of the MER are covered by silicic pyroclastic materials, mainly per alkaline rhyolitic ignimbrites, interlayered with basalts and tuffs associated with unwelded pumice (Mohr, 1962; Di Paola, 1972; Gidey Woldegebreil, et al., 1990). They are early to middle Pliocene. Alkaline and Per alkaline rhyolitic lava flows associated with pumice and ash represent the late silicic volcanic events (Di Paola, 1972), where they were erupted from late Pliocene to middle Pleistocene, and in some places outcrop as remnants of large caldera.

A more recent volcanic rock occur along the Wonji Fault Belt, which is made up of basaltic lava flows, associated with Hayaloclastites and Scoria cones (Di paola, 1972.). It is very recent and localized, with a radiometric age of 0.13Ma (Gidey Woldegebriel et al., 1990). The Bora Bericco complex, the Aluto volcano, Ficke, and Corbetti calderas are the youngest volcanoes & calderas in the region started to be active from middle Pleistocene (about 0.25Ma) (Di Paola, 1972; Gidey Woldegebriel et al., 1990). They are made up of rhyolitic lava flows, unwelded pumice flows & falls and ashes with obsidian, the obsidian flow represent the final product of the volcanic activity. Obsidian flows and pumices were dated 2000yBP (Gianelli, et al., 1993).

The study area is mainly covered with different volcanic sequences and minor fluvial and lacustrine sediments.

3.2 Local Geology

3.2.1 Lithologies

According to Kedir Yasin (2002) and Wondwosen Mokennen (2005), in the study corridor, six lithologic units in the southern part (Upper Gidabo River catchment) and five in the northern part (Lake Awassa basin) have been identified and discussed, respectively. These have also been confirmed through field observation and past working experience. The lithologic units are described here from the oldest to the youngest as follows:

The lithologic unit in the southern part of the study corridor (Upper Gidabo River Sub Catchment)

♣Basaltic lava flows (Old)

It is found in the eastern part of the catchment and the unit is covered with ignimbrites except where the streams rushing from the escarpment cut deep gorges exposing the unit. Radiometric age determination of the basalt some 2 km to the south of the sub catchment show an age of 29.7 Ma (Giday WoldeGebriel *et al*, 1990). The unit may belong to the Kella basalt.

♣ Rhyolitic Ignimbrite (Old)

The ignimbrite overlying the basalt is highly welded, gray in color and porphyritic texture with phenocrysts of feldspars and quartz. They are overlain by thin ash fall deposits, which are quarried by the local community in the plateau for construction purpose. These ignimbrites also belong to the Kella basalts.

♣ Basaltic lava flows (Young)

They out crop in a localized area along the Kola river valley. The basalts are aphanitic, highly fractured and the top parts are highly vesicular. They may be the bottom formation in the rift floor and belong to the Gurage basalts.

♣ Young rhyolitic ignimbrites

Observed to overlay the young basaltic lava flows they cover large area especially the southern central part in this sub catchment. The ignimbrites are highly welded in which the degree of welding decreases to the top and sometimes laterally. They are characterized by gray and sometimes brown color with flattened and glassy clasts "fiamme" and having eutaxtic texture. This unit may belong to the Butajira ignimbrite.

♣ **Un-welded pyroclastic flow deposits**

They are pumiceous pyroclastics and their origin is assumed intimately associated with the collapse of the Awassa caldera, which might have created fresh fissures in the Yirga Alem area from which great quantities of pyroclastics might have erupted (Berhane Melaku *et al*, 1979). They are exposed mainly in the southern and central part of the study corridor especially in the river valley between Aposto and Yirga Alem.

♣ **Rhyolitic dome and lava flows**

This unit outcrops in the western part of the basin that is affected by a series of normal faults dipping to the west and the east forming local horst and graben structure. There is a talus deposit in the lower parts of the slope especially around the dome (Boricha Ridge). Radiometric age determination from this rocks show an age of 2.5 million years (Giday WoldeGebriel *et al*, 1990).

Lithologic units of the northern part of the study corridor, Lake Awassa Sub Catchment

◙ **Basalts of the plateau trap series (Late Miocene)**

These are the most ancient rocks of the area, which are found on the eastern and southeastern part of the caldera wall where the caldera wall overlaps with the eastern escarpment. These rocks are geochronologically grouped under Gurage basalts (Woldegebriel et al., 1990). These rocks are assumed to be the foundations where the mega Awassa caldera was constructed with age of 9.8Ma (Gidey Woldegebriel, 1987; Gidey Woldegebriel et al., 1990).

◙ **Old Alkaline and Peralkaline silicic rocks (Late Pliocene-middle Pleistocene)**

This unit constitutes the rift pyroclastics and the old rhyolitic lava flows that includes unwelded to moderately welded tuff, pumaceous pyroclastics, ignimbrites, and tuffs. It covers large parts of the periphery of the caldera where it is widely distributed on the eastern wall of the caldera. The ignimbrite is also found south of Lake Awassa forming a ridge (Dulecha ridge). The rhyolitic ridges at Wendogenet, with age 2.45Ma (Gidey Woldegebriel, 1987) and the rhyolitic necks on the floor of the caldera south east of lake Awassa are also included in this unit, having vertical sheeting and flow folding structures.

- **Recent Basaltic lava flows, Hayaloclastites and Scoria cones (recent Pleistocene)**

This unit contains Basaltic lava flows associated with scoria cones and Hayaloclastites forming smaller scattered relief on the floor of the caldera with thickness of a few dozen meters. The Scoria is mainly associated with scoraceous basaltic flows, exposed east of Lake Awassa such as Mt. Tumura. The Hayaloclastites are yellowish to brown in color, mainly containing fine glassy material with large blocks of basaltic, rhyolitic and ignimbritic rock fragments. This unit is found on the west and north east of Lake Awassa such as Werensa ridge.

- **Recent Acidic volcanics (< 1.6Ma)**

This unit is the youngest volcanic product in this sub catchment consisting of unwelded pumice flows, pumice falls, ashes, welded fine tuff and rhyolites with associated obsidians and pitchstones. This unit is exposed north and North West of lake Awassa around Corbetti volcano. The pyroclastic deposits, welded and unwelded tuff deposits of the eastern and western caldera wall and the product of Chebbi volcano (Mt. Chebbi and Urji).

- **Volcano-lacustrine deposits (Pleistocene to recent)**

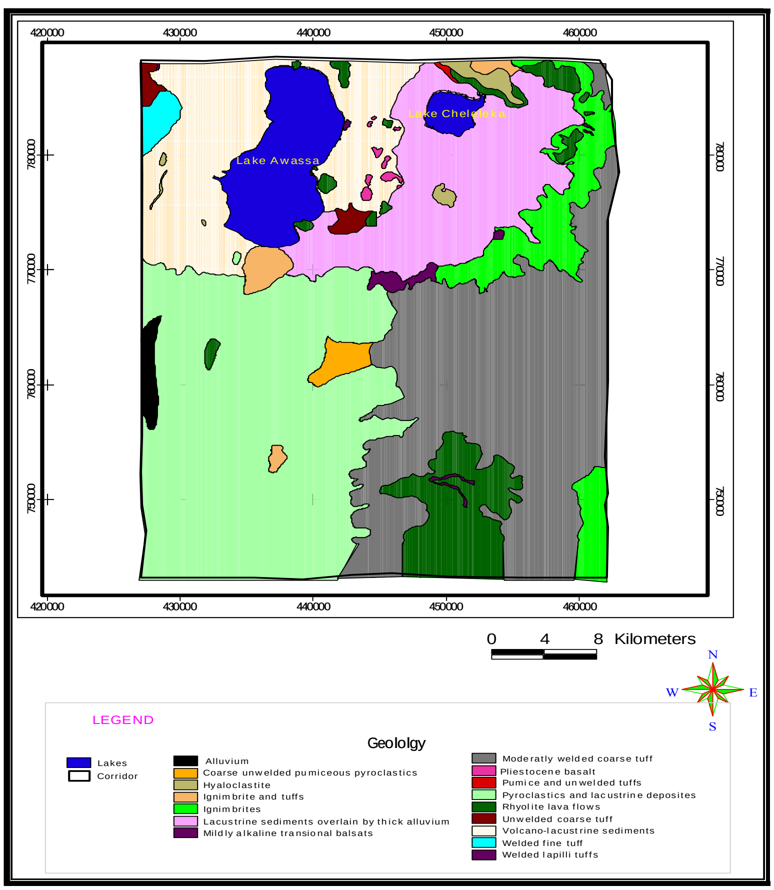
This unit is the only non-volcanic formation in the area covering almost all parts of the floor of this sub catchment, deposited as a result of the recession of the lake. These sediments are volcanic in origin and covered by alluvium along river beds. These lacustrine deposits have variable lithology which is related with their mode of origin (Tenalem Ayenew, 1998), i.e. they are either quiescent lake deposits, water deposited volcanic ejecta or coarse sediments intruded in to the lake by flood events.

Generally, Figure 3.1 shows the geological map of the study area. In this map the lithological units that exposed on the study area are summarized as follows:

- Pyroclastic and lacustrine deposits, these units are exposed on the wide area of south western part of the study corridor including alluvium, ignimbrite and tuff.
- Moderately welded coarse tuff is found on eastern and mostly south eastern part of the study area.
- Rhyolitic lava flows are exposed on the southern part of the corridor; on the eastern escarpment of the rift & its floor as dome near the lake.
- The entire part of the rift floor is occupied by mainly two lithologic units such as Volcano-lacustrine and lacustrine sediments overlain by thick alluvium. In this part there are also minor units namely plistocene basalt, hayaloclstite, pumice and unwelded tuff, unwelded coarse tuff are exposed well.
- Ignimbrite is exposed on the eastern rift escarpment. Wondogenet ridge is made of this unit. It is also found on plateau and south western margin of the study corridor

Figure 3.1 *Geologic Map of the study area*

Modified after Wondosen Mokonnen, (2005)



3.2.2 Structures

Generally the study area is characterized by both volcano-tectonic structures such as fault, fractures (cracks), caldera, and volcanic domes and cones. The structures observed in the southern part of the corridor (Gidabo River sub-basin) are generally extensional and there are two sets of structures. The faults that are related to the collapse of the Main Ethiopian Rift and those associated with the collapse of the Awassa caldera. The faults are oriented in NNE-SSW direction. The western central part of the study area is generally affected by the faults and extension fractures associated with the collapse of Awassa caldera.

The faults in the area are steeply dipping. The fault in the eastern part of the catchment is dipping to the west where as the faults in the western part dip to the west and the east forming local horst and graben structure (Kedir Yasin, 2002).

Volcanic domes, cones, caldera, faults and intense ground cracks and fractures are the frequent structures in the northern part of the study corridor around the Lake that can be easily identified and mapped. There are at least three types of faults, which are present in the area based on their strike directions, NNE-SSW, N-S running, NW-SE and E-W running faults/fracture zones.

The youngest part of the Rift is the axial zone, which presently coincides with the Woji Fault Belt, mainly formed during Quaternary (Mohr, 1967, 1987). The WFB is characterized by NNE-SSW-trending active extension fractures and normal faults, which in many places are associated with fissural or central volcanic activity (Gibson, 1969; Mohr, 1987; Chorowicz et l., 1994)

In the study corridor, the NNE-SSW and N-S running faults are the Rift escarpment faults, dominant in the area where Lake Awassa is also oriented in this direction. These faults are expansion normal faults forming steps and are found mainly on the southern and eastern part of the lake. These faults made parallel-elevated blocks and depressions such as southwest of the Lake near Muleti, where the depressions have no surface connection with the Awassa Lake.

The NW-SE transfer faults are rare in the area but observed on the northwest part of the area around Corbetti, northeast part of the Lake and on the eastern margin of the rift. The E-W running faults are dominantly found on the southern watershed where the rivers/streams in this area are controlled by the direction of these faults/fracture zones (Wondwosen Mokonnen, 2005). Buried faults of this type are also found on the floor west of the Lake, which are traced by geophysical survey from WWDSE, (1999).

According to Acocella et al.,(2003), E-W running faults are crossing the entire corridor at three places (north, centre and south).They join together approximately at UTM location of 486661E and 765303N further east out of the study corridor those can easily be observed from the modified map in Figure 3.2. The interaction of faults implies that the area is affected by the sub-regional normal faults which favor the circulation of groundwater in between the two catchments. This is witnessed by the northern fault crosses the Wondogenet ridge where there is high discharge zone.

Structurally, the area is complex by the presence of Corbetti caldera, which is located at north of the corridor and affected by the NNE-SSW running faults; it is nested in the larger Awassa caldera. The remnants of the larger Awassa caldera preserved on the eastern and western part accompanied by normal faults and fracture zone.

The Awassa caldera is situated on the axial zone of the MER. The axial zone is a place where younger and active volcanism and recent tectonic activities are took place as evidenced by high seismicity and geothermal activities. This zone is presently coincides with the NNE-SSW trending WFB where active extensional fractures and normal faults are found. Recent ground cracks were developed in the area west of Lake Awassa since 1996. This ground cracking is situated on the axial zone with similar trend of propagation with the adjacent fault scarps and mountain ridges.

The ground cracks occurred in two places; west of Lake Awassa around Muleti village and further south of Muleti on Derba area. The cracks on Muleti developed in 1996 and have average width of 2.5m, with measurable depth of 8-12m and maximum length of 2.4km (Lulseged Ayalew,et al.,2004).

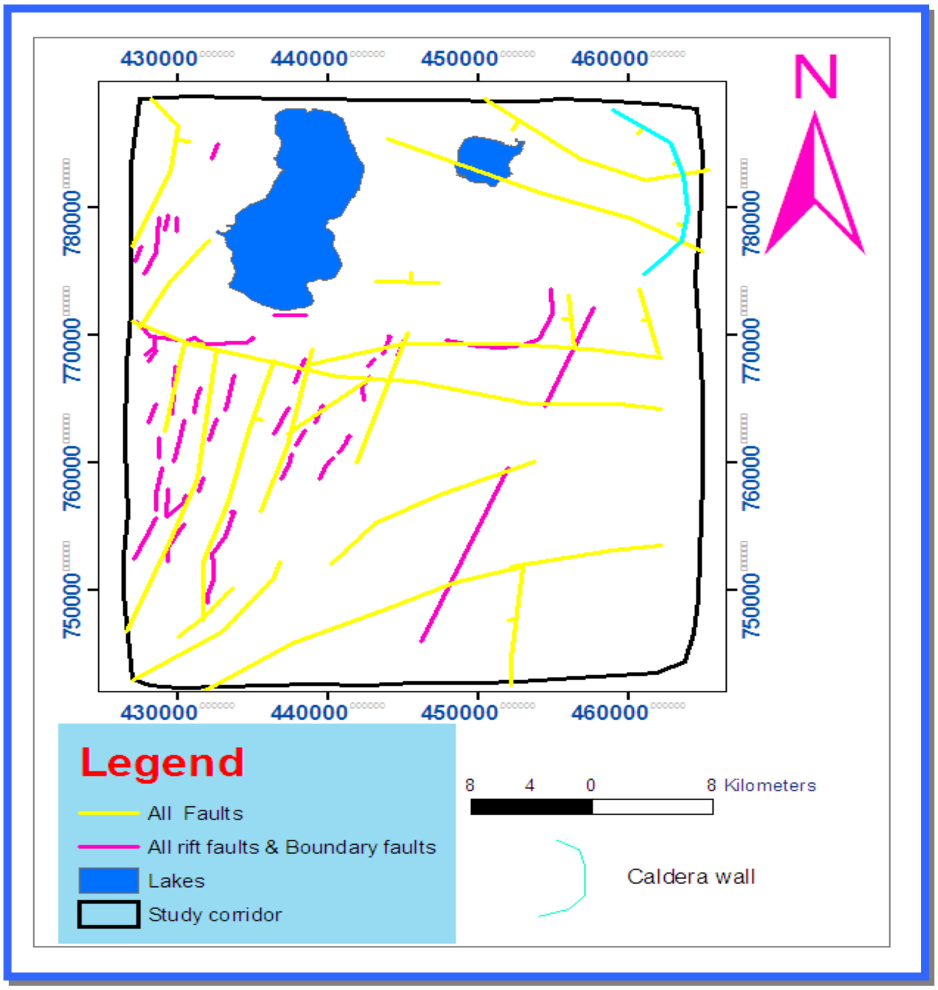


Figure 3.2 *Structural Map of the study corridor, modified after Acocella, et al., 2003 and Bekele Abebe,et al., 2007.*

The cracks on Derba area have a width of 2-8m and observable depth up to 5m with no vertical displacement. The cracks strike approximately $N30^0E$ with a characteristic of intersecting oblique extension cracks trending $N60^0W$. The features are observed on top of the alluvial deposits. Figure 3.3 shows the photographs of the cracks in Derba and Muleti area). The Derba area is previously occupied by a pond which is Derba Pond. The water of this pond was disappeared through these cracks three years before (2002) when they were formed (information from the residents). From this it can be deduced that these cracks are also propagated with depth. Even though, there are no substantial evidences, (Wondwosen Mokonnen, 2005).

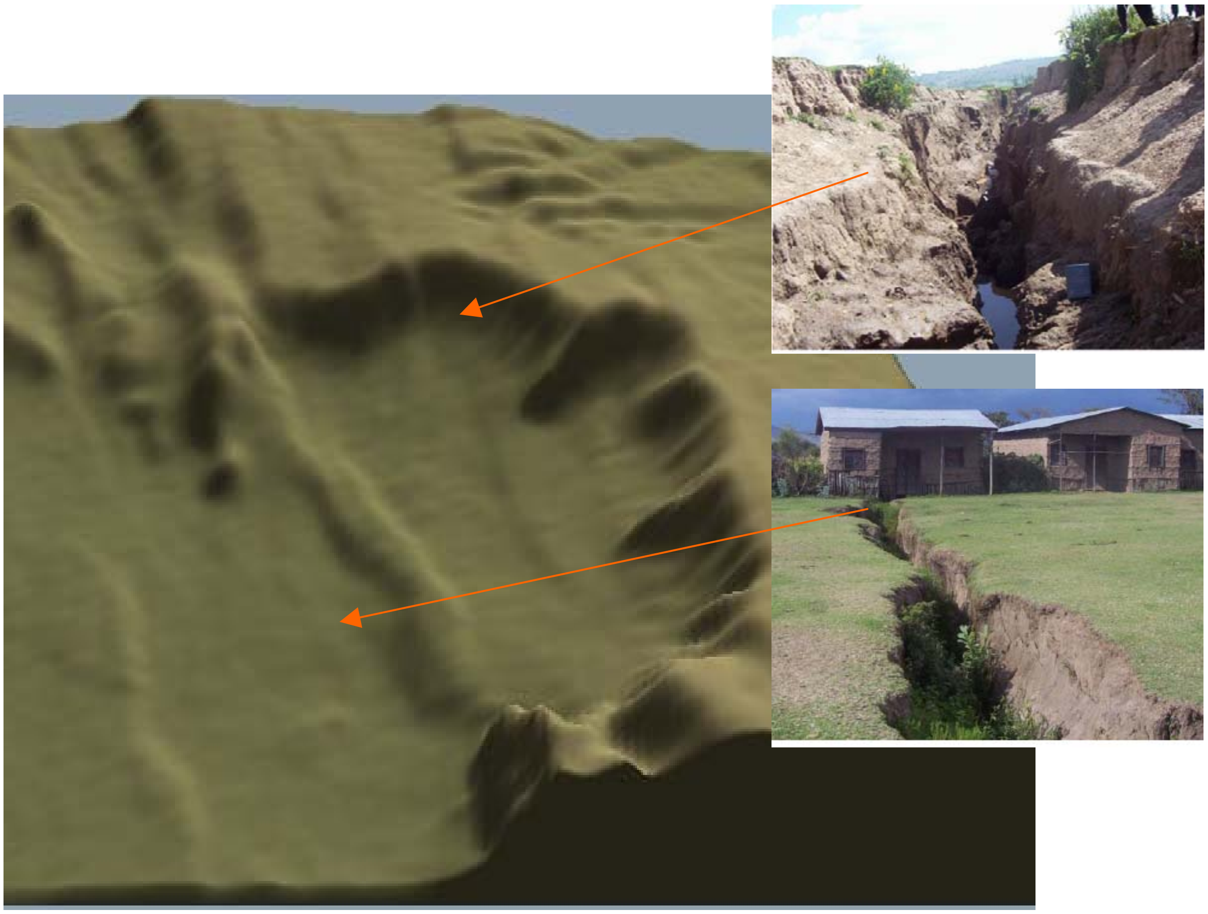


Fig. 3.3 *A DEM along with a photographs showing the area where the cracks are formed. (Source: Wondwosen Mekonnen,2005)*

CHAPTER FOUR
SURFACE WATER HYDROLOGY

4.1 General

The surface water resources of the study corridor occur in the form of rainfall, runoff, perennial and intermittent streams, rivers, and lakes. The amount of annual evaporation is almost twice as much as the amount of rainfall per annum at Lake Awassa area. The rainfalls occur nearly throughout the year with a greater portion it being received during the period April to September.

The various springs, streams and rivers that emanate from the Wondogenet ridge in the east and south eastern plateau are contributing much of the surface water resources of large area of the study corridor. In one hand, in the northern part of the study area, converging at the downstream end streams and rivers feed the swamp in the south of Lake Cheleleka and drained by Tikur Wuha into Lake Awassa. On the other hand, in the southern part of the corridor, so many tributaries those originated from the eastern high plateau end up at river Gidabo. This finally drains to Lake Abaya, which is found further south of the study area. In short, the perennial and intermittent streams, and rivers and lakes are the major constituents of surface water. Quantitatively there is an adequate amount of surface and subsurface water resources in the area. Among them the major surface water bodies are discussed here blow as follows:

4.2. Lake Cheleleka (Shalo)

Lake Cheleleka is situated at about eight kilometers north-east of Lake Awassa. The surface area of Lake Cheleleka was about 12km^2 in 1972 but currently it is completely disappeared as a result of siltation. The lake floor, which once was covered by water, is now filled by sediment transported from the eastern highland as a result of deforestation that has taken place over the last short time. In what once there was water, now tall papyrus like grasses have gown.

However, it receives inflow from streams and springs those originate from the Wondogenet ridges and run off from its water shade. The water quality of Lake Shalo is characterized by relatively low salinity. Its EC varies between 500-750 µs/cm depending on the seasons with average EC value of 625 µs/cm. The major ionic composition is $NaHCO_3$. Lake Awassa has been replenished by inflow from Lake Cheleleka through Tikur Wuha River (Wondosen Mekonnen, 2005).

The lake receives untreated and improperly treated industrial wastes from the major industries of Awassa town that are discharged into the wetland. Hence, it most probably contains some toxic and carcinogenic chemicals, which are dangerous for human health. However, the wetland (swamp) around the lake Chheleleka serves as retention media for the effluents entering from the Awassa town factories. Also the wet land traps much of sediment yield of the streams descending from the Wondogent ridges.

4.3 Tikur Wuha River

Tikur wuha, which is the outlet of Lake Cheleleka, is the major tributary river of Lake Awassa. Lake Cheleleka and the Tikur Wuha have concentrations between upland waters and Lake Awassa. This evolution is due to evaporative concentration and inflow of saline thermal springs.

The water chemistry of Tikur Wuha is dominated by $NaHCO_3$. The EC and SAR values are 515 µs/cm and 4.2 respectively, which puts the irrigation water quality into C2-S1 suitability class. Therefore the water is suitable for growing moderately salt tolerant plants or crops in most soil types (Zenaw Tessema, 2001).

4.4 Lake Awassa

The main Ethiopian Rift (MER), from Lake Ziway to Lake Awassa, seems to have been occupied by a single huge lake during late Pleistocene wet climatic period. The lake then dried to a degree more sever than at the present day (Mohr, 1960). Awassa, Ziway, Langano, and Abijata are lakes of tectonic origin with alignment to the main tectonic trend of the rift (Mohr, 1967). Shalla and Abijata were first roughly mapped by Travers (1887) and Lake Awassa by Darragon (1898).

Lakes Awassa and Cheleleka swamp, situated in Awassa caldera, were united as a single lake last century (Mohr, 1971). However, recent terraces are much less well preserved in the lake Awassa basin than Ziway-Shalla lakes to the north, the reason may lay in the wetter climate of the Awassa region. The existence of terraced pumiceous lacustrine sediments both sides of the fresh transverse faulting which limits the present lake Awassa basin to the north suggests that in pluvial times this basin was connected to that of Ziway-Shalla. They were separated by post pluvial block faulting and tilting (Mohr, 1960).

Lake sediment related to ancient Awassa lake level was encountered in bore hole located north of the lakeshore at 1700m elevations, which shows a drop of 30 m to the present lake level. If the level of hyaloclastite at 1725m is taken, the present day level of Awassa has dropped by 40m. Recently the level of Awassa Lake has been rising. The lake level has been recorded since 1969 and the level has increased by about 3.8 meters over the last 30 years (1969-1999) while the level has increased by about 2 meter since January 1996 showing that the level is increasing at an unusual rate in recent years (Zenaw Tessema, 2001). This condition is a threat to Awassa town, a capital of the Southern region and rural communities who inhabiting the area and the main highway linking Addis Ababa to Moyale.

Lake Awassa has a drainage area of about 1440 km^2 including lake surface area. The lake surface area is about 100 km^2 with the maximum depth of 22 m. The major tributary of the lake is Tikur Wuha, which overflows from the Lake Cheleleka and drained into the Lake Awassa. The water quality of Lake Awassa is oligosaline and its water chemistry is dominated by $NaHCO_3$. Its EC varies from 760 to 900 µs/cm depending on seasons, and SAR value varies from 7.5 to 10, which puts the irrigation water quality class into C3-S2, which is not suitable for most salt sensitive crops. However, the lake water can be used for growing salt tolerant crops if there is proper drainage and water management practices (Zenaw Tessema, 2001).

The water of Lake Awassa contains about 3 mg/l fluoride, which is by far exceeded the maximum recommended level of WHO guideline for drinking water that is 1.5 mg/l F^{-1}. Hence, the lake water is not fit for drinking purpose. However, the local people especially farmers living around the lake depend on the lake water for the domestic use and livestock drinking. The effect of high fluoride concentration has been reflected on the health situation of the local people living around the lake. Considerable number of the population is suffering from various degree of bone fluorosis and almost every local people who regularly used the lake water for drinking purpose possesses mottled tooth.

Eutrophication results in a variety of growth and biomass responses at all levels of the food chain, which are commonly caused by the increase in Phosphorus and Nitrogen concentrations. Therefore eutrophication status of the lake can be interpreted in terms of NO_3, PO_4, and chlorophyll a concentration.

The Nitrate and Phosphate concentrations of the Lake Awassa are 5.06 and 0.565 mg/l respectively, while the chlorophyll a concentration varies between 23 and58 µg/l (Elizabeth Kebede and Amha, 1994). These figures according to OEDC 1982 classification put the lake into eutrophic class (Table 4.1). The high concentration of chlorophyll a is attributed to the high amount of Algal population in the lake, while the high amount of nitrate and phosphate are attributed to the high amount of domestic, agricultural and industrial wastes directly or indirectly discharged into the lake.

Nitrogen to Phosphorus ratio (N/P) of the Lake Awassa is 6.2. This shows that nitrogen is the nutrient most likely limiting the lake primary production.

Trophic category	TP., µg/l	Mean chl.a, µg/l	Mean Secchidisc (m)
Ultra oligo trophic	< 4	< 1	> 12
Oligotrophic	<10	<2.5	> 6
Mesotrophic	10-35	2.5-8	6-3
Eutrophic	35-100	8-25	3-1.5
Hypertrophic	> 100	> 25	< 1.5

Table 4.1 OECD boundary values for fixed trophic classification system (as cited in S-O.Ryding and .Rast, 1989)

Lake Awasa is classified as warm, discontinuous polymictic. Stratification is strongest between February and May (Zinabu Gebremariam and Taylor, 1989) followed by mixing in June and July. Short periods of stratification occur between August and January. Mixing is associated with high rainfall and lower air temperature (Elizabeth Kebede and Amha.1994). While the lake is stratified, hypoliminetic concentrations of ammonia and oxygen increase and decrease respectively (Zinabu Gebremariam and Taylor, 1989).

The Awassa Lake level has been gauged daily since 1969. Monthly lake level increments have been computed using 30 years data (1969-99). The Lake level increment is computed from the following relation:

$$\Delta h = h_2 - h_1$$ Where h_1 = Lake level at earlier time

h_2 = Lake level at later time

The mean annul increment of Awass lake level is 76 mm per year .The table below gives the mean monthly increments. A negative increment values represent decrements of lake level. Over the last thirty years the maximum increment is 1090 mm where as the minimum increment (decrement) is –900mm.

Table 4.2 Mean Monthly Stage Increment of Lake Awassa in mm (1969 – 1999)

Mean Monthly Stage Increment of Lake Awassa in mm (1969 – 1999)													
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann
Mean	**-138**	**-123**	**-83**	**-53**	**13**	**42**	**52**	**118**	**143**	**171**	**38**	**-104**	**76**
SD	49	62	55	67	58	115	79	82	101	99	124	76	480
Min	-290	-260	-170	-200	-80	-100	-30	-20	0	30	-140	-210	-900
Max	-40	10	30	90	130	370	360	300	390	370	380	110	1090
n	30	30	30	30	30	30	30	30	30	30	30	30	30

(Source: Zenaw Tessema, 1999)

4.5 Perennial Streams and dry gullies around Lake Awassa area

There are eleven perennial streams which have their headwater in the eastern highland and flow to the west, Awassa Caldera, crossing the Wondogenet escarpment that finally join together to form Tikurwuha river which subsequently leads into Lake Awassa. Seasonal courses and dry gullies that carry a lot of water and sediment during rainy seasons to Lake Awassa are common in the western part of Awassa caldera.

The table, below, shows list of those perennial streams that originate from the eastern highland and join the Tikurwoha River. The discharge rates were measured, during the fieldwork in April 2001, using floating method (Zenaw Tessema, 2001).

No	Name of a stream	Discharge (m^3/d)
1	Bela	6,598
2	Wesha	64,895
3	Werka	32,400
4	Sole	20,412
5	Shenkora woha	2,800
6	Gomesha	3,733
7	Gimatam woha	48,384
8	Wodesa	74,756
9	Abosa	5,184
10	Kedo	43,131
11	Bogete	2,117
Total		304,410

Table 4.3 Discharge Rates of Tributaries of Tikurwuha River (, 1999)

4.6 Gidabo River

Gidabo River is one of the major rivers in the study corridor which has a large catchment area. It drains starting from the high Garamba Mountain (3320m.a.s.l) which is found in the southeastern part of the study corridor and ends finally at Lake Abaya at south west, out of the study corridor. The catchment area of the upper Gidabo River is 1196Km^2 (Kedir Yasin, 2002) and obviously the total catchment area will be more when the middle and lower sub-basins are quantified. This river is fed by many known perennial and intermittent rivers and streams. Among them Bungude, Woyima, Gedi-o, Geo, Mete, Kubamo, Kolba, Orsha, Naniga, Gangeba, Lalage, Gidabo, Teticho, Shigaro, Raro, etc., are some examples to mention out and there are many others.

As it is being the biggest river and has the large catchment area this river has high potentials and can be used as water supply sources for human and livestock consumption, and constructing irrigation schemes for sustainable food security of the zone. Accordingly, in the future, the water supply source for Awassa flourishing town and construction of irrigation schemes should be planned to develop from this river. The potential irrigation sites are found towards the middle sub-basin, and outlet of the Gidabo River Catchment.

CHAPTER FIVE

HYDROGEOLOGY

5.1 General

The nature and distribution of aquifers and aquicludes in a geologic system are controlled by the lithology, stratigraphy and structures of the geologic deposits and formations (Freeze and Cherry, 1979).

Volcanic rocks, due to the difference in mineralogy, texture and structure, its water bearing potential varies. Groundwater circulation and storage in the volcanic rocks depend on the type of porosity and permeability formed during and after the rock formation. All rock structure possessing a primary porosity may not have necessarily permeability: i.e. without the original interconnection, the primary porosity may not give rise to the primary permeability, but later connection, by means of weathering or fracturing may results a secondary permeability (Tamiru Alemayehu,2006).

Acidic volcanic rocks may or may not contain groundwater although generally they possess interstices. The reason is that the interstices may be filled up with ash and other material, and hence uncertainty. Pyroclastic rocks associated with lava flow are generally porous. However, their permeability varies depending on the interconnection of the pore spaces (Davis and DeWiest, 1966).

Because volcanic rocks are crystalline at the surface, they can retain porosity associated with lava-flow features and pyroclastic deposition. Hydraulic conductivity of volcanic rocks such as lava flows and cinder beds is typically quite high. However, ash beds, intrusive dikes, and sills may have a much lower hydraulic conductivity. On a large scale the permeability of basalt is very anisotropic. The centers of lava flows are generally impervious. Buried soils that produce high permeability develop in the top of cooled lava flows. Stream deposits occur between the flows. The zones of blocky rubble generally parallel to the flows.

The most important features governing the groundwater flow and storage in volcanic rocks are the following: (Tamiru Alemayehu, 2006).

- ♣Vertical permeability due to primary and secondary fractures.

♣Horizontal permeability due to horizons containing openings due to the lava flow and gas expansion during solidification.

♣ Occurrence of impervious horizons and dikes

Intrusive igneous and highly metamorphosed crystalline rocks generally have very little, if any, primary porosity. Solid samples of unfractured those rocks have porosities that are rarely larger than 2 %(Fetter, 1994). The intercystalline voids that make up the porosity are minute and many are not interconnected. Because of the small pore sizes and low degree of pore interconnectivity, the primary permeabilities of these rocks are extremely small.

In order for groundwater to occur, there must be openings developed through fracturing, faulting, or weathering. Fractures can be developed by tectonic movements, pressure relief due to erosion of overburden rock, loading and unloading of glaciations ,shrinking during cooling of the rock mass, and the compression and tensional forces caused by regional tectonic stresses.

Chemical weathering of crystalline rock can produce a weathering product called Saprolite. This material has porosities of 40% to 50% and specific yield of 15% to 30%. It acts as reservoir, sorting in filtered water and releasing it to wells increasing fractures in the underling crystalline rocks (Welby, 1984).

The probability of obtaining a high yield well in crystalline rock areas can be maximized if drilling takes place in an area where fractures are localized. It has been observed that zones of high conductivity in crystalline rock areas underlie linear sags in the surface topography (LeGrand, 1962). Such sags are the surface features that overlie major zones of fracture concentration. These show as fracture traces and lineaments on the aerial and satellite photographs (Littman Parizek, 1964).

5.2 Hydrogeological Units and Aquifer System

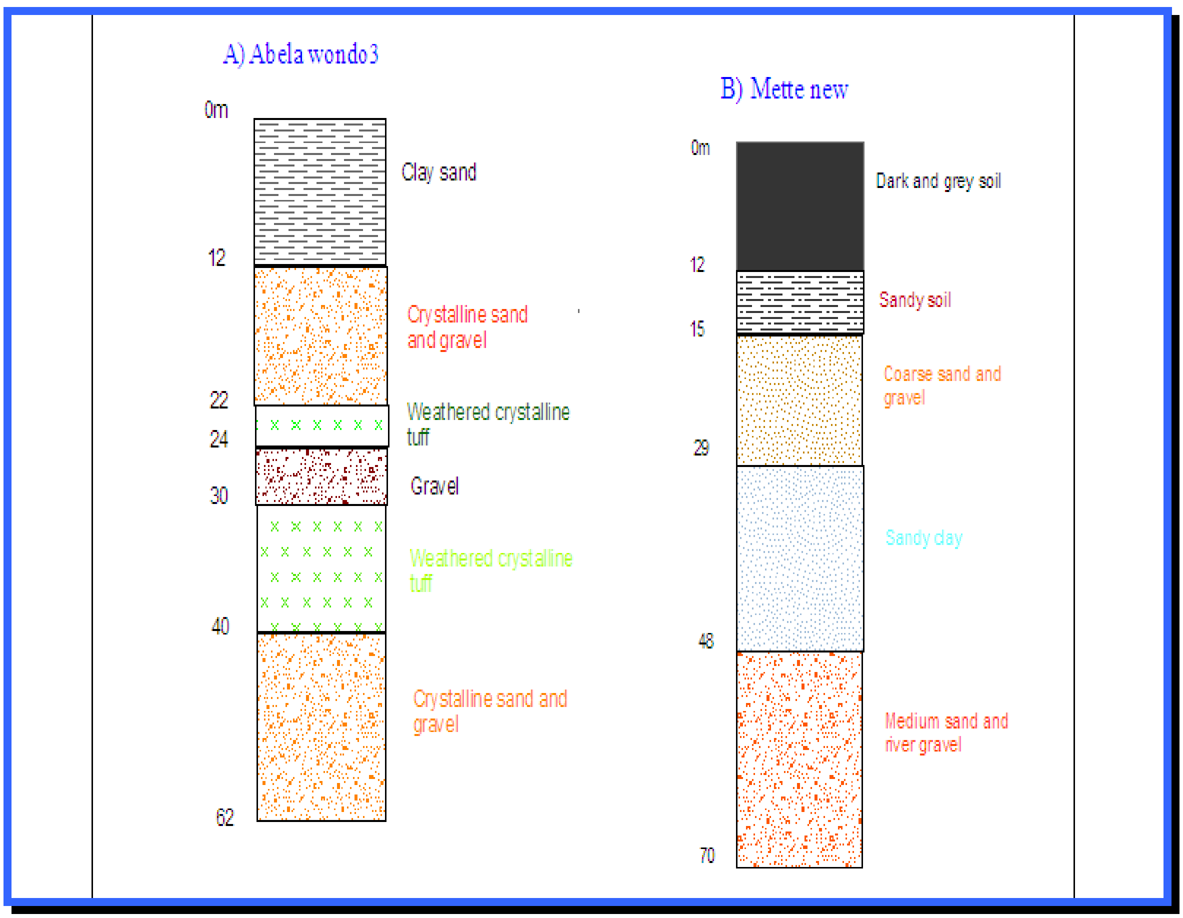
In general the hydrogeologic units found in the study area are lacustrine sediments and volcanic rocks those have both primary and secondary porosities with high and medium permeability, respectively. The secondary porosities have been facilitated through intensive physical and chemical weathering, fracturing and faulting. The primary porosity has been encountered from the lake area at the floor of Awassa caldera. Comparing to the secondary structure, primary one has a significant role in the circulation and occurrence of groundwater in this sub-area.

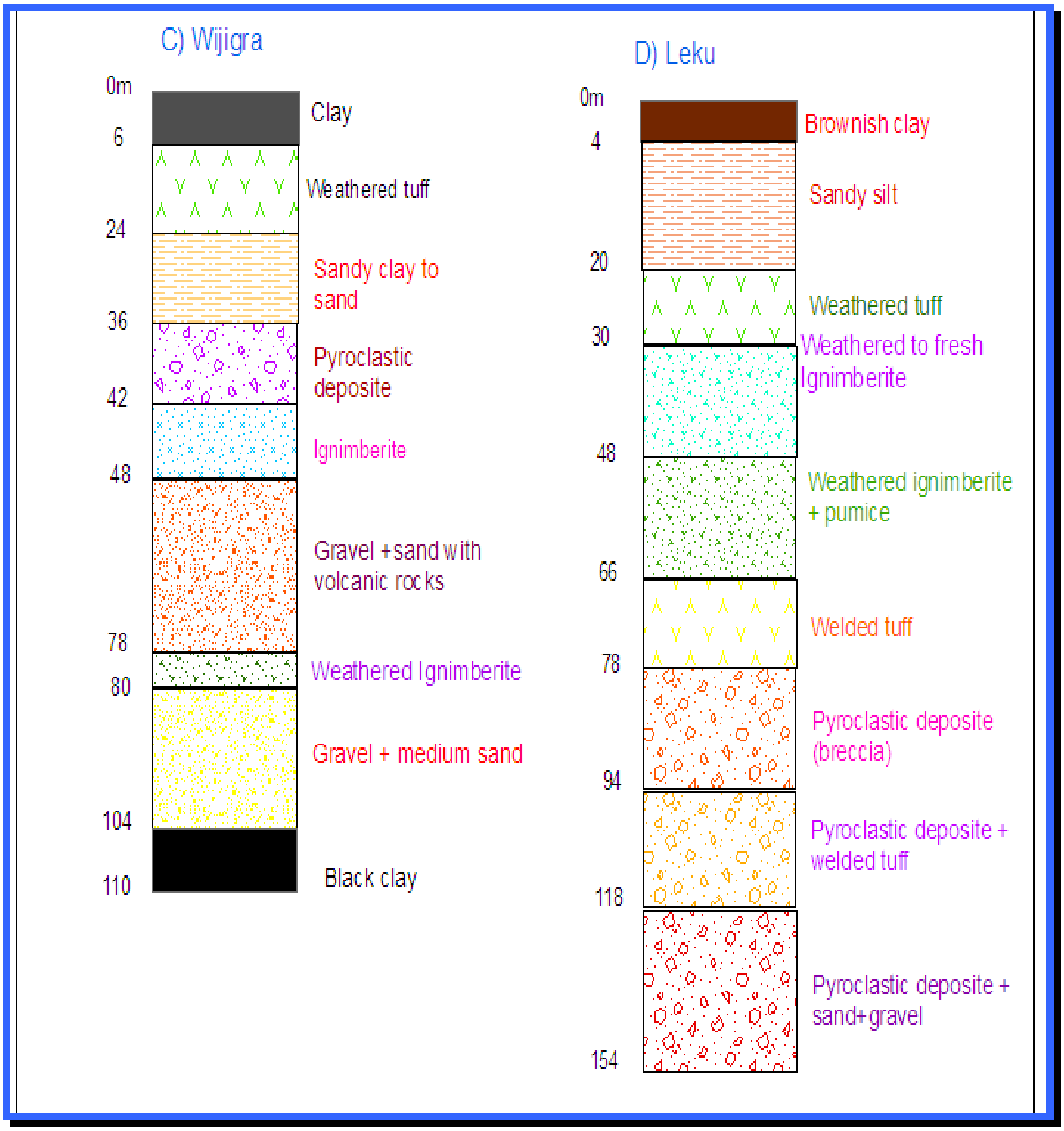
This is confirmed through studying the lithological logs of some boreholes in Figure 5.1 those are found on the eastern part of the lake with in the study area. For example, boreholes which are found at Gemeto well field namely Abela Wond 3 (Figure 5.1 A) and Mitte New (Figure 5.1 B) and Treatment site tapped from sand and gravel aquifers a yield of 17, 6.2 and7.7 l/s, respectively. Moreover, according to this figure and by understanding that the area is affected by the same volcanic processes like eruption of volcanoes, generally, it is possible to say that there is a clear similarity among lithologies in the study corridor. For example, from the lithologies of consecutive boreholes from north to south of the study corridor namely AbelaWondo3 and Mitte, Wijigra and Gobo Hebisha with the respective ranges of depths: 40 to 70m, 48 to 70m and 38 to 78m, the lithologies encountered are crystalline sand and gravel; gravel and sand with volcanic rocks and silty sand to coarse sand.

As far as the aquifer formation systems are concerned there are lacustrine sediments and weathered and fractured volcanic rocks those are classified as high and moderate to low permiabilities respectively. The major water bearing formations in all of the boreholes of deep and shallow wells are summarized as lacustrine and alluvium (silt-sand -Gravel) sediments (the high yield boreholes from Gemeto well fields are belong to this group); welded and fractured ignimbrites, weathered and fractured pyroclastic deposit, fractured lithic pumaceous pyroclastic deposit, and highly and slightly fractured basalt.

It is a well-known fact that the factors such as geology, topography and climate play a significant role in determining the distribution, quality and quantity of surface and ground water. Accordingly rocks can be described qualitatively in terms of their capacity to store and transmit groundwater. Hydrogeological units in the study area are divided into high,

high to moderate, moderate, low to moderate and low permeability groups based on the lithologic description, degree of fracturing, type of fracture filling, extent of weathering, existing data on wells, distribution and magnitude of spring discharge, and drainage density. Thus rock formations with similar hydrogeological character are grouped into one and also a rock with different hydrogeological character may be grouped into more than one permeability group. Besides to these there are also aquiclude which is the geological unit that does not store and transmit a significant amount of groundwater to the well.




C) Wijigra
0m
6
24
36
42
48
78
80
104
110
Clay
Weathered tuff
Sandy clay to sand
Pyroclastic deposite
Ignimberite
Gravel +sand with volcanic rocks
Weathered Ignimberite
Gravel + medium sand
Black clay
D) Leku
0m
4
20
30
48
66
78
94
118
154
Brownish clay
Sandy silt
Weathered tuff
Weathered to fresh Ignimberite
Weathered ignimberite + pumice
Welded tuff
Pyroclastic deposite (breccia)
Pyroclastic deposite + welded tuff
Pyroclastic deposite + sand+gravel

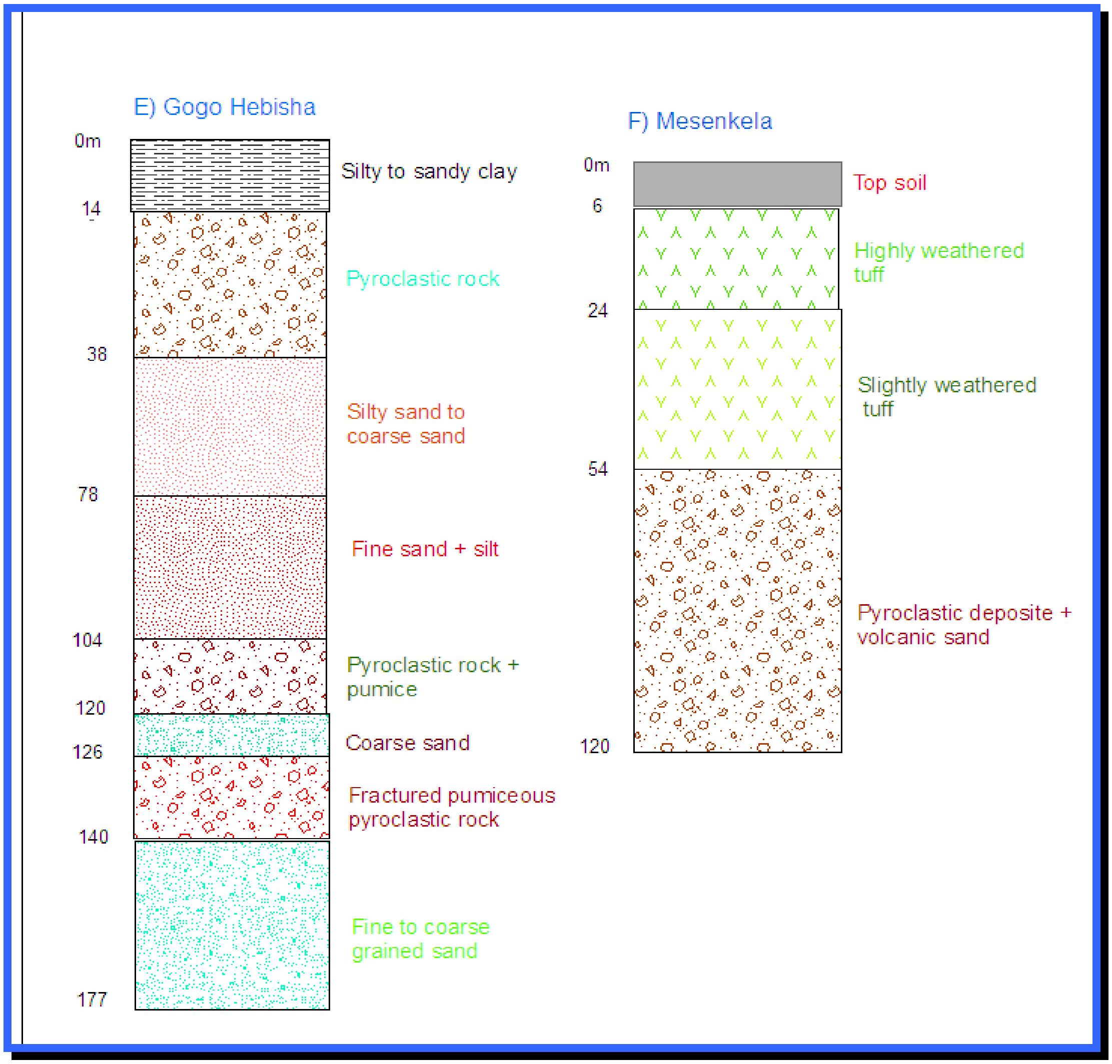


Figure 5.1(A, B, C, D, E and F) *Lithologic logs of the selected boreholes with no scale from the study corridor (Not scaled).*

The hydrogeological map (Figure 5.2) below is then produced through the modification of the existing map at a scale of 1:50,000. The comparison of permeability of the rocks is among the rocks with in the corridor. Based on the map, the following hydrogeologic units are depicted:

- Aquiclude, this comprising mainly rhyolite and trychite those are found on the south eastern part of the study area and around the lake .Mt Tabor belongs to this unit

- ♣ High potential Intergranular aquifer of lacustrine and alluvial sediments. These are mainly exposed on the eastern part of the rift floor. Gemeto well field belongs in this unit and it has a known yield in the range of 6 to 17 l/s.
- ♣ High to moderate potential intergranular aquifer of dominantly lacustrine sediment which extensively surrounds the lake region. It has also the known yield in the range of 2 to 7 l/s.
- ♣ Moderate potential fractured ignimbrite aquifer yielding of known values 3 to 5 l/s and also covers a wide area of south west and escarpment of the rift.
- ♣ Low to moderate potential aquifer of welded tuff and lacustrine sediment. These units are the larger area of south eastern part of the study corridor.
- ♣ Low potential aquifer of predominantly volcanic ash, pumice and basalt those are exposed at the center and northern part of the study corridor.
- ♣ Low to moderate potential aquifer of welded tuff and lacustrine sediment. These units are the larger area of south eastern part of the study corridor.

The springs emanating from rocks of weathered and fractured ignimbrite formation, which are located at the foot and neck of the Wondogenet ridge, are generally of high discharge and structurally controlled. They are here grouped to the high permeability group.

5.2.1 Aquifer Formation, type, Depth and Lateral Extent

From hydrogeological classification of rocks, the distribution, type and discharge of springs, hand dug wells and boreholes, in the study corridor, it can be deduced that two types of aquifer systems: shallow and deep are present.

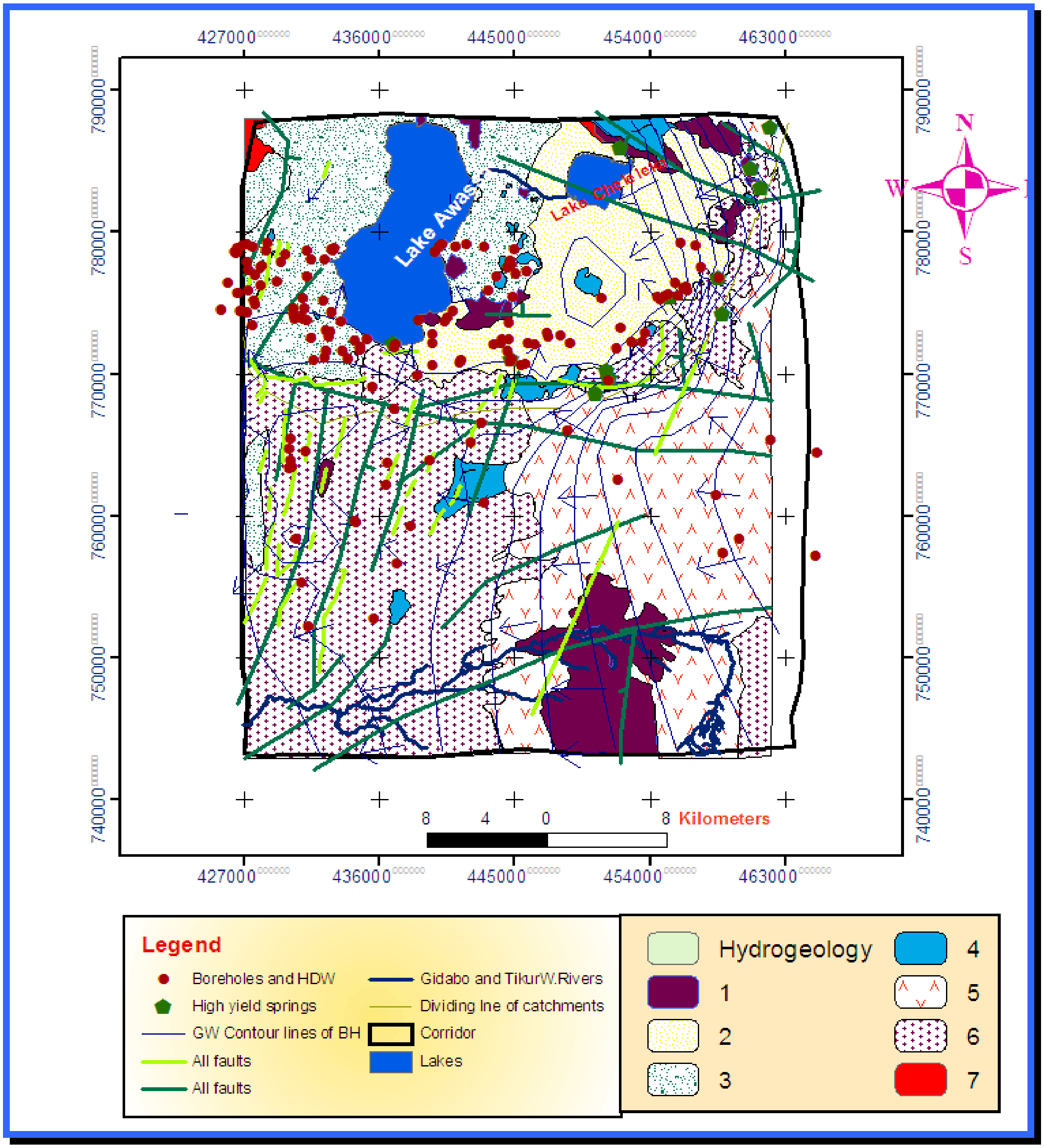
The shallow aquifer system is mainly localized and occupies the wide valley bottoms, plain areas and rift floor near the lake areas. This can be observed from shallow wells found around Awassa town and Wondogenet area. The shallow aquifer system is believed to be characterized by the shallow wells, their depth ranges from 40 to 70m and have shallow groundwater circulation system. The existence of this aquifer system is related to climatic and topographic conditions. In high rainfall areas with a more or less flat topography the shallow aquifer is found to be prominent.

Thus in the western part of the corridor especially west of the Yirba town, where precipitation is low and there are acidic volcanic rocks such as ash, pumice and welded tuff are deposited, the existence of this aquifer system is rare. In some cases, from the pre knowledge of the area, unproductive wells are encountered from deep aquifer system, this is witnessed by boreholes drilled at Fulasa and Konsore Chaffa (depth of 307m and 94m respectively) localities in the same area. On the other hand, the aquifer system is extensive in the central and northern parts of the study area as well as in the plateau of the eastern part.

The aquifer is mainly composed of lacustrine and alluvial sediments and pyroclastic materials such as fractured ignimbrite and its weathering products. From the lithologic log of some shallow wells, it is observed that the range of depths of aquifers is 9 to 50 meters at Yuwo, near Gemeto well field and Dikicha (Boricha woreda) at the central part of the study corridor, respectively. There are numerous low yields springs in the highlands emanating from the contact of this aquifer system with the underlying low permeability unit. Groundwater generally exists in an unconfined or semi-confined condition, the low permeability paleosols that are present between the successive eruptions and flows acting as semi-confining layers.

As far as the deep aquifer system is concerned the depths of the aquifers range from 49 to 174 meters. This shows it's being deep confined aquifers with regional lateral extension. The aquifer is mainly composed of lacustrine sediments, volcanic sands and pyroclastic deposit, fractured rhyolitic ignimbrites, weathered ignimbrite and tuff. There are more than 40 boreholes tapping from this aquifer system.

Some of the high discharge structurally controlled springs those emanate from the foot and neck of the Wondogenet ridge are Kikie (UTM location 461355E and 783109N), Melgewondo (Elfora), Borja, Basha, Wondogenet, Gemeto, Isawa, and Aruma Chemo with estimated yields 200, 8, 20, 4, 15, 40,7 and 6 l/s, respectively, and Loke palace spring (30 l/s) that is found at the southern part of the lake with UTM location 436994E and 772114 N are also believed to get their water source from this aquifer.



1:-Aquiclude composing of mainly rhyolite and trachyte. High potential intergranular aquifer of lacustrine and alluvial sediments. Yield of known values are 5 to 10 l/s. 3:-High to moderate potential intergranular aquifers of dominantly lacustrine sediments. Yield of known values of 5 to 7 l/s. 4:-Low potential aquifers of predominantly volcanic ash, pumice and basalts. 5:-Low to moderate potential aquifers of welded tuff and lacustrine sediments .Yield ranges 1 to 5l/s. Moderate potential fractured ignimbrite aquifers.Yield of known values are 3 to 5l/s. 7:-Very low potential aquifer of tuffs & pumice.

Figure 5.2 Hydrogeology Map of the Study Corridor Modified after Wondwosen Mekonnen, 2005

The highest and lowest yields of boreholes tapping this aquifer are found at Yirba 2 (UTM location 430000 E and 765500 N) with 1 l/s and Mette New (UTM location 444394 E and 770060 N) with 17 l/s. They are located at the recharge and discharge areas of the study corridor, respectively.

In general it can be said that there is deep and shallow circulation of groundwater giving different aquifer systems and various high and low yield springs. Groundwater in the study corridor is of good yield in low relief areas along the major structures mainly at the foot of the eastern escarpments (Wondogenet ridge) of the rift.

5.3 Groundwater Sources Inventory

5.3.1 Hand dug wells

There are numerous dug wells within the study corridor those are mainly used for public and livestock consumptions. Among which around 60 dug wells have been collected from secondary data sources and inventoried for hydrochemical analysis purpose. Depth and static water level of the majority of dug wells could not be obtained due to lack of the information and problem faced to measure them since they are fitted by hand pump. However, from the existing data, the range of their depth is from 3 to 45m with variable static water levels of 1 to 40m.

The dominant aquifer formation is known to be lacustrine and alluvial deposits in the northern, east of the Awassa Lake and central parts of the study corridor respectively. Most of the dug wells provide a perennial source of water and however, yield is substantially decreasing during dry season. The seasonal fluctuation of the static water levels in most of the wells is highly attributed to the direct recharge condition from precipitation into the well which intern indicates the unconfined nature of the aquifers. Dug wells are constructed in both of recharging and discharging zones/rift floor of the study area.

5.3.2 Boreholes

Both deep and shallow boreholes are drilled in the study area by Governmental, Non Governmental and Private Drilling Company. There are about 42 deep boreholes where the depth varies between 56 to 224m, and 50 shallow boreholes with the range of 34 to 70m depth. The deepest borehole has a depth of 224m drilled at Midregenet with SWL 45m and has 5 l/s yield. Where as shallowest borehole is drilled at Bushulo Hospital with SWL 8m and yield more than 4.5l/s. Most of the deeper boreholes are fitted with submersible electrical pumps and the others boreholes are equipped with Indian mark II.

The main aquifer formations of the boreholes are Lacustrine and volcanic sediments, pyroclastic deposits, weathered and fractured basalt, ignimbrite, rhyolites and welded tuff having a variable thickness, weathering and fracturing intensity. The static water level of the wells lies within the range of 0 m for artesian Melgewondo boreholes of 78m depth to 94.7 for deep well of Konsore Arke ,203.8m depth.

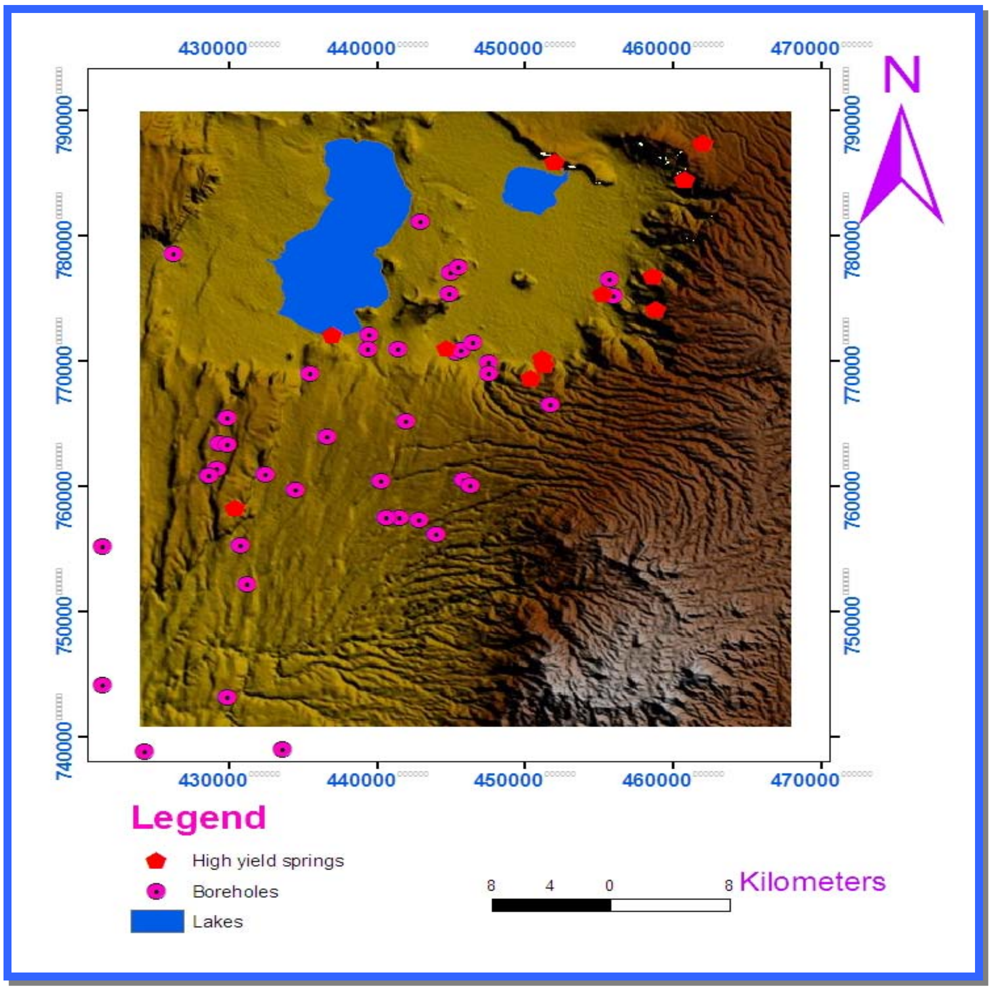


Figure 5.3 *Distribution of some selected Boreholes and High Yield Cold Springs With in the corridor with Digital Elevation Model (DEM).*

Aquifer thickness, drawdown and yield of the aquifers lie between 17 to 59m, 0.02 m to 69.85m, and 0.6 to 17 l/s respectively.

5.3.3 Springs

Springs are the most conspicuous forms of natural returns of groundwater to the surface. They come in all sizes from trickles to large streams. The three principal variables that determine spring discharge are aquifer permeability, area contributing recharge to the aquifer and amount of recharge (Davis and Dewiest, 1966).

Springs and seeps occur where down gradient parts of aquifers materials are exposed to the surface, as in outcrops of aquifers at mountain sides or canyon walls, or shallow water table reaching the surface at the base of long slopes. Springs also form where discontinuities like faults or dikes present hydraulic barriers and force groundwater to flow upward. In fractured rocks fissures can be filled with rainwater, which then flows through the same fracture system to form springs at lower points.

Springs can be generally grouped in to two as gravity and non-gravity springs. The gravity springs result from water flowing under hydrostatic pressure, where as non-gravity springs are results of fractures extending to great depths in the crust and are called thermal springs (Todd, 1980).

- ***Cold Springs***

There are abundance of cold springs in the study corridor. The types of these springs are generally contact and depression. Contact springs between the more permeable overburden and the low permeability rocks. These types of springs are common in the eastern part of the corridor on the plateau and the escarpment. They have variable discharge depending on the seasonal variation of precipitation, but generally low. They have also low EC value indicating the shallow groundwater circulation. On the other hand, many fracture (structure) controlled contact springs are found along the foot and neck of Wondogenet ridge with known yield of 200 l/s (Kikie Spring) and the lowest yield is 1.5 l/s of Finchawa spring. The information about the yield of Kikie spring is obtained from Awassa Water Supply Services office. Cold springs from the escarpment emanate from E-W and NNE-SSW faults of the eastern margin of the rift. The Loke Palace spring which is found near the southern shore of the Lake with estimated yield of 30 l/s is also belongs to this type of spring and is emanating from Dulecha ridge. Formerly it directly drains into the lake but by now it is used as water supply source for Awassa town and rural communities. The distribution of higher yield cold springs is displayed on Figure 5.3.

Depression springs formed when the ground surface intersects the groundwater table. It occurs when the underlying bed rock unit exposed on the open channels. They are common in the central part of the study area along valley cuts. They have variable discharge mostly less than 1 l/s and characterized by drainage basin.

♣ ***Hot Springs***

In the Ethiopian rift, more than 500 hydrothermal features were indicated in UNDP (1973).Thermal springs occur in all topographic range from the Rift floor up to 2200m a.s.l. The distribution of thermal springs in Ethiopia was first presented by Kundo (1967) where thermal springs are largely clustered in the Rift due to its peculiar characteristic of thermal anomaly. The concentration of major ions and trace elements is high in thermal springs than in the cold springs. Thermal springs that are associated with volcanic activity are loaded with Na, HCO_3, and Cl (Tamiru Alemayehu, 2006).

Non-volcanic thermal springs get temperature from deep circulation of water, where the temperature of the rocks is high because of the normal temperature gradient of the earth. Where as the volcanic thermal springs attain their temperature from underlying hot acidic magma chamber that is located at shallow depth. Thermal springs both volcanic and non-volcanic type, are part of deep-seated water. The association of volcanic springs with acidic magma chamber could imply their origin. It is either the water expelled from the magma (juvenile water) or the surface water that came in contact with highly heated rocks.

According to Tenalem Ayenew (1998) the stable isotope ($^{2}H/^{18}O$) composition of most thermal springs in the lakes region fall close to the local meteoric water line indication the recharge from precipitation. In a volcanically non-active area, extension fractures and normal faults are important thermal conduits to the surface. Even the Rift Valley, geysers and fumaroles that are associated with volcanic centers uses tectonic fractures as a pipe.
Some examples of geothermally controlled thermal centers (non-volcanic type) are Sodere(Nazareth), Gidabo(Yirgalem), Filwuha(AddisAbaba), Nech-Sar (Arbaminch), etc.While volcanic controlled thermal centers are Lake Shalla shore springs, Lake Langano shore springs, Edu geysers, Wondogenet, Aluto, Boku, Beseka, Bulbula springs (Wonji) , hippo springs (Wonji), Gemeto (Awassa),etc .The main characteristic features of volcanic controlled thermal centers is the presence of fumaroles, geysers and thermal water (Tamiru Alemayehu,2006).

Volcanic thermal springs are strictly associated with acidic volcanic centers that could have shallow magma chamber. Faults play and important role by acting as conduits to transport thermal water to the surface. Even in this case, the addition recharging water comes from precipitation. Non-volcanic springs that are structurally controlled in central Ethiopia are generated from water having variable depth of circulation. The thermal waters are recharged from internal highlands.

As the studied area is parts of the Main Ethiopian Rift (MER), tectonic and volcanic activities (processes) are highly reworked in the area. The manifestation of volcanic and tectonic structures like caldera, cinder cones, rhyolitic domes, and normal faults and fractures (ground cracks), respectively are some of the features that can be observed in the area and which favors for the existence and circulation of underground hot water.

The major hot springs in the study corridor are located along fault zones and fracture lines are both volcanic and non-volcanic with the temperatures ranging from 30 to 80.2^{O}C. They are found in Wondogenet, Gemeto gale, and near Yirgalem town.
Springs found near Yirgalem town are non-volcanic and structurally controlled springs having discharges of 10-15 l/s and three of the hot springs is developed for different

purposes. Gebriel hot spring for Aposto town water supply and Kidanemihret hot spring developed by the Orthodox Church and used as a holy water. Near Kidanemihret hot spring there is a large hot springs emanating from the floor of Gedi-O stream (Kedir Yasin, 2005).

The Yirgalem hot spring is developed for bathing purpose. Where as the Gemeto hot spring is used traditionally for curing purpose by the rural communities from near and far areas. It has pool and many sources of outlet which is so hot with 80.2ºC of temperature and is not developed yet. Moreover, this spring is emanating from the foot of small rhyolitic dome and has continuous geysers at the eastern part of this dome.

A hot groundwater comes to the surface and cools; it may precipitate some of its dissolved ions as minerals. Travertine is a deposit of calcite that often forms around hot springs, while dissolved silica precipitates as sinter (called geyserite)which deposited by a geyser. The composition of the subsurface rocks generally determines which type of deposit forms, although sinter can indicate higher subsurface temperatures than travertine because silica is harder to dissolve than calcite (Plummer et al., 2004). This feature is observed at Gemeto hot spring where there is geyser manifestation and it is thought to be sinter (geyserites) of silica precipitate as the area is dominated by volcanic rock origins.

As long as the concentration of the hot springs of the study area is concerned, relatively they have high values and according to Figure 7.7, the water type is Na-HCO3. The hot springs which have the water type similar to that of other water bodies (Boreholes, HDW and river) and findings by Tenalem Ayenew, (1998) and Tamiru Alemayehu, (2006), mentioned above lead to the conclusion that these hot springs receive the recharge from internal highlands, in turn this indicates the presence of groundwater circulation from Upper Gidabo basin to Lake Awassa basin.

Ignimbrites, fractured and weathered rhyolites, and lacustrine sediments are the major water bearing formations of the geothermal fluid in the study area. The lacustirne sediment serves as a cap formation, where it is not broken by young wonji faults, to impede the free movement of geothermal fluid to the surface.

Thermal groundwater

Geothermal energy electricity can be generated by harnessing naturally occurring steam and hot water in area that are exceptionally hot underground. In such a geothermal area, wells can tap steam (or superheated water that can be turned into steam) that is then piped to a power house where it turns a turbine that spines a generator, creation electricity (Plummer et al., 2004).

The Ethiopian rift valley is known to have good potential of geothermal energy. The thermal anomalies are very well marked and widespread all along the rift. A relatively high temperature is characteristic of the entire rift valley with geothermal gradient of 1ºC for every 6m depth (Tamiru Alemayehu and Vernier, 1997) where as areas of very high temperature with steam can generate geothermal power and they are limited to few often-silicic-volcanic centers. Important geothermal energy exploration areas are Lake District and Tendaho areas within which large numbers of sub areas are included such as Lake Langano, Lake Shalla area, Lake Awassa area, Wondogenet areas, and North West of Lake Abaya areas (Tamiru Alemyehu, 2006).

Accordingly the study area mainly in Awassa lake basin, it is believed and agreed with Tamiru Alemayehu (2006) findings that there is geothermal energy potential. This is observed by the presence of important thermal manifestations such as geysers, fumaroles, extremely hot water and hot grounds at Gemeto hot springs and the rift floor around this area. Hydrothermal deposits like silica sinter is also observed around the springs. As there are many acidic volcanic centers nearby the springs and generally the area is characterized by frequent tectonic and volcanic activities like ground cracking, fracturing, earthquake, etc., these all act as the sources of heat that implies the existences of geothermal energy at the depth.

CHAPTER SIX
GROUNDWATER FLOW SYSTEM

6.1 General

Chebotarev (1955) recognized that groundwater tends to chemically evolve in long flow chemically changes within flow systems toward a more concentrated solution similar to the composition of seawater. The systematic changes in anion composition in aquifers of this type have become known as the Chebotarev sequence. In the direction of flow, from the recharge area, the sequence can be illustrated as follows:

$HCO_3^- \rightarrow HCO_3^- + SO_4^{-2} \rightarrow SO_4^{-2} + HCO_3^- \rightarrow SO_4^{-2} + Cl^- \rightarrow Cl^- + SO_4^{-2} \rightarrow Cl^-$

The relationships between groundwater chemistry and flow systems can be considered in two ways: (1) chemical differences between types of flow systems and (2) chemical changes within flow systems (Kehew, 2001).The basic classification of groundwater flow systems was set forth by Toth (1963), who recognized local, intermediate, and regional flow systems.

The size of these flow systems is governed by the topography in the drainage basin relative to the depth of the flow system. High-relief undulating or hummocky surface topography will increase the depth of local flow systems, and if the depth to a regional aquitard is shallow, the drainage basin may contain only local flow systems, By contrast, in basins of great depth in which the surface relief is small compared to the depth of the base of the flow system, a regional flow system will predominate.

Local flow systems recharge at topographic highs on the water table and discharge in adjacent topographic lows. Intermediate flow systems recharge at topographic highs and discharge in topographic lows farther down gradient than the adjacent low. The regional flow system recharges near the drainage divide in the basin and discharges at the topographic low point of the basin.

The chemical composition of groundwater in flow systems is a function of aquifer mineralogy and the rate at which groundwater moves through the system. Local flow systems display vigorous flow that flushes soluble mineral salts out of the aquifer in a relatively short period of time. As a result, the groundwater may never progress past the bicarbonate hydrochemical facies on the Chebotarev sequence. Flow velocity is progressively more sluggish with depth in a drainage basin, and intermediate and regional systems are therefore more likely to evolve into the sulfate or chloride facies, depending on the availability of evaporate minerals in the drainage basin. Because of the sluggishness of groundwater circulation, particularly in regional flow systems, soluble salts are flushed out of the system very slowly and persist for thousands or millions of years.

Changes in water chemistry within a flow system are highly variable. In small, local flow systems in permeable aquifers with uniform lithology, very little change in the chemical composition of groundwater may take place. If carbonate minerals are present, equilibration may occur under open-system conditions in the vadose zone. Few changes occur after the water reaches the water table and moves through the groundwater flow system to the discharge area. In any flow system in which the aquifer mineralogy changes, corresponding water chemistry changes will be noticed (Kehew, 2001).

6.2 Groundwater Flow

Groundwater is an important source of water; it may provide the base flows for rivers, or act as an underground reservoir from which water can be pumped as a location into which water can be drained. Consequently, it is the flow of groundwater which must be examined. Usually, groundwater travels very slowly; one hundred meters per year is a typical average horizontal velocity and one meter per year is a typical vertical velocity. Where these velocities are multiplied by the cross-sectional areas through which the flows occur, the quantities of water involved in groundwater flows are often substantial. Consequently, the essential feature of an aquifer system is the balance between the inflows; outflows and quantity of water stored (Rushton and Kruse, 2004).

Unlike a surface reservoir, the upper surface of the groundwater (the water table or phreatic surface) is not horizontal; a sloping water table results from the resistance to flow caused by the hydraulic conductivity. Due to the slow movement of groundwater, care is necessary when positioning any man-made outflows, such as pumped boreholes, to ensure that they collect water efficiently from the aquifer system.

The direction of flow of groundwater is depicted from groundwater contour maps. Hence groundwater contour maps for the shallow and deep aquifer systems are constructed from water level elevations of bore holes in the corridor. However, the water level data used is collected at different times and this will be affected by the seasonal fluctuation of water levels.

From the study of Yetnayet Nigussie (1990) it is observed that the fluctuation of the shallow aquifer, which is highly affected by amount of precipitation, evapotranspiration and diurnal factors, is up to 2.5 meters. Thus, from this result it can be deduced that the effects of the time of measurement of water levels is minimum.

Moreover, the construction of the groundwater contour was based on the following assumptions, which are characteristics of the corridor under consideration:

1. There is hydraulic connection between the different lithological units and
2. The fractures in the corridor are extensional and they will act as conduits of groundwater and
3. The groundwater is continuous across the fractures.

6.3 Groundwater Source, Recharge, and Discharge

6.3.1 Groundwater Source

A study of the groundwater flow within an aquifer requires information about inflows and outflows. The term recharge is used for the inflow to an aquifer system arising from precipitation; return flow irrigation and flows from various surface water bodies such as rivers, canals and lakes. The magnitude of the recharge is likely to change significantly with time.

The estimated precipitations around Yirgalem and Awassa stations are 1379.22mm and1032mm (Kedir Yasin, 2002 and Wondwosen Mekonnen, 2005) , respectively.

Outflows from the aquifer system can be divided into natural outflows and man-made outflows. Natural outflows occur when water leaves the aquifer at springs or into rivers. Other natural outflows include low-lying areas which act as sink to groundwater systems; this form of outflow may be associated with areas of evapotrnspiration especially from deep-rooting vegetation .One further natural outflow occurs when water flows into other aquifers. There are also man-made outflows, pumped wells and boreholes are the main means of withdrawing water from an aquifer.

The main groundwater source of the study corridor is eastern high plateau areas which included Garamba Mountain that is the highest pick of the study corridor and available/surplus water from precipitation.

6.3.2 Groundwater Recharge

Natural source of freshwater that become groundwater are (1) aerial recharge from precipitation that percolates through the unsaturated zone to the water table and (2) losses of water from streams and other bodies of surface water such as lakes and wetlands. Arial recharge ranges from a tiny fraction to about half of averages rates of recharge (for example, a few inches per year) represent significant volumes of inflow to groundwater.

Streams and other surface water bodies may either gain water from groundwater or lose water to groundwater. Stream commonly are a significant source recharge to groundwater down stream from mountain fronts and steep hill slopes in arid and semi arid areas and in karts terrains (areas underlain by limestone and other soluble rocks). Recharge can be broadly defined as water that reaches an aquifer crossing the water table from any direction, which contributes an addition to the ground water reservoir (Lerner, 1997).
There are three principal mechanisms of recharge defined by Lerner et al. (1990) as:

- ♣ Direct recharge (Diffuse): water added to the ground water reservoir in excess of soil moisture deficits and evaporation by direct vertical percolation from precipitation or irrigation.
- ♣ Indirect recharge: recharge to the water table through the beds of surface watercourses, such as beneath rivers and lakes.

♣ Localized recharge: an intermediate form of ground water recharge resulting from the horizontal, near surface concentration of water in the absence of well defined channels such as small depressions, joints and rivulets.

The above mechanisms usually do not occur individually rather in combination which makes the assessment complex. On the other hand, the recharge and discharge conditions of an area is controlled by several factors such as; climate, topography, drainage, geologic frame work, soil condition, land use/land cover and vegetation etc. For instance in semi-arid areas where potential evapotranspiration exceeds average precipitation, the ground water recharge depends on high rainfall events. Besides, this process is also controlled by soil infiltration capacity, hydraulic nature of sub surface material, the presence of surfacial fractures, joints and depressions so as to escape evapotranspiration, etc. For example poor vegetation cover on a permeable soil cover along with high rainfall can favor the recharge process.

Regarding topography, in areas of steep slopes and rugged terrains, favor run off and evaporation rather than infiltration. Where as in flat land, it creates favorable condition for infiltration. On the contrary, in humid areas recharge is mainly controlled by precipitation surplus (rainfall minus potential evaporation) other factors being present.

According to the map generated by delineating topographically low and high areas from digital elevation model in Figure 6.1 and based on the various factors controlling the recharge processes, the qualitative discharge and recharge areas in the study corridor are described as follows:

♣ **Eastern high plateau, rift escarpment and central parts of the study areas.**

As it is mentioned above as a groundwater sources, the studied area gets large amount of recharge from the eastern high plateau area, which possesses the most elevated area with the characteristics of high rainfall and flat topped hills that facilitate infiltration than surface run off. The rift margin area is also highly affected by rift faults, which produces fracture zone and joints on the volcanic rocks. In addition to these the drainage densities of the areas are very high.

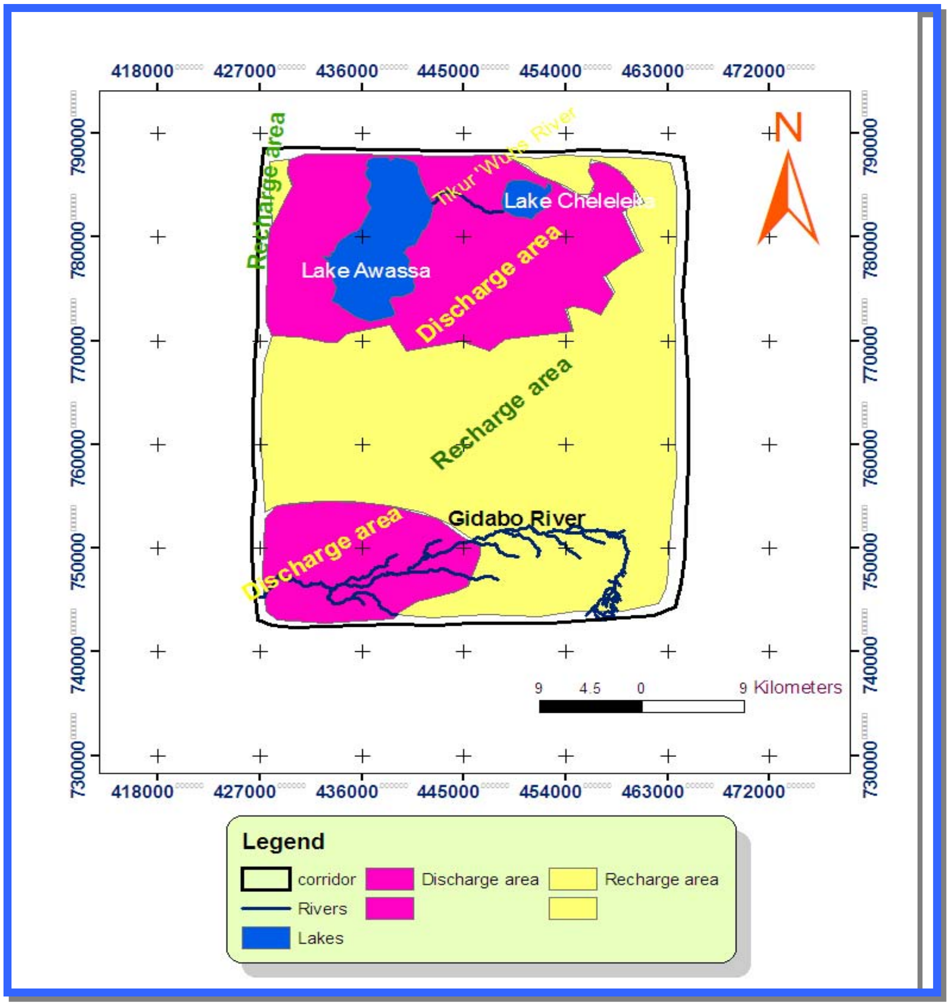


Figure 6.1 *Recharge and Discharge area From Digital Elevation Model*

The fracture and joint along with dense open channels facilitate the recharge processes. The areas get relatively high amount of rainfall. Cold springs emanate from this area have a characteristics of low EC value. This implies fast infiltration and shallow circulation of groundwater, where the area gets substantial amount of direct recharge. The central area has radial flow and relatively gets medium to low rain fall.

6.3.3 Groundwater Discharge

Groundwater Discharge can be defined as the release of water from the saturated zone across the water table together with associated flow towards the water table within the saturated zone (Freeze and Cherry, 1979). Groundwater discharge areas can be manifested by surface water features such as springs, swamps and seepages. In addition, in arid and semi-arid regions discharge areas can be identified by topography, vegetation covers, soil and land surface features.

The floor of the Caldera and down stream of Gidabo River areas are the main discharge zone on the study corridor. These comprise the northern and south western parts of the study area, which are getting relatively low amount of rainfall comparing to that of the plateau and have higher evapotranspiration. The manifestation of discharge areas with characteristics of lake Awassa, Cheleleka swamp and other swamps areas, springs (hot and cold), and depressions are clearly observed in the study area.

The high yield cold springs are found on foot of the Wondogenet ridge and south of the Lake Awassa where as the low yield cold springs are abundantly found on the plateau and south western parts of the study corridor. The volcanic (Gemeto, Wondogenet,Shallo and others) and non-volcanic(Yirgalem) hot springs are discharged from the rift floor and Gidabo river bank, respectively are the main thermal springs that can be mentioned from this area. They are well discussed in the previous chapter under the topic of Groundwater Sources Inventory.

On the other hand, swamps occur on low lying depressions when the groundwater table coincides with the surface of the ground. Lake Cheleleka has been covered by vegetation is already become the form of this type of discharge area. In addition to this on the northern part of the study corridor including some areas out of the study area, there are swamp containing Lake Cheleleka(Shallo), depression of Wendokosha area (near Corbetti), and depressions formed by parallel faulted blocks on south west of Lake Awassa (Derba).

6.4 Groundwater Movement

Generally, groundwater movement takes place from highlands (recharge area) to lowlands (discharge area). Since the study area is a part of the rift system, groundwater flow is strongly controlled by the rift structures like faults and fractures. Darcy's law shows that for flow to occur there must be differences in hydraulic head, providing what has been referred to as a hydraulic gradient. From a field perspective, it follows that a value for hydraulic head can be defined and measured at every point with in some region. The term field is generally used to describe a region where some physical quantity can be described in terms of a space coordinate system and time.

Excess soil moisture is pulled downward by gravity, a process known as gravity drainage. At some depth, the pores of the soil or rock are saturated with water. The top of the zone of saturation is called the water table. Water stored in the zone of saturation is known as groundwater .It then moves as groundwater flow through the rock and soil layers of the earth until it discharges as a spring, or as seepage into a pond, lake, stream, river, or ocean.

There are two contrasting role in the movement and occurrence of groundwater in terms of structural controlling groundwater flow systems. In one hand faults act as conduits for groundwater flow and circulation that may bring groundwater from far recharging to the discharging areas. On the other hand, they act as groundwater barriers which divert the flow direction from its course of head.

In contrast to the high hydraulic conductivity of the rift fractured volcanic, some faults act as barriers of groundwater flow. This is a common case in areas of rift-in-rift structures where the faults deep against the topographic slope forming local grabens and horsts. Beyond the barrier faults most volcanic rocks do not form large extended aquifers, even if they are highly permeable. The barrier faults form local swampy areas (Sileshi Mamo, 1999).

In the rift valley the direction of groundwater is strongly governed by the orientation of faults, which is often perpendicular to the regional groundwater contours in the highlands and escarpments. It was found that these axial faults have governed strongly the subsurface hydraulic connection of the rift lakes and the river-groundwater relations.

◙Groundwater flow in the study area can be categorized as:

- ♣Groundwater flows in the Shallow Aquifers System in the study corridor.
- ♣Groundwater flows in the Deep Aquifer System in the study corridor

6.4.1 *Groundwater flow in the study corridor from Shallow Aquifer System*

In the figure 6.2 and 6.3 below, some important features such as regional and local groundwater flows, divergent and convergent zones, and local ground water divide of shallow aquifer system from the existing shallow well data are described as follows:

♣***Ground water flows***

In order to depict the groundwater flow in the study corridor, from shallow aquifer system, surfer and ArcGIS softwares together with shallow wells data were used. Accordingly, north and south-eastern parts of the study areas are generally the main source of water that migrated to different directions. There is also some localized source from west of the central part where Boricha ridge (Yirba area) is located and groundwater flows from this area towards the lake is clearly observed.

After having high amounts of recharge from eastern high plateau(observed from big arrow in Figure 6.4, which shows high flows) , groundwater moves both towards north western (Lake Awassa sub-basin) and western parts following Gidabo River flow direction within the study corridor. However, when the magnitude of the flow is concerned, high flow is observed in the northern part, which is towards Lake Awassa sub-basin. This is shown on the Figure 6.2 using vector arrows. Local groundwater flow leads to regional flow in most part of the area as observed in the figure below but in some case, the local flow disturb the regional one like in the divergent zone.

♣***Divergent and Convergent Zone***

Groundwater contour map with the appropriate perpendicular vector map can determine divergent and convergent zones. According to the figure below, which shows the groundwater flow direction below, when the groundwater contour map forms circular or semi circular lines, it is either divergent or convergent zone.

Divergent zone is a specific area where the water starts to flow to any other area of different direction and consider as recharging zone. In the corridor, there are two divergent zones such as the entire north and south eastern high plateau and the central western parts, those are major one for shallow aquifer flow system. Other than the topography, if the water potential of a specific zone is relatively high, it has plenty of contribution for existence of divergence zone.

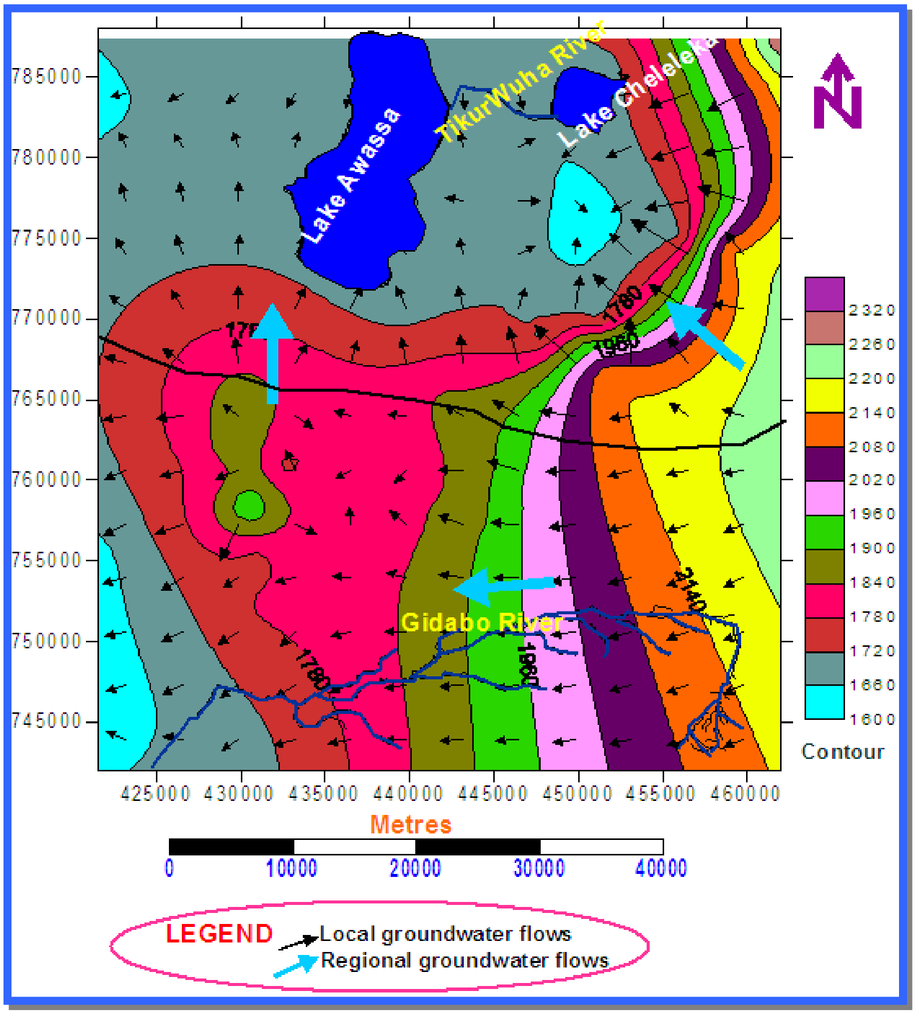


Figure 6.2 *Groundwater Flow from Shallow Aquifer System*

On the other hand, convergent zone is specific area where the water flows toward specific zones that comes from its surrounding of any other direction and consider as discharging zone. From Figure 6.3 below, similarly, there are two major convergent zones in the study corridor which are found at northern part, where Lake Awassa is located. Especially it is localized at the eastern part of the lake (at the foot of Wondogenet ridge) and south west part, at the down stream of the Gidabo River. At the foot of Wondogenet ridge, groundwater converges to these areas that originate and flows entirely from eastern plateau area via the escarpment. Similarly, the south western convergent area receives water from the same source. Existence of convergent zone may depend on several factors among which structure is the main one. Accordingly, the area where convergence observed in the study corridor is dominated by structures.

Local ground water Divide

Groundwater divides are imaginary and vertical impermeable boundaries across which there is no flow (Freeze and Cherry, 1979) or the flow is in the opposite direction of these ideal lines. The divide can be generated from ground water contour map and vector map which is perpendicular each other, specially vector lines shows opposite direction representing groundwater flow direction. This imaginary line may be locally or regionally extends from one direction to the other direction. In the study corridor, for shallow aquifer system there are two areas where ground water divides those exist in the localized form.

As they are portrayed on map in the figure 6.3, one groundwater divide is found at the eastern part of the lake which is very localized due to fault structure whereas the other is located at the center of the study area near to Boricha ridge. Based on groundwater flow line determination, it is believed that this groundwater divide has no lateral extension towards the eastern part of the study area. But in most case, in the zone of divergence, there are also local water divide which may not consider as a divide. In this study, such a divide is observed at the divergent zone. This may because of faults which act as barriers of groundwater flow sometimes.

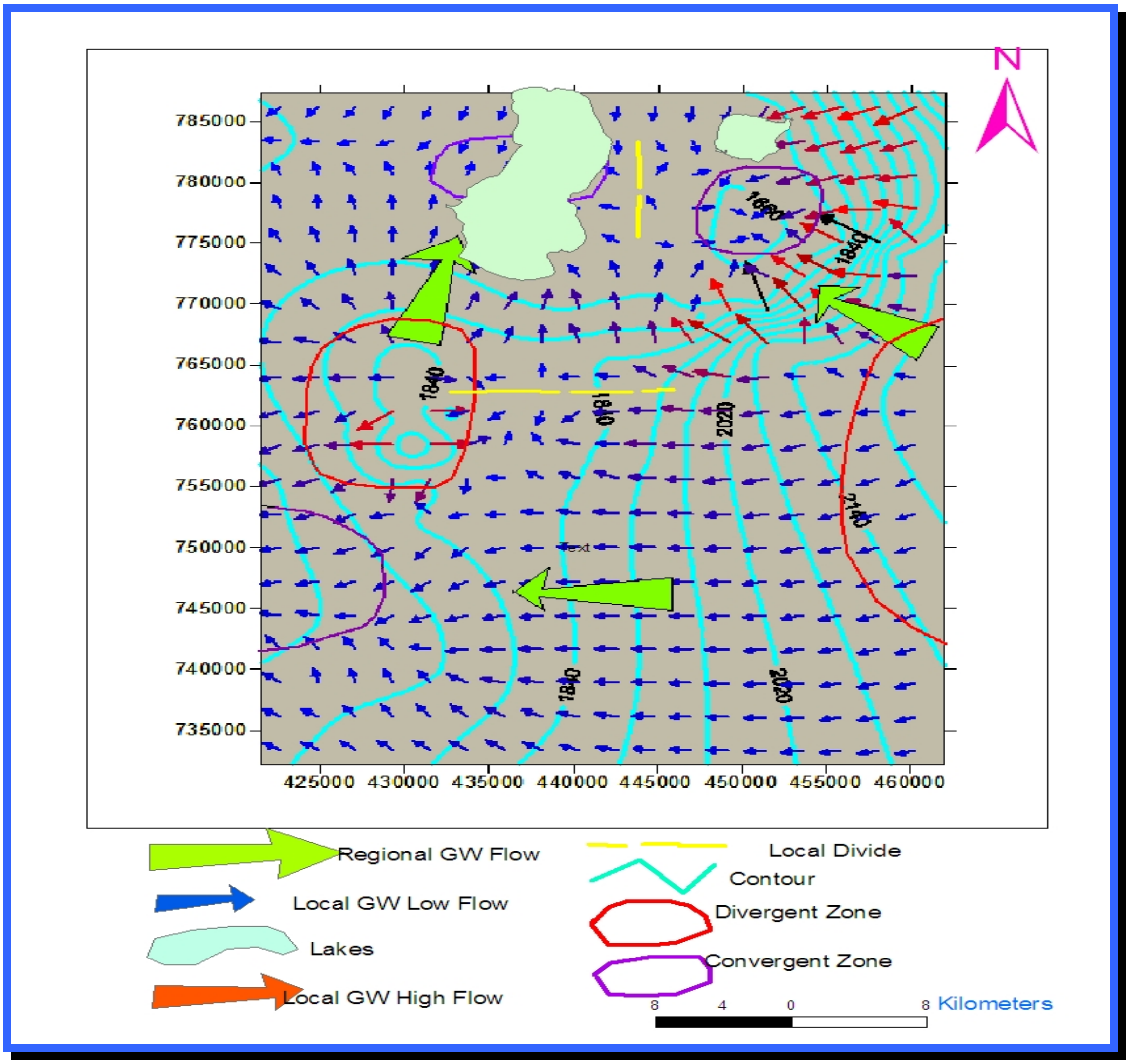


Figure 6.3 Groundwater flows with convergent and divergent Zone resulted from shallow well

6.4.2 Groundwater flow in the study corridor from Deep Aquifer

Deep aquifer system can be characterized by data obtained from boreholes which have high depths. The deepest well in the study area is found to be 224m. Generally the ground water flow direction from deep aquifer system has entirely similar trend from that of the shallow aquifer system. Besides to groundwater flow direction, divergent and convergent zones and groundwater divide found in the same place and characterized in the same manner to that of the shallow aquifer system. This can be observed on both shallow and deep aquifer flow direction maps Fig.6.2 and Fig.6.4, respectively.

From the previous research works, it has been observed that Lake Awasssa sub-basin is a closed basin for surface water and there would be groundwater inflow to the lake region. Especially, the two recent studies by Kedir Yasin(2002) and Tamiru Alemayehu(2006) revealed the existence of groundwater flow from the upper Gidabo River towards the lake Awassa sub-basin.

In this study, using the existing well data collected from the appropriate offices and field survey together with softwares like Surfer and ArcGIS, the following ground water contour and vector map displayed in order to determine the flow direction of ground water in the corridor. As a result, by using different vector map frequency, the resulted map of deep aquifer system has been obtained. The general groundwater flow direction in the corridor is towards both Lake Awassa in the north and Gidabo River in the south.

As it is discussed above in shallow aquifer system, also in this flow system, the higher vector map frequency indicates that there is high groundwater flow takes place from south east to north west of the study area (Lake Region). This is well observed on the figure 6.4. The high yield in eastern rift escarpment along the foot of Wondogenet ridge has confirmed this fact. Red arrow vector shows high yield groundwater flow where as the blue one shows low groundwater flow. The general Groundwater flow is indicated by light blue arrow in Figure.6.5.
As long as the quantification of the amount of the groundwater flows from the Upper Gidabo River catchment to the Lake Awassa basin is concerned, from a short period of time and very limited access surveying of springs was conducted along the foot of eastern rift escarpment (Wondogenet ridge) and Loke area, southern part of lake shore.

Accordingly, in these areas, there are many high yield cold springs. Among them Kike, Wondogenet, Basha, Melgewondo(Elfora), Borja, Finchawa, Isawa, Aruma Chemo,Loke Palace and Gemeto with the estimated discharges 200, 12, 4,7, 21,1.5,7,6, 30, 40 l/s, respectively were some springs those encountered during field work. The information about yields of Kike, Gemeto and Loke Palace springs were obtained from Awassa

Water supply Services, Kedir Yasin(2002), and Regional Water Bureau respectively. Thus the total yield of all springs sum up is 288.5 l/s except for the Gemeto spring ($8.4x10^5 m^3/y$), it's flow amount was quantified by Kedir Yasin(2002) that will be used later.

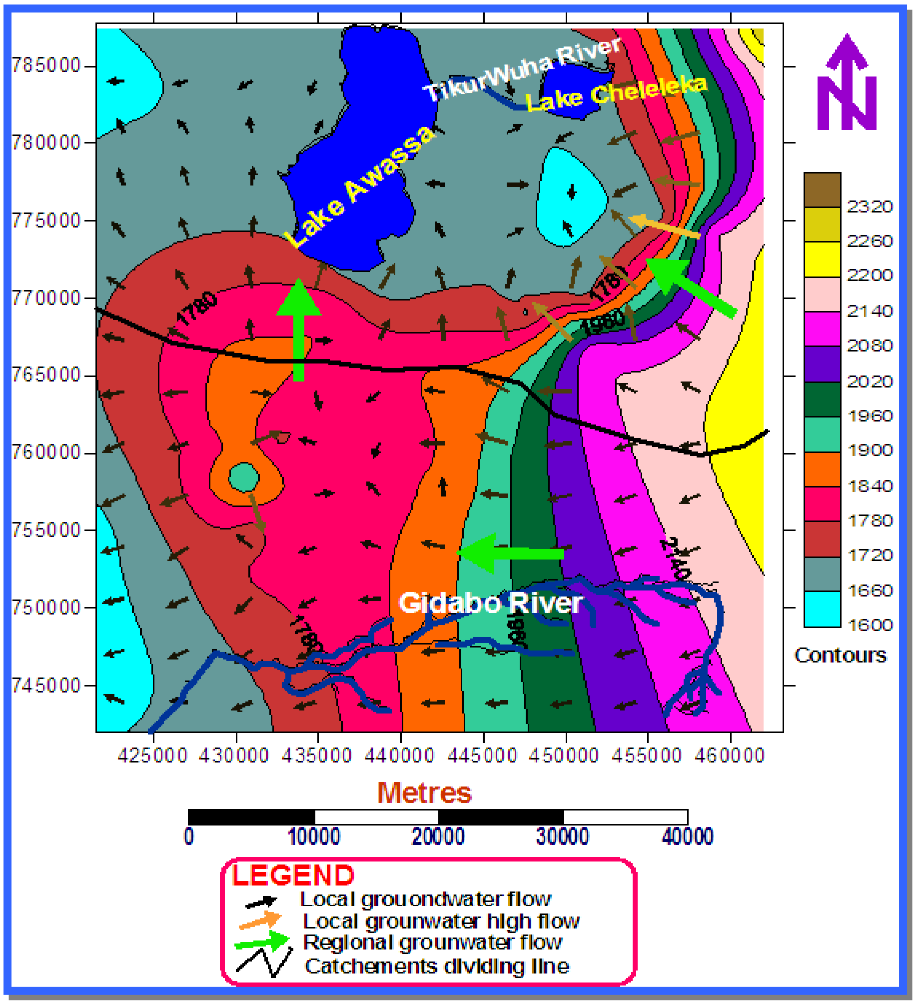


Figure 6.4 *Groundwater flow direction resulted from deep wells data.*

According to Kedir Yasin(2002), the catchments of the springs were delineated from topographic map and gives the total area of about $19.5km^2$. These was calculated by summing up an individual and as well as some the near by springs, through grouping together assuming that they have the same chtchment area. The annual recharge for the catchment was computed to be 211mm (Dessie Nedaw, 1997). Hence by considering the annual recharge and the catchment area, discharge of all springs computed to be $4.11x10^6 m^3$. On the other hand, considering the present yield of the springs, the annual discharge is calculated as to be $9.08x10^6$ m^3. Thus, the difference between the two amounts was assumed to be the amount of groundwater flowing from upper Gidabo River catchment to the Awassa Lake catchemnt. This is $4.97x10^6 m^3$ (4.97mcm). Including the Gemeto spring flow amount, the total estimated amount is found to be $5.81x10^6 m^6$ (5.81mcm). However, when the detail investigation on the area is made, the amounts will be quite more.

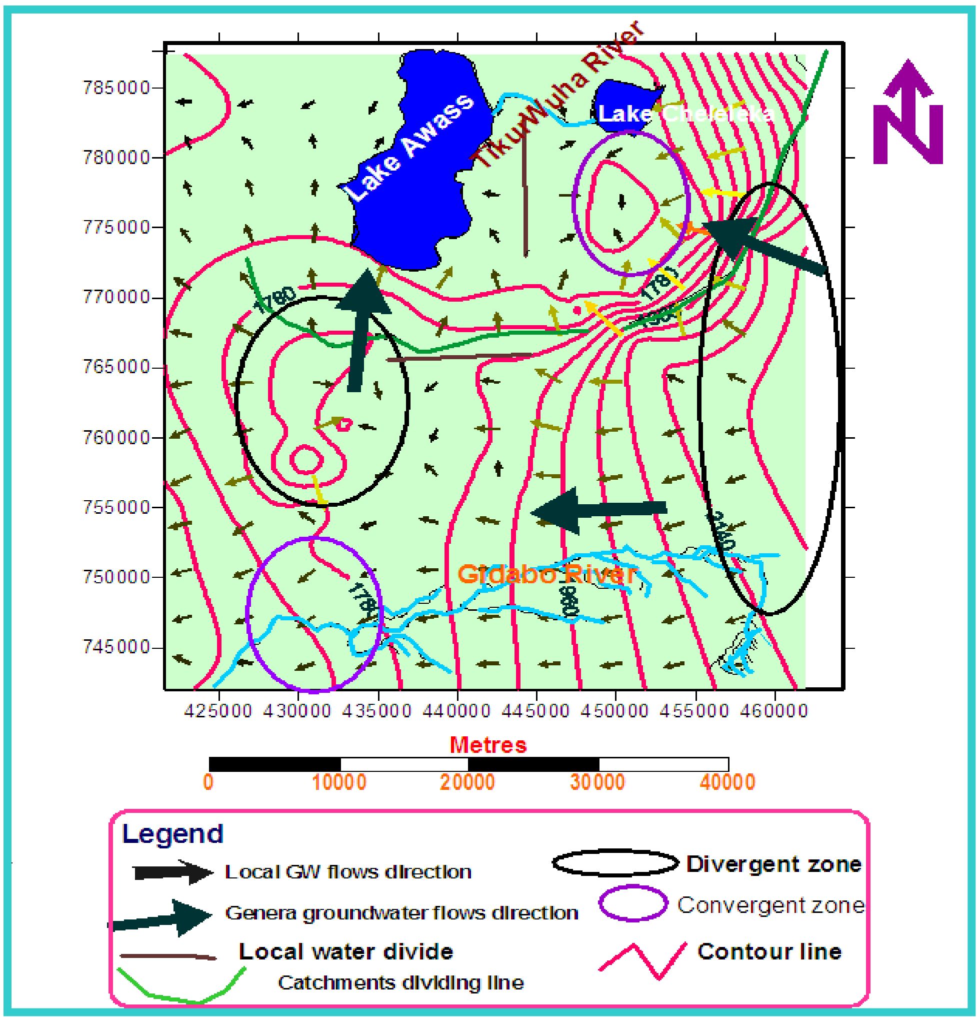


***Figure 6.5** Groundwater Flow from Deep wells showing local water divide, divergent and convergent zones and general groundwater Flow*

CHAPTER SEVEN

HYDROCHEMISTRY

7.1 General

The fundamental concepts relating to chemical processes that are most useful in developing a unified approach to the chemistry of natural water are mainly related to chemical thermodynamics and to reaction mechanisms and rates. Thermodynamic principles may also be useful in correlating chemical processes with biological or physical processes. Thermodynamics principles, applied to chemical energy transfers, form a basis for evaluating quantitatively the feasibility of various possible chemical processes in natural water systems, for predicting the direction in which chemical reactions may go, and in many instances for predicting the actual dissolved concentrations of reaction products that should be present in the water.

The chemical reactions in which elements participate involve changes in the arrangement and association of atoms and molecules and interactions among electrons that surround the atomic nuclei. The field of neural water chemistry is concerned principally with reactions that occur in relatively dilute aqueous solution, although some natural waters have rather high solute concentrations. The reacting systems of interest are generally heterogeneous-that is, they involve both a liquid phase and a solid or a gaseous phase, or all three.

As a check on the chemical analysis, a cation-anion balance is usually performed. This is accomplished by converting all the ionic concentrations to units of equivalents per liter. The anions and cations are summed separately, and the results are compared. If the sum of the cations is not within a few percent of the sums of the anions, then either there is a problem with the chemical analysis or one or more ionic species that have not been identified are present in significant amounts (Fetter, 1994).

Recognition of the anion evolution sequence as a characteristic feature of many groundwater systems resulted from the compilation and interpretation of chemical data from regional flow systems.

The anion evolution sequence and the tendency for total dissolved solids to increase along the paths of groundwater flow are generalizations that, when used in the context of more rigorous geochemical reasoning, can provide considerable information on the flow history of the water. Large variations in the major cations commonly occurs in groundwater flow systems. Since cation exchange commonly causes alterations or reversals in the cation sequences, generalization of cation evolution sequences in the manner used by Chebotarev for anions would be of little use because there would be so many exceptions to the rule.

For major cation and anion data to provide greatest insight into the nature of groundwater flow systems, interpretations must include consideration of specific hydrochemical processes that can account for the observed concentrations (Freeze and Cherry, 1979)

7.2 Sampling Site and Methods

Due to the natural and unexpected inconveniency and problem faced to sample and analyze water bodies during field survey, which was intended to do so in regional water bureau, the primary data was not collected in so far as expected except confirming for some physical parameters. However, the secondary data were collected as much as possible that may represent the entire study area of the corridor (especially from the interaction zone). Accordingly, the physico-chemical analysis those were analyzed mostly by regional water bureau in 1997/8 E.C are used in this work. Some of them are also obtained from previous authors: Kedir Yasin (2002), Shiferaw Lulu and Abebe G/Hiwot(2004) and Wondwosen Mekonnen (2005) on personal communication.

The distributions of boreholes, hand-dug wells, springs (cold and thermal), rivers and lake have been investigated in a view to identify reference areas, to give a representative aerial and hydrogeological sample distribution. Their distribution consisted of a total of 167 samples all from recharging and discharging zones. Their particular numerical distributions are 46, 65, 39, 7, 5 and 5 for Borehole, HDW, Cold springs, Hot springs rivers and lakes, respectively displayed in the figure below.

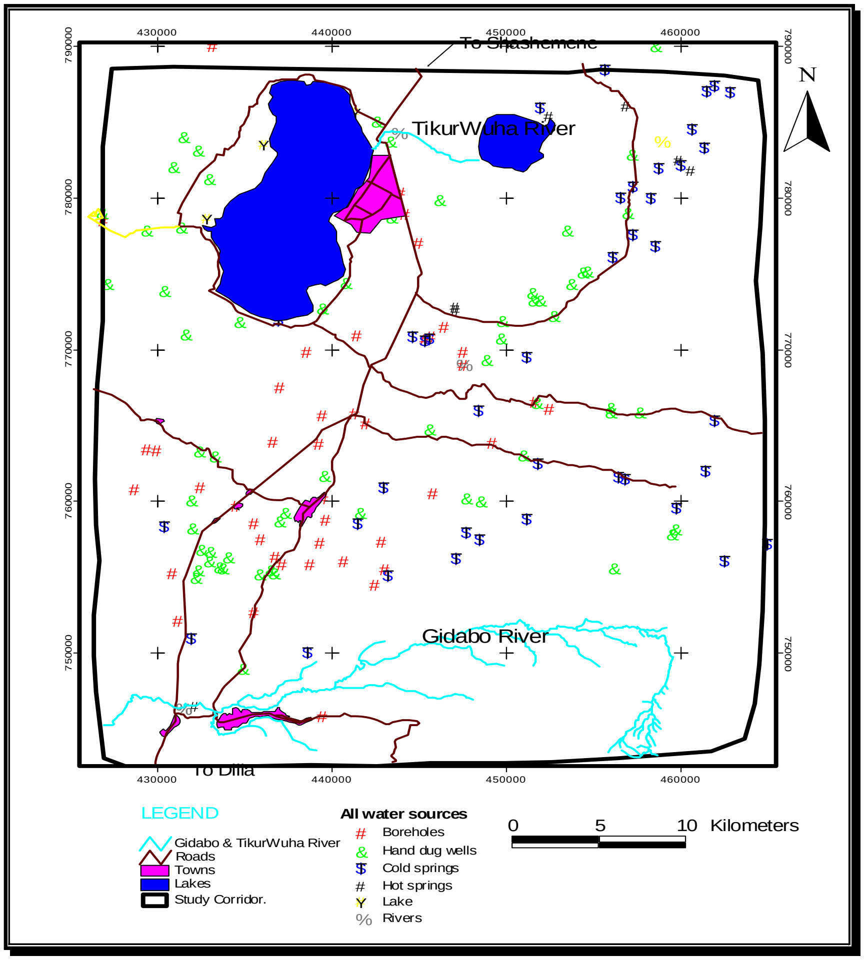


Figure 7.1 *All Water Source Site Distribution*

The method was involved the withdrawal of water from pumping boreholes sufficiently in order to insure that the sample represents the groundwater that feeds the well and in situ measurements of pH, EC, TDS and Temperature has been conducted(Personal communication from the sampler at regional water bureau).

7.3 In situ Parameters

The physical parameters of natural water like pH, Eh, Temperature, Conductivity and TDS should be measured on the field for that they will easily be changed due to environmental dynamics. According to the regional water bureau, these parameters were measured in the field using conductivity meter to measure conductivity and TDS. While pH meter was used to measure pH and temperature and few of them were also confirmed during the field survey. The geochemical analyses also measured in the laboratory as obtained from secondary data and previous authors. They are discussed here below:

7.3.1 P^H

Although water molecules are quite stable chemically they still tend to break down or dissociate into their component parts, H^- (Hydrogen) ions and OH^-(Hydroxyl) ions:

H2O = HOH= H+ OH-

Water is said to be either acidic or alkaline (basic), depending on the relative concentration of hydrogen ions. Hydrogen ions in water cause it to act as an acid. The capability of water to neutralize acid, that is, reduces the number of hydrogen ions in solution, is called alkalinity. The acidity-alkalinity characteristics of water are basic to an understanding of water chemistry (Driscoll, 1995). The hydrogen ion concentration of water is expressed as pH. The pH is equal to the logarithm of the inverse of the hydrogen ion concentration, or

pH = Log 1/H+

This particular equation is used because the actual number of ions is very small. The pH range is from 0 to 14 , with a pH value of 7 at 25°C (77°F) indicating a neutral solution in which H^+ and OH^- ions have the same concentration. A pH less than 7 indicates an acid solution; whereas a pH grater than 7 indicates an alkaline solution. Temperature plays a roll in determining the pH at which neutrality occurs. For example, at 0°C (32°F) the concentrations of positive and negative ions are equal at pH 7.53, where as at 50°C (122°F) neutrality occurs at pH 6.65 (Freeze and Cherry, 1979).

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 main once are the reaction of acidic solutes and hydrolysis reaction. River water in areas not influenced by pollution generally has a pH in the range 6.5 to 8.5. Consequently, from the existing water bodies' data, the pH values of the entire studied corridor ranges in between 6.00 to 8.4 and therefore, pH values of water in the area can consider as neutral and it is potable.

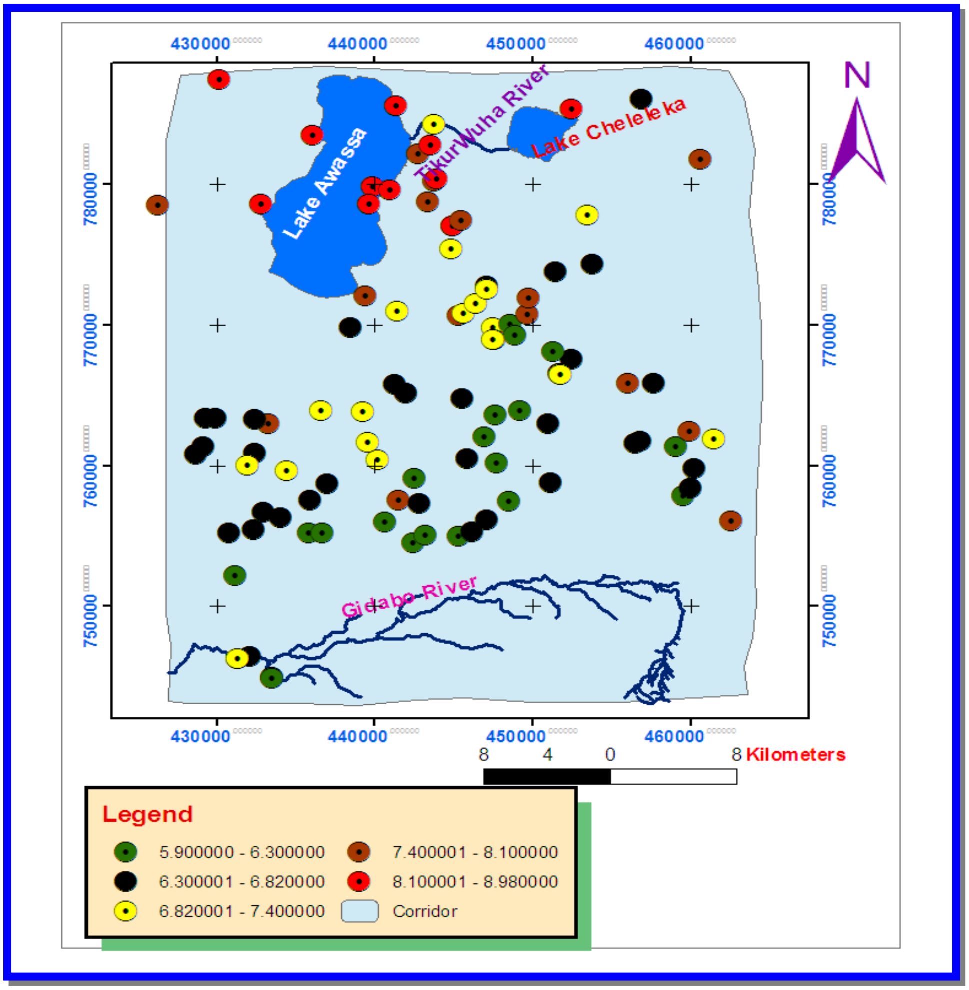


Figure 7.2 pH range map of all water sources

When the pH value increment trend is concerned, the lowest value is observed at south central part (Upper Gidabo River sub-basin) of the study corridor and the highest one is found at lake area. As figure above shows that pH spatial distributions are increasing towards the north (Lake Awassa sub-basin) which follow the groundwater flow trend.

7.3.2 EC (Electrical Conductivity)

Electrical conductivity of water is its ability to conduct an electric current at a specified temperature and it is usually measured in micro siemens per centimeter or micromhos per centimeter (Weast, 1968). The values of EC increase with temperature, between 20ºC and 30ºC, an increase in 1ºC, increases the EC by two percent on the average (Hem, 1992).

The American Society for Testing and Material (1964, p.383) defined electrical conductivity of water as “the reciprocal of the resistance in ohms measured between opposite faces of a centimeter cube of an aqueous solution at a specified temperature”. Pure liquid water has a very low electrical conductance: a few hundredths of a micromho per centimeter at 25ºC. This value has only theoretical significance, because water this pure is very difficult to produce. The presence of charged ionic species in solution makes the salutation conductive. As ion concentrations increase, conductance of the solution increases; therefore, the conductance measurement provides an indication of ion concentration. Electrical conductivity values show significant variations with the different sources of water.

Generally, as it is observed on Fig.7.3, there is a gradual increment in EC from south eastern part towards the north western (Lake Awassa) part of the corridor and at the time the highest EC value,1228µS/cm is found at Mulete area(426369E and 778520N). This EC value rise towards Lake Awassa sub-basin is also strengthened the existence of groundwater flow from the Upper Gidabo River towards the rift floor.

7.3.3 Eh (Redox Potential) and Temperature

The electrochemical evolution sequence that founded on geochemical theory refers to the tendency for the redox potential of groundwater to decrease as the water moves along its flow paths. This tendency was first recognized by Germanov et al, (1958). As water from rain and snow enters the subsurface flow system, it initially has a high redox potential as a result of its exposure to atmospheric oxygen. The initial redox conditions reflect high concentrations of dissolved oxygen, with pE values close to 13, or, expressed as Eh, close to +75 mV at pH (Freeze and Cherry).

Although there is no enough measured as well as complete secondary data concerning this parameter, based on the limited data, there is high Eh value in the south eastern part and low value, less than one, at Lake Awassa area (Discharge zone).

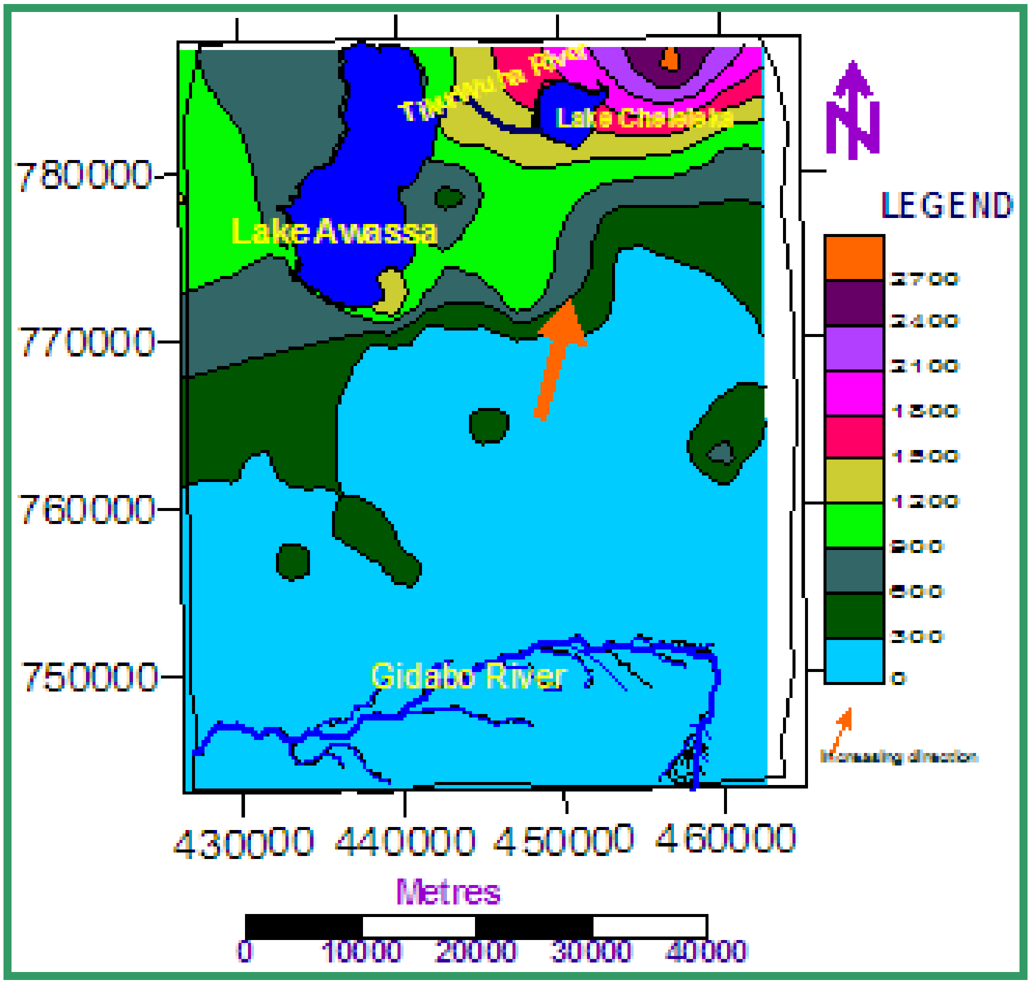


Figure 7.3 EC map of all water sources

On the other hand, temperature has remarkable influence on certain physical, chemical and bacteriological characteristics of groundwater; the solubility of CO_2 in water at atmospheric pressure, the variability of dissolved oxygen important for water life, and microbiology are all affected by change in temperature (Hem, 1989). Temperature also like other parameters measured in the field by using conductivity meter/ pH meter. In most case, shallow ground water are normally characterized by a temperature which is strongly affected by the type of overlying surface environment. In the area, almost all wells have the same depth with same climatically situation but shows temperature variation. Temperature of the area ascending when moving to Lake Awassa sub-basin with the maximum of 82ºC at Gemeto hot spring.

7.3.4 Total Dissolved Solids (TDS)

Total dissolved solids (TDS) can be determined by evaporating a known volume of the sample and weighing the residue. TDS can be estimated by summing the concentrations of the individual ions. This method does not account for any dissolved substances. For example, dissolved silica, SiO_2, may not be reported but contributes to TDS.

One basic measure of water quality is the TDS, which is the total amount of solids, in milligrams per liter that remain when a water sample is evaporated to dryness. Water naturally contains a number of different dissolved inorganic constituents. The major cations are calcium, magnesium, sodium, and potassium; the major anions are chloride, sulfate, carbonate, and bicarbonate. Although note in ionic form, silica can also be a major constituent.

These major constituents constitute the bulk of the mineral matter contributing to total dissolved solids. In addition there may be minor constituents present, including iron, manganese, fluoride, nitrate, strontium, and boron (Fetter, 1994).

The surface water may be adversely impacted by human activity. If organic matter, such as untreated human or animal waste, is placed into the surface-water body, dissolved oxygen levels diminish as microorganisms grow, using the organic matter as an energy source and consuming oxygen in the process. The total dissolved solids may increase owing to the disposal of wastewater, urban runoff, and increased erosion due to land-use changes in the drainage basin. The natural quality of groundwater varies substantially from place to place. It can range from total dissolved solids contents of 100 mg/l or less for some fresh groundwater to more than 100,000 mg/l for some brine found in deep aquifers (Fetter, 1994).

As it is related to the sum of the concentration of all ions, it is directly related to the electrical conductivity. TDS of natural water range from less than 10ppm of dissolved solids for rain and snow, to more than 300,000ppm for some brine.

Thus, the total concentration of dissolved solids can be used for simple classification of water (Tenalem Ayenew and Tamiru Alemayehu, 2001).

Table: 7.1 Classification scheme for water based on the total dissolved solids.

Class	TDS (mg/l)
Fresh	0-1000
Brackish	1000-10000
Saline	10000-100000
Brine	->100000

A groundwater moves along its flow paths in the saturated zone, increases of total dissolved solids and most of the major ions normally occur. As would be expected from this generalization it has been observed in groundwater investigations in many parts of the world that shallow groundwater in recharge areas is lower in dissolved solids than the water deeper in the same system and lower in dissolved solids than water in shallow zones in the discharge areas (Freeze and Cherry, 1979).

TDS values in the Figure7.4 of the studied corridor show their spatial distribution with in the area. The concentration has entirely the same trend with that of EC. It increases from south east towards northwest part of the study area and also concentrated (has a highest value) at the same location (at Mulete) which is mentioned above and as well coincided with groundwater flow direction. This is, probably due to high rock-water interaction at the course of long groundwater flow (long residence time). Since this area is highly affected by tectonic effect like fractures and faults, that may also favour the interaction. Natural geological processes and/or man made effects can add some contribution for high TDS concentration around Lake Awassa area.

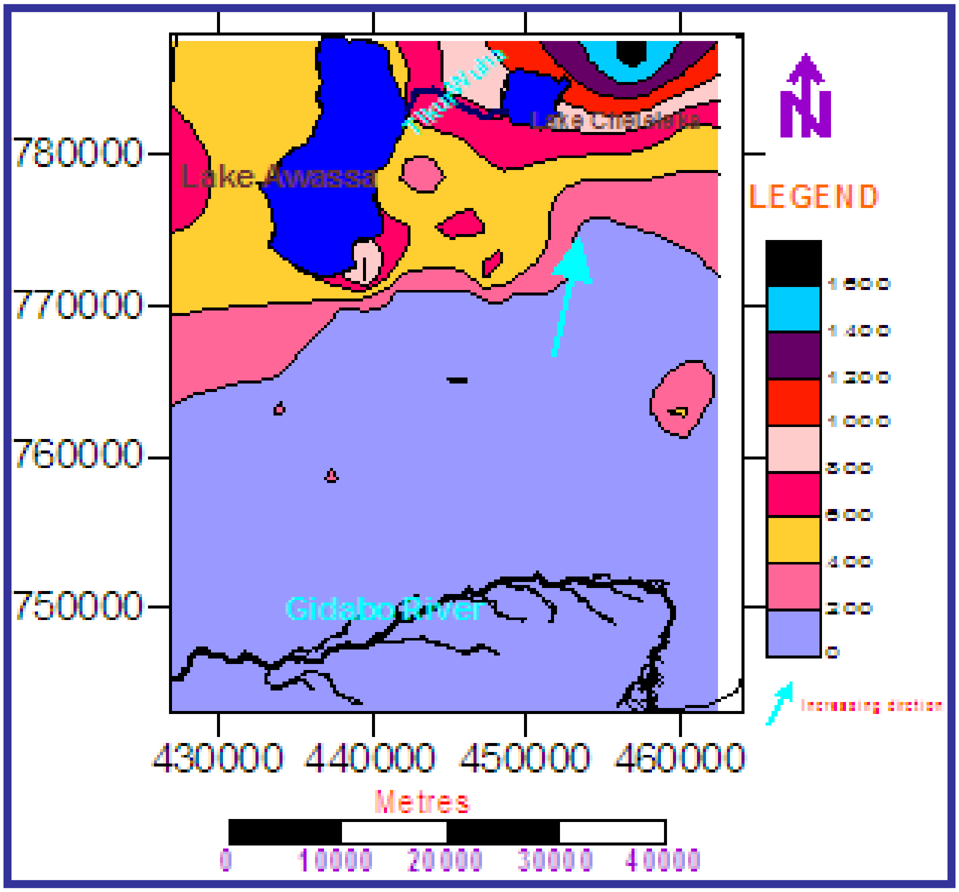
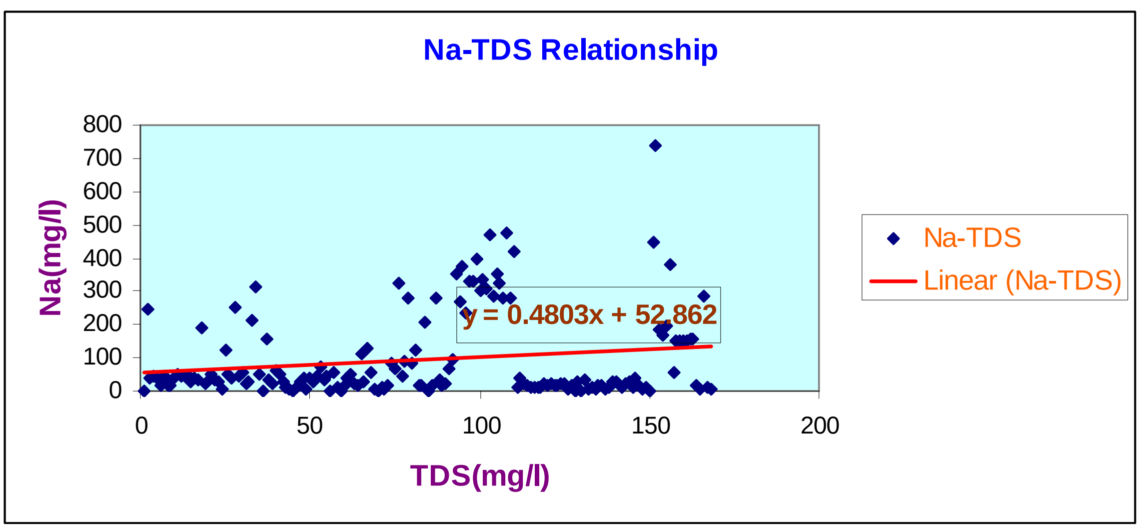
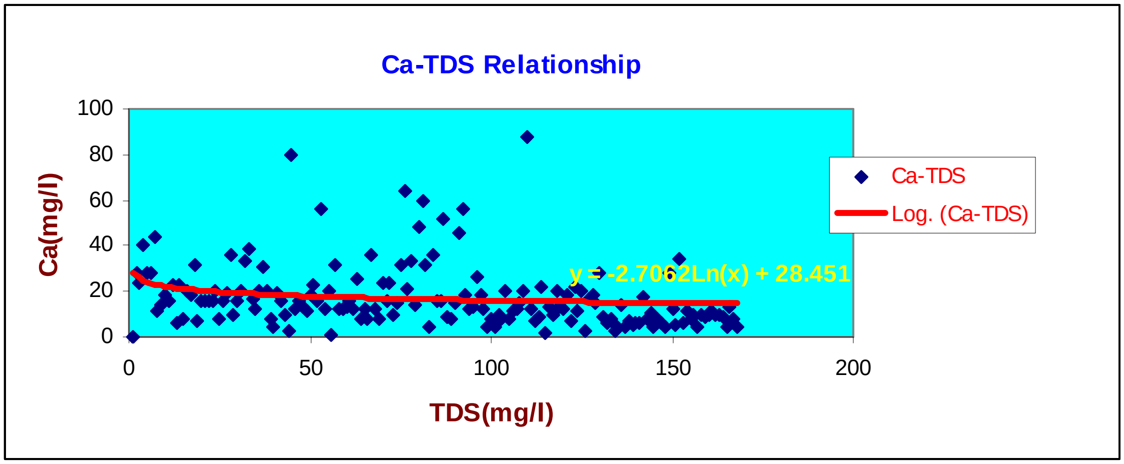


Figure 7.4 TDS Map

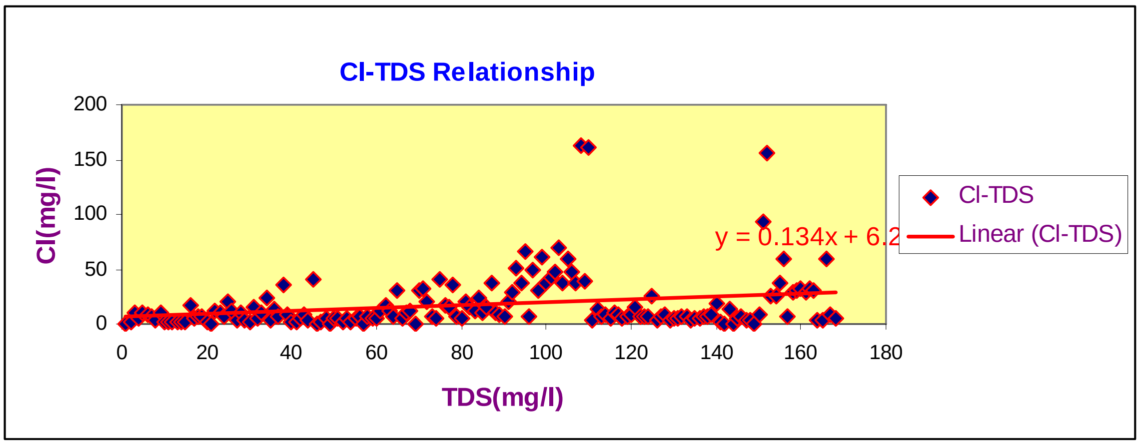
A



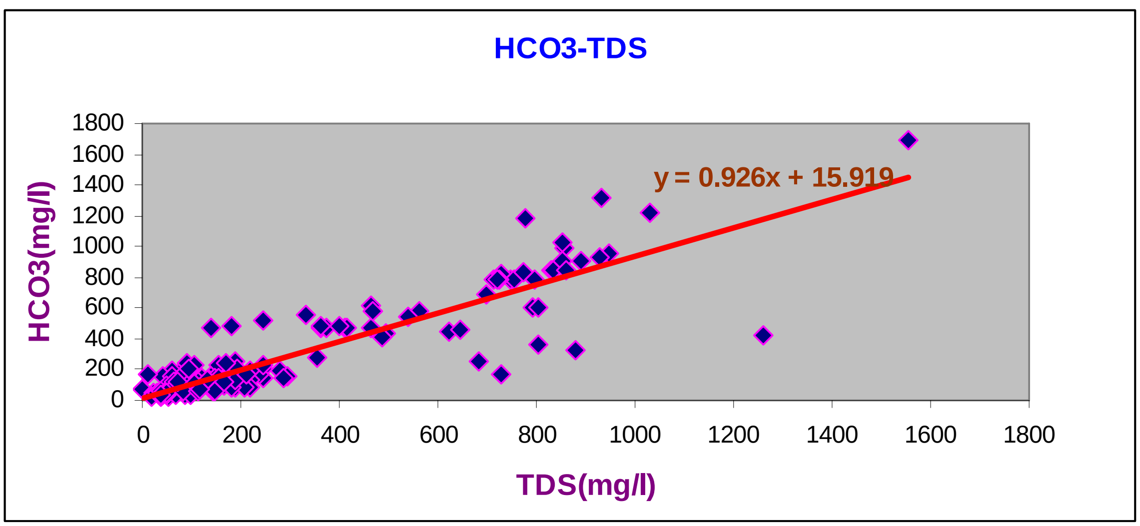
B


Ca-TDS Relationship
100
80
60
40
20
0
Ca(mg/l)
0
50
100
150
200
TDS(mg/l)
Ca-TDS
Log. (Ca-TDS)
y = -2.7062Ln(x) + 28.451

C


Cl-TDS Relationship
200
150
100
50
0
Cl(mg/l)
0
20
40
60
80
100
120
140
160
180
TDS(mg/l)
Cl-TDS
Linear (Cl-TDS)
y = 0.134x + 6.2

D


HCO3-TDS
1800
1600
1400
1200
1000
800
600
400
200
0
HCO3(mg/l)
0
200
400
600
800
1000
1200
1400
1600
1800
TDS(mg/l)
y = 0.926x + 15.919

E

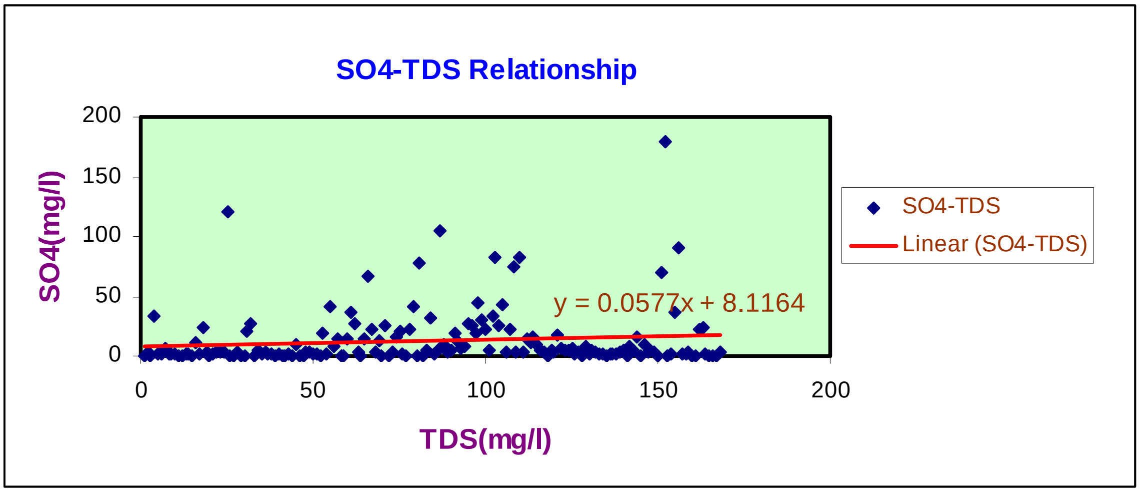


Figure 7.5*(A, B, C, D and E) Relationships of TDS with other Cations and Anions*

From TDS and major cations and anions relationships, shown on the above figure7.5 (A-E), it can be seen that there is more or less a linear relationship between TDS-HCO_3 and TDS-Cl though the contribution of HCO_3 and Cl ions for TDS concentration is far different(more in HCO_3) . Where as Ca-TDS relationship is negative, which indicates that Ca has a limited role for high TDS in the water.

7.4 Classification and Presentation of Laboratory Analyzed Parameters

The spatial variability observed in the composition of the major ions can provide highlight to aquifer heterogeneity and connectivity as well as the physical and chemical processes controlling water chemistry. Generally the approach is to divide the samples in to hydrochemical groups, which are group of samples with similar chemical characteristics that can then be fitted with location. Verification that systematic variations along the flow path are related to reactions between ground water and surrounding formation which can provide the hydro chemical evolution trend for the study area. This is vital for interpreting the spatial variations of water chemistry that helps to determine potablity of water and defining ground water flow direction along the corridors and characterization of the hydrologic systems. By using Aquachem Software, it is tried to use two of the many available graphical and statistical methodologies to classify the water samples.

7.4.1 GRAPHICAL PRESENTATIONS

Over the years, a considerable number of techniques for graphical representation of analyses have been proposed. Some of these are useful principally for display purposes that is, to illustrate oral or written reports on water quality, to provide means for comparing the analyses with each other, or to emphasize differences and similarities. Graphical procedures do this much more effectively than numbers presented in tables (Hem, 1989).

Most of the graphical methods are designed to simultaneously represent the total dissolved solid concentration and the relative proportions of certain major ionic species (Hem, 1989) and all the graphical methods use a limited number of parameters, usually the available data, unlike the statistical methods that can utilize all the available parameters.

In addition to the types of graphs suitable for displays and comparison of analyses, graphical procedures have been devised to help detect and identify mixing of waters of different composition and to identify some of the chemical processes that may take place as natural waters circulate. Graphing techniques of the latter type may be useful in the study of data prior to preparing reports or arriving at conclusions. For this purpose several commonly used graphical methods are available from simplest to complex one like Stiff diagram, Pie chart, Box-whisker, and Piper diagram and Schoeller respectively. Among them, for this work, Box-Whisker and Piper diagram are used to present the analyses of groundwater chemistry result.

7.4.1.1. Box and Whisker for Major ions chemistry

Water is naturally balanced in terms of the existing cations and anion (Na, K, Ca, Mg and CL, SO_4, CO_3, and HCO_3) but because of its distribution, occurrences and movements with in geological formation, the neutrality of water disturbed. On the study corridor, variable ions like Fe^{+2} ,F^{-1} ,Mn^{+2} and Cu^{+2} are observed together with major ions concentrations.

From figure below, it can be seen that the major ions concentrations from all water bodies show considerable variations. The minimum, maximum and mean concentrations of the major cations and anions of groundwaters (boreholes, cold springs, hot springs, and dug wells) and surface waters (Lake and Rivers) are presented on the figure below from the study corridor.

In the case of groundwater, sodium is the dominant cations followed by calcium and Magnesium. On the other hand from anions bicarbonate is the dominant followed by Cl and SO_4. Major cations concentration descending uniformly from Na, Ca, and Mg in the groundwater of the study area .The dominance of Sodium in the study area is likely to be attributed to the dominance of the acidic volcanic rocks, mainly ignimbrite, rhyolite and pyroclastic deposits which contain pumice, tuff, etc.

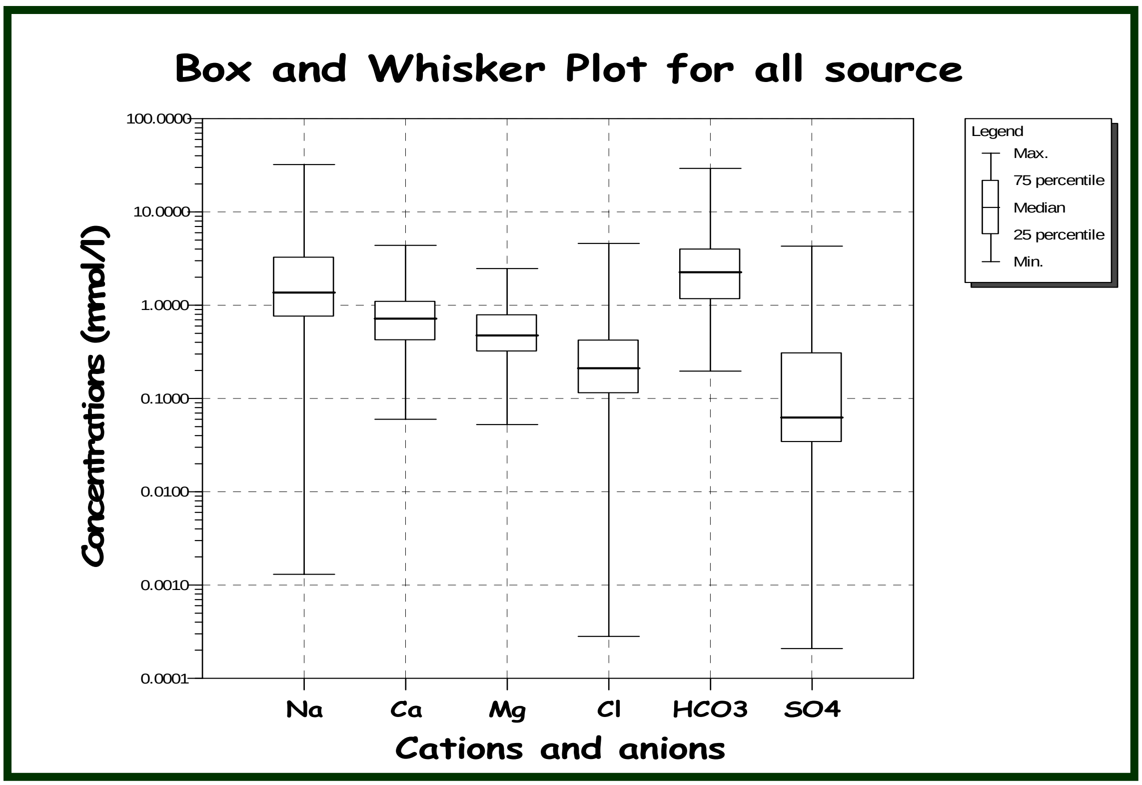


Figure7.6 Semi-log plot of major ions concentration of all water sources

Calcium is also sourced from many igneous rock minerals, especially in the silicates of pyroxene, amphibole and feldspars (plagioclase feldspars). In the volcanic the main sources of these ions come from the basic volcanic rocks. Magnesium is typically a major constituent of the ferromagnesian minerals such as olivine, pyroxenes, amphiboles and dark-colored micas along with various less common species.

The dominance of Bicarbonate in the study area is likely to be the reaction of dissolved CO_2 with rocks dominated by minerals with Na, K-Silicates common in acidic rocks. Other anions, CL and SO_4 more importantly sourced with an association of sedimentary rocks, volcanic gases from geothermal fields may also introduce Cl in the groundwater system and in some rift lakes. Some unusual high Cl in the rift lakes is likely to be related to the influence of geothermal fields. High SO_4 waters in the Main Ethiopian Rift are probably attributed to the effect of local lacustrine deposits associated with evaporates (Tenalem Ayenew, 1998).

7.4.1.2 Piper Diagram and Water type

Piper diagrams permit the cations and anions composition of many samples to be represented on a single graph in which major groupings or trends in the data can be identified visually and also showing the effects of mixing two waters from different sources. The mixture of the two waters will plot on the straight line joining the two points. The intersection of lines extended from the two sample points on the triangles to the central rectangle gives a point that represents the major-ion composition on a percentage basis. From this point, lines extending to the two adjacent scaled rectangles provide for representation of the analysis in terms of two parameters selected from possibilities, in this case, total major-ion concentration.

In Fig.7.7, in one hand, all cations concentrated nearly on calcium and sodium bar line and slightly go to the centre of the triangle that reflected to almost evenly in the central diamond shaped rectangle, at left lower bar. On the other hand, all anions nearly concentrated to bicarbonate bar line reflected to the central diamond shaped rectangle.

The two major cations and anions simultaneously reflected on the rectangle and forming intersection which is representing of water point. The reflection values in the central rectangle concentrated on its entire left side bar, which shows the Na + K + HCO_3 and Ca +Mg+ HCO_3. Accordingly, the water is Na-K-HCO_3 and Ca-Mg- HCO_3 types.

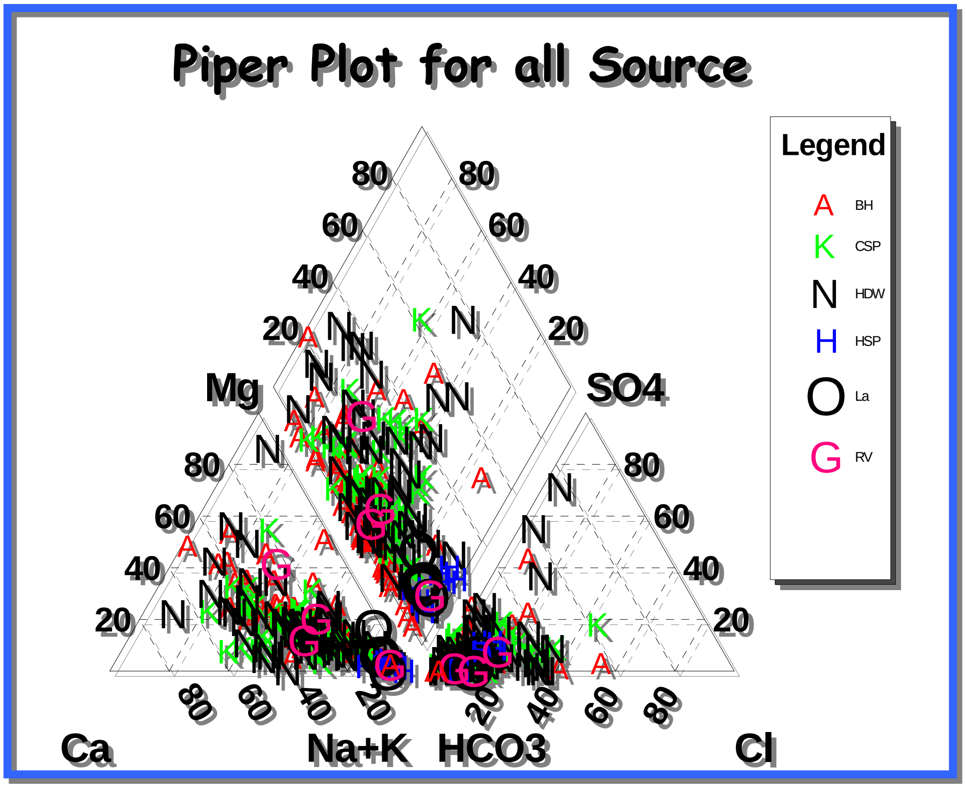


Figure 7.7 Piper plot for all water sources

In addition to represent all water source together, piper diagram also important to display each water source of more than one sample. In the figure below, six piper plots observed which are representing Borehole; Hand dug well, Lake, Rivers, Hot and cold springs.

Hot spring and Lake Awassa water Samples positions on the piper plot (Figure7. 9 and 7. 10) represent hot springs from Wondogenet, Gara rikata and Yirgalem and Lake waters. The dominant cations in these waters are sodium and potassium, and the dominant anion is bicarbonates. Thus, water falls in the Na–HCO_3 type in the Piper plot.

In the majority of waters from the study corridor boreholes (Figure 7.8), dug wells (Figure 7.12 and river (Figure 7.11); Na dominate their cations species followed by Ca and Mg, while bicarbonate dominate their anions. These waters fall in the Na–HCO_3 and Ca-Mg-HCO_3 type in the Piper plot and most of them have moderate to high TDS. The cold spring (Figure7.13) sample located in the piper diagram shows slightly equal dominance of Na and Ca cations, and concerning to the anions, HCO3 is the dominant one. Accordingly, the water type of this source is Na-Ca- HCO_3.

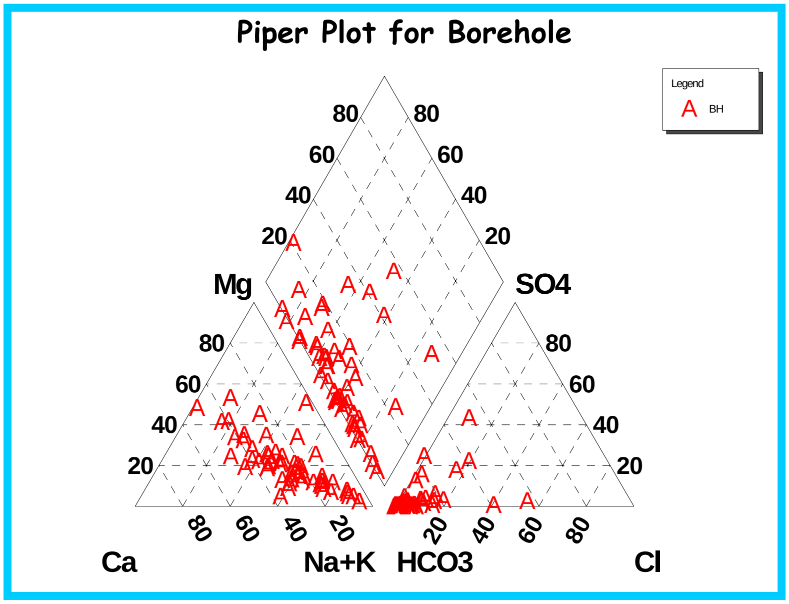


Figure 7.8 Piper plot for all Boreholes

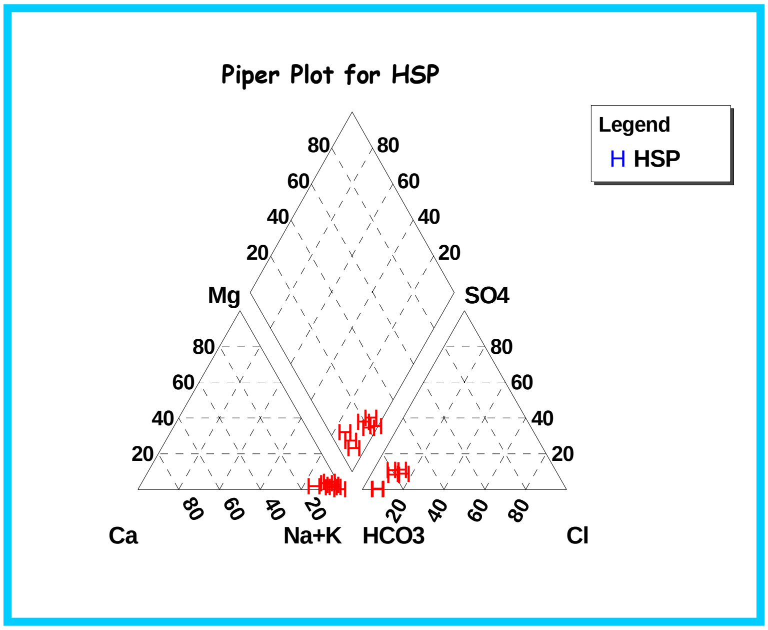


Figure 7.9 Piper plot for all hot springs

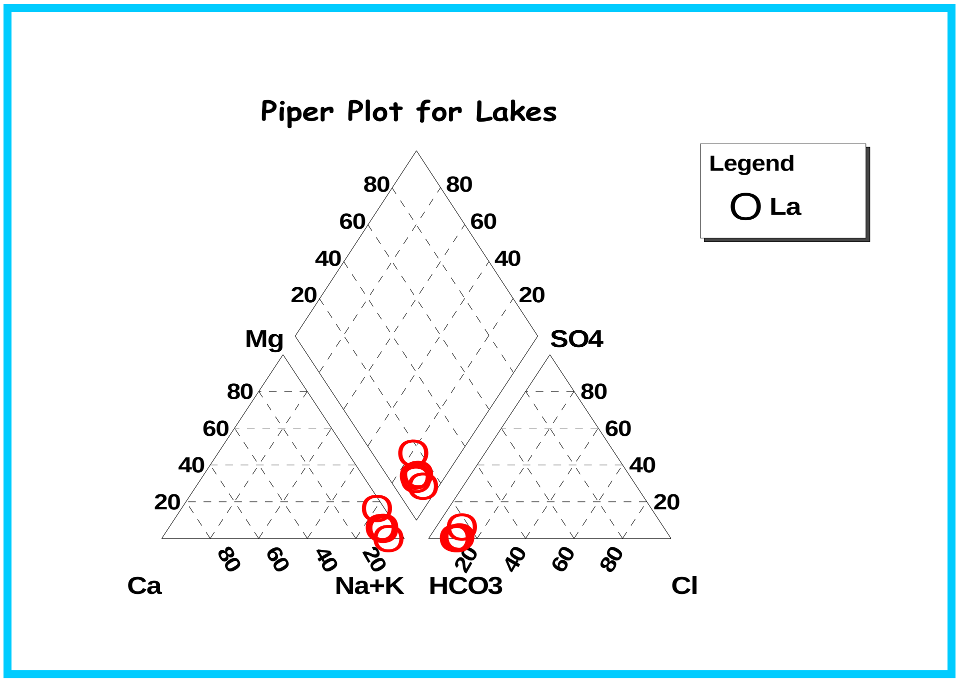


Figure 7.10 Piper plot for lake

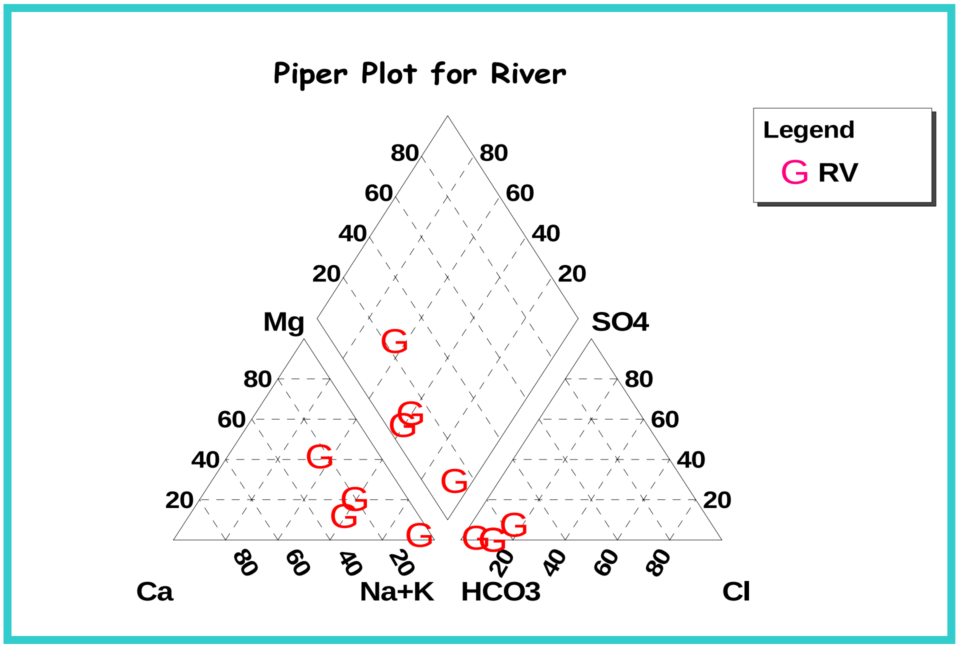


Figure 7.11 Piper plot for rivers

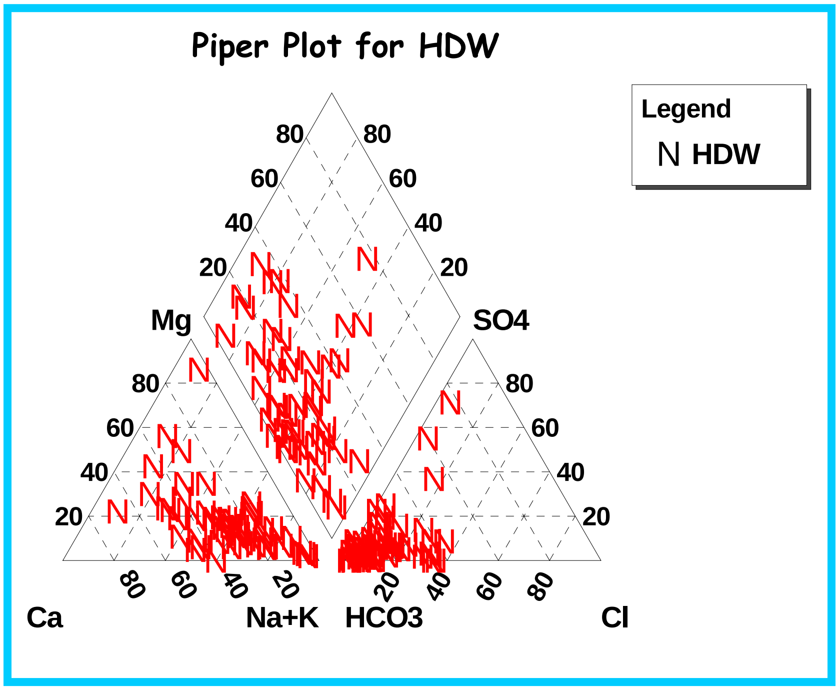


Figure 7.12 Piper plot for HDW

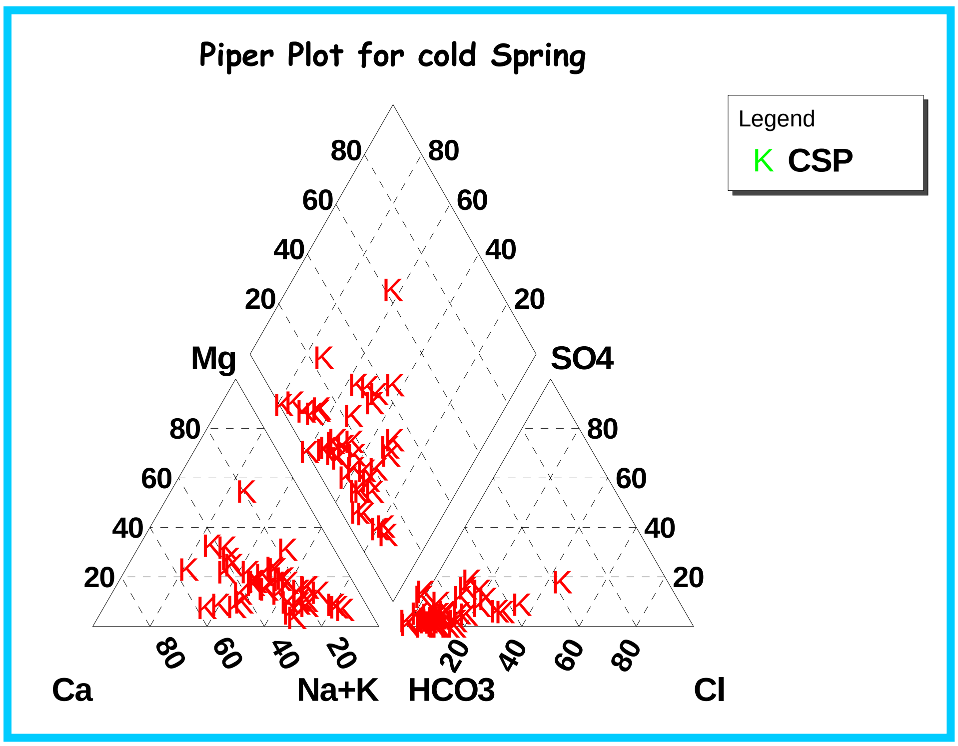


Figure 7.13 Piper plot for all cold springs

7.4.2. Spatial Trends of the Chemical Parameters of Water Samples in the Study area

The spatial distribution of groundwater chemistry is greatly affected by the lithological and hydrogeological properties of the geologic unit. On the other hand, as earth is dynamic, there are so many natural and man made processes, which operate on the surface and underground of the earth. Among the natural processes, the various types of physical and chemical weathering take a large part in order to form a pre-existing material into a new one. Man-made activities such as deforestations, urbanization and all agricultural practices including fertilizers and pesticides have their own contribution on the composition of groundwater chemistry.

The source and chemical composition of recharge water, and the amount of time (residence time) the water has remained in contact with the geologic units can also affect the type and quantities of dissolved constituents in groundwater. The measured major cations and anions which are the most abundant dissolved constituents including some other ions like iron and fluoride are discussed here blew. The spatial trend (evolution) of the cations and anions for each of the sources are separately plotted, and analyses are made on the basis of the trending direction and patterns so as to determine their contribution on the ground water flow direction and also potability of water for public consumption.

7.4.2.1 Chlorine, Sodium, Fluorine, Iron, and Bicarbonate

Chlorine

Chloride ions do not significantly enter into oxidation or reduction reactions, form no important solute complexes with other ions unless the chloride concentration is extremely high ,do not form salts of low solubility, are not significantly adsorbed on mineral surfaces, and play few vital biochemical roles. The circulation of chloride ions in the hydrologic cycle is largely through physical processes (Hem, 1986).

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. Even though, more important source of Cl is association with sedimentary rocks, volcanic gases from geothermal fields may also introduce in the ground water system and in some rift lakes (Tenalem Ayenew, 2005).

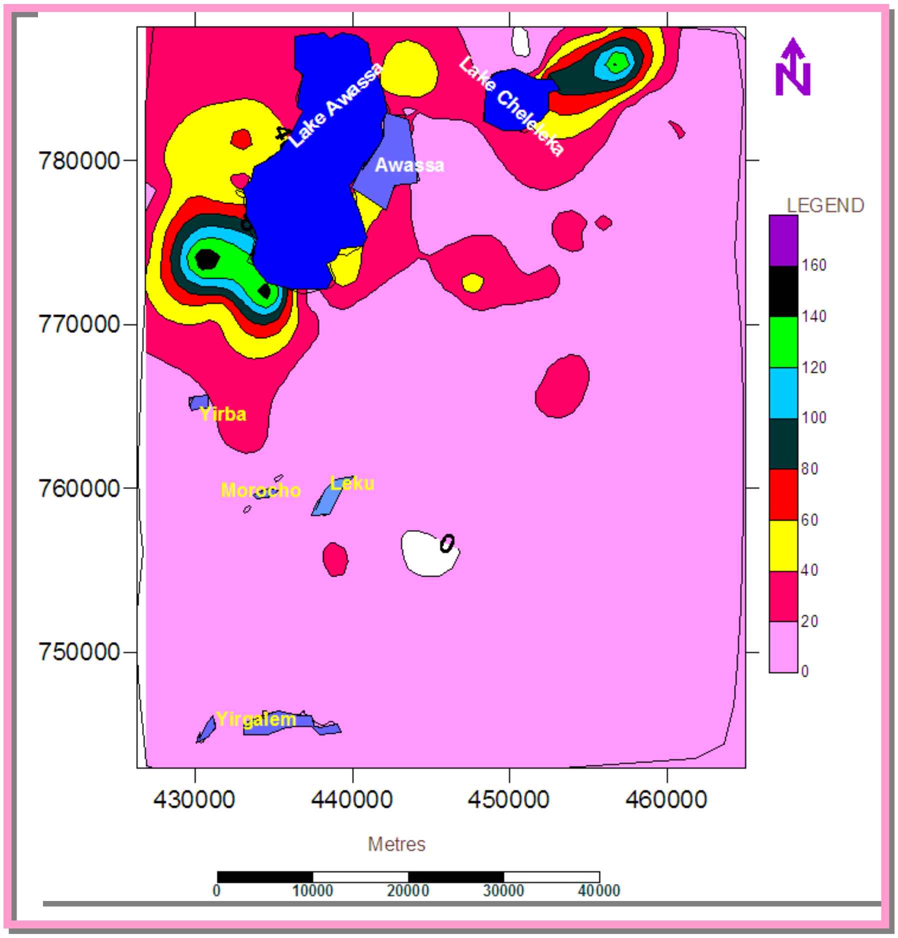


Figure 7. 14 Chloride Map

Chloride is present in all natural waters, but mostly the concentrations are low. In most surface streams, chloride concentrations are lower than those of sulfate or bicarbonate. Exceptions occur where streams receive inflows of high-chloride groundwater or industrial waste or are affected by oceanic tides. Chloride that is not accounted by rain and snowfall is most logically assignable to leaching of sediments (evaporates). Pollution caused by humans is a major factor in some basins. The most common type of water in which chloride is the dominant anion is one in which sodium is the predominant cation. Waters of this type range from dilute solutions influenced by rainfall near the ocean to brines near saturation with respect to sodium chloride (Hem, 1986).

In the study corridor one of the surface streams that is Tikur Wuha, which, has a chloride concentration greater than the sulfate but less than HCO_3. This is happened, perhaps due to effluents released from lagoon which is intended to treat the wastes from Awassa Textile Factory and/or the river receives chloride ions from groundwater that circulate from the recharge area.

On the other hand, Cl ion concentrations show three spatial distribution trends. Generally it increases from south to north of the study corridor. Exclusively, within the lake region, it radially increases at the water point of borehole (Jara Dado with GPS location 430456E and 773897N) in south west and hot spring of Bela (456965E and 786018N) north east of Awassa Lake. The highest concentration values for both water sources are found to be 163mg/l and 156 mg/l, respectively. The ranges of the chloride ions in the study corridor are in between 4 to 163. According to WHO guidelines for drinking water quality 2004, the concentration of Cl has to be less than or equal to 250Mg/L. As of these, in terms of Chloride, almost all parts of the area are safe for the drinking water supplies point of view.

Sodium (Na)

Sodium is the most abundant member of the alkali metal group of the periodic table. In igneous rocks, Na is slightly more abundant than potassium, but in sediments, Na is greatly less abundant. The amounts of Na held in evaporate sediments and in solution in the ocean are important parts of the total. When Na has been brought in to solution, it tends to remain in that status (Hem, 1986). There are no important precipitation reactions that can maintain low Na concentrations in water, in the way that carbonate precipitation controls calcium concentrations. Na is retained by adsorptions on mineral surfaces, especially by minerals having high cation-exchange capacities such as clay. However the interaction between surface sites and Na, with monovalent ions generally, is much weaker than the interactions with divalent ions.

It is one of the major cations characterized ion exchange chemical reaction during evolution process by Ca and Mg and passing though void space because of its small atomic mass (small radius).

Cations exchange is the chemical reaction frequently cited to explain the high percentage of sodium compared to calcium and magnesium in water (Lee, 1981; Woessner et.al., 1981, Wilson et.al., 1986). 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).

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

$Na_2X + Mg^{2+} \rightarrow MgX + 2Na^+$ Where X = aquifer solid

Generally, Na ions concentrations show an increasing trend in the studied area from south east to north west, especially high value is observed at north east of the study corridor. There is also Na ions increment to wards the west of the lake. As it is observed from figure 3.1, the geological map of the study corridor, these areas are covered by lacustrine sediments overlain by thick alluvium and volcano-lacustrine sediments, their Na ion concentration should be low according to the above discussion.

The presence of high concentration of Na ions in these areas might be either ion exchanges, dissolution of minerals or it comes from the recharge areas and that strengthen the idea of groundwater flow from south to north of the study corridor.

Na varies from 0(plateau area) to740mg/l (for Bela hot spring). Generally hot springs and dug wells found around the lake, lake water, and all water bodies located at south and south eastern part of the study corridor have high(>300mg/l,) medium(150mg/l) and low(<100mg/l) of Na ion concentrations, respectively. Cold springs around the lake area especially at the eastern part of the lake along the foot of Wondogenet ridge, have also low Na ion concentrations.

According to WHO guidelines for drinking water quality 2004, the concentration of Na has to be less than or equal to 200Mg/L. As of these, in terms of sodium, the areas where there is high Na concentration is encountered are not safe for the drinking water quality.

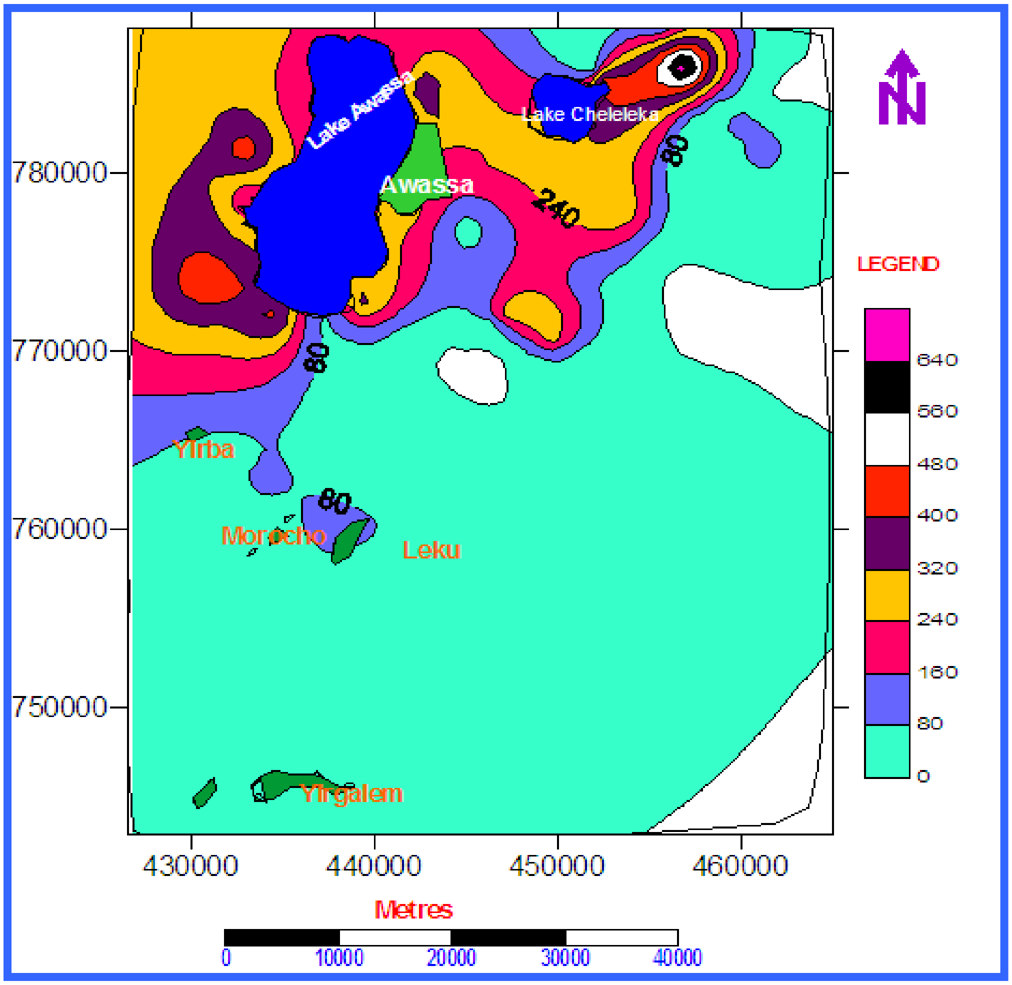


Figure 7.15 Sodium Map

Na varies from 0 to740mg/l (for Bela hot spring with UTM location 456965E and 786018N). Generally hot springs and hand dug wells found around the lake, lake water, and all water bodies located at south and south eastern part of the study corridor have high(>300mg/l,) medium(150mg/l) and low(<100mg/l) of Na ion concentrations, respectively. Cold springs around the lake area especially at the eastern part of the lake along the foot of Wondogenet ridge, have also low Na ion concentrations.

According to WHO guidelines for drinking water quality 2004, the concentration of Na has to be less than or equal to 200Mg/L. As of these, in terms of sodium, the areas where there is high Na concentration is encountered are not safe for the drinking water quality.

Fluorine

Fluorine is the lightest member of the halogen group of elements. It is the most electronegative of all the elements. In solutions, it forms F^{-1} ions. Fluoride ions have the same charge and nearly the same radius as hydroxide ions; thus the ions may replace each other in mineral structures. A significant fact noted in geochemistry of chlorine is that more than 75% of the total amount of that element known to be present in the outer part of the Earth is contained as chloride in solution in the ocean. Fluorine, on the other hand, is almost all tied up in rock minerals, and only a small percentage of the total is contained in seawater (Hem, 1986).

In nature F comes from chemical weathering product of igneous rocks, magmatic emissions, atmospheric dusts from continental sources and industrial pollution (Hem, 1970). Sources of fluoride in water are: fluorite (CaF_2) this is a common one that has rather low solubility and occurs in both igneous and sedimentary rocks. Apatite ($Ca_5(Cl,F,OH)(PO_4)$), Amphiboles, such as hornblende and some of the micas.

There is no agreement among researchers as to how the high F is introduced in to the groundwater and surface water bodies. According to Gerasimovskiy and Savinova (1969) the volcanic rocks of East Africa are richer in F than similar rocks in other parts of the world. The most important sources are acidic volcanic rocks such as tuff, pumice and obsidian and emanations from geothermal systems (Tesfaye Chernet, 1982; Tesfaye Chernet et al., 2001).

High F in saline lakes of the East African Rift reflects the nearly complete removal of Ca by carbonate precipitation usually as calcium carbonate (Darling et al. 1996) probably from CaF2. Calcium exchanges in the lacustrine sediments also the probable source of F in ground water. These are two methods of Calcium depletion in the rift that may facilitate fluoride concentration.

From the available data of all sources of water bodies, the spatial distribution of fluoride is displayed figure 7.16, in the study area. Based on this figure below, there is the high concentration of fluoride at the vicinity of Lake Awassa and in Awassa town itself. The fluoride ion concentration of these areas is found to be > 4 mg/l that is far beyond WHO standard for fluoride optimal level of 1.5 mg/l, 2003 for safe drinking water.

The concentration in Lake Awassa is 6 to 7 mg/l. Like the sodium ions, Chloride ions are also highly concentrated in hot spring waters. The highest value is encountered in Shallo hot spring (28 mg/lt). Where as the rest of areas, which comprising the eastern high lands and central part of the study corridor have fluoride value at safe limit, except for one borehole, which is located at Konsore Arke(429409E & 763401N) with 2.37 mg/l. These areas have also been identified as a major groundwater recharge zones on the basis of its low EC and high Eh values.

High concentration of fluoride causes the known problems of dental and skeletal fluorosis. This was obviously observed on the inhabitants of Awassa town two decades ago, before using drinking water supply from other source (surface water like river). Nevertheless, fluoride is an essential nutrient to healthy dental growth, provided its concentration is in the range of 0.5 to 1.5 mg/l.

Generally, the study area can be sub divided in to two, on the basis of fluoride concentration: high fluoride area, Northern part especially, at the Awassa Lake and its vicinity and low fluoride area in he rest of the area. Knowing the spatial distribution of the fluoride ions is very useful to locate the productive wells for safe and potable water development.

Iron

Concerning the existence of iron in the study area there is high concentration of iron (Fe^{+2}) ions are observed in the central and even in the plateau areas beyond world health organization guidelines(2004). Accordingly, some of the encountered concentration values of Fe^{+2} from boreholes are Wijigra(2.79mg/l), Telamo kentise(1.25mg/l), Gemeso Kenera(0.7mg/l),Hoboso(0.9mg/l),Futo(1.06), Dobe Bute(0.43mg/l), Fayich goja(0.43mg/l) those are found in highlands and MelgeWondo artesian well(beyond WHO's guidelines) located at rift caldera ,and Gidabo river (1.5mg/l).

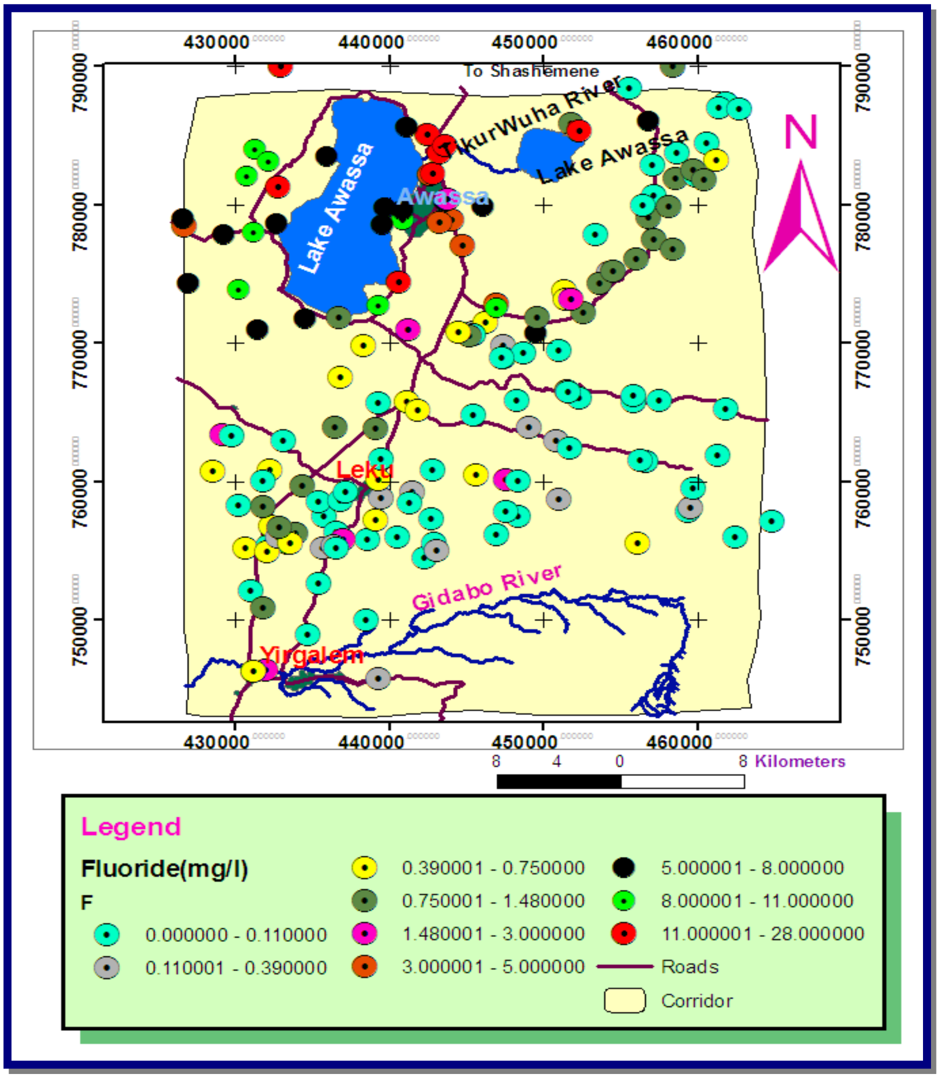


Figure 7.16 Fluoride Map

Bicarbonate

The Bicarbonate concentration of natural water generally is held within a moderate range by the effects of carbonate equilibria. The concentration in rain water commonly is below 10mg/l and sometimes is much less than 1.0mg/l depending on pH. Most surface streams contain less than 200mg/l, but in ground water some-what higher concentrations are not uncommon. Concentrations over 1000 mg/l occur in some waters that are low in calcium and magnesium, especially where processes releasing carbon dioxide (such a sulfate reduction) are occurring in the groundwater reservoir.

Ground water associated with recharge is represented by water dominant in calcium, magnesium and sulphate with lesser amounts of sodium and bicarbonate. As the groundwater flows away from the source of recharge towards the rift floor, the interaction between water and rock increases. Sodic lithologic units are encountered as the ground water moves along a flow path, and calcium and magnesium ions are exchanged for sodium ions attached to aquifer solids.

Anaerobic sulphate-reducing reactions also act on the groundwater as it moves along a flow path. Therefore, both reactions result in a decrease in calcium, magnesium and sulphate and a corresponding increase in Na^+ and HCO_3^- as groundwater flows away from the source of recharge and results in water that evolves to a sodium-bicarbonate-type in the deep geochemical zone.

Bicarbonate ions have exactly the same spatial distribution trend in the study corridor with that of Sodium ions as described above. According to the figure below, they are increasing from Upper Gidabo River sub-basin to Lake Awassa sub-basin, which also shows the presence of groundwater circulation between the two basins. The higher bicarbonate ion concentrations are found at north east and south west of the lake. HCO_3 varies from 0 to1553 mg/l (for Bela hot spring). Generally hot springs and hand dug wells found around the lake, have higher HCO_3 ion concentrations.

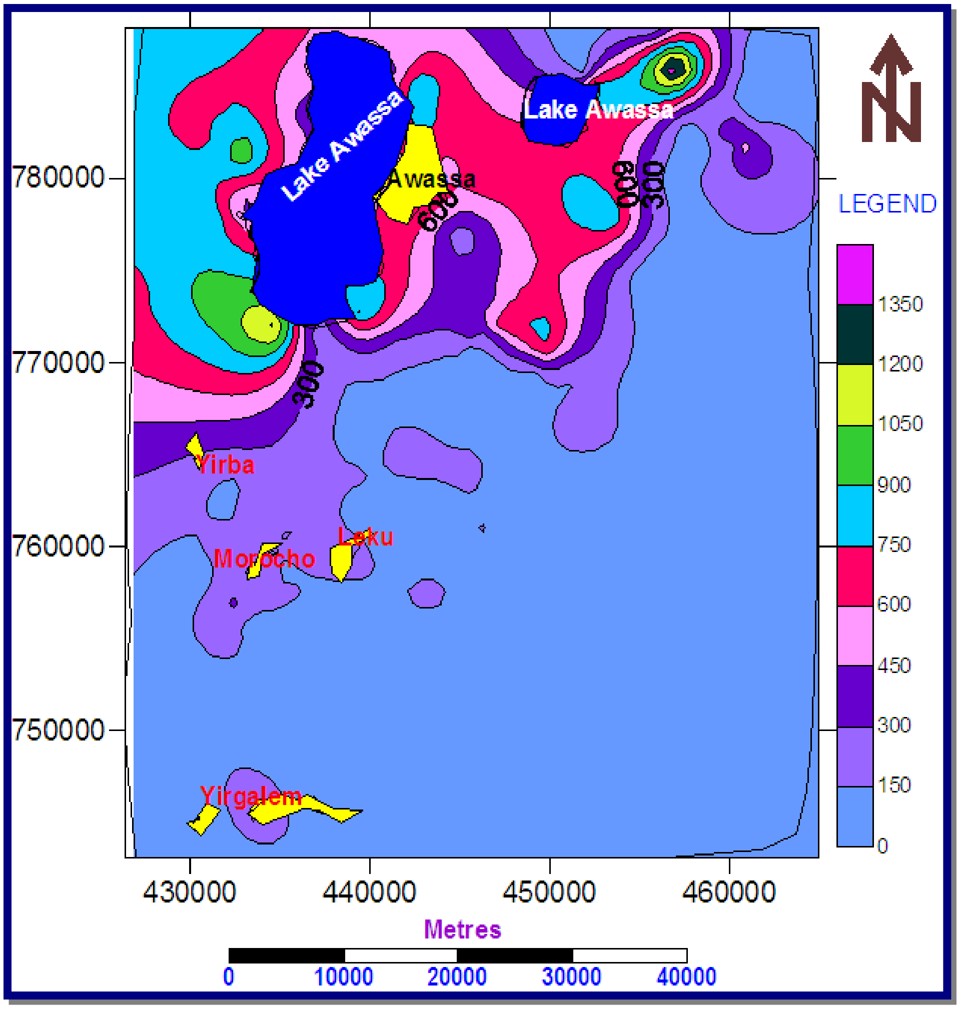


Figure 7.17 HCO $_3$ Map

CHAPTER EIEGHT

SYNTHESIS

From the very beginning, the intention of commencing this study work is to determine and identify whether there is a groundwater circulation between Upper Gidabo River and Lake Awassa basins. Having this thought in mind, the practical work was started through delineation of areas where there would be an interaction between the two catchments that include lakes in the north, Gidabo river in the south and eastern plateau areas in which the Garamba Mountain (3200m.a.s.l) is located. Particularly the latter one has the potential recharge for the entire corridor .The overall aerial coverage of the studied corridor is1582 Km^2.

Concerning the Lake Awassa cachment, according to the knowledge of the author, the previous research studies revealed that Lake Awassa is a closed lake for surface water and there would be groundwater inflow towards the lake. On the other hand, in this study the attempt was made to determine groundwater circulation between the two catchments and quantifying the amount, and then accordingly they were done.

For this study conventional methodologies along with different softwares were used to reach to the formulated objectives. Among which mainly collection of the secondary and primary data together with literature review have been well done. As long as the primary data collection is concerned, inventory of different water bodies on the study corridor have been done in taking yields, SWL, depths and the UTM locations. However, due to many constraints few works were performed in sampling and analyzing the sampled water.

Measurements of some physical parameters those help for the comparison of the existing secondary data were done along with lithologic description of the wells during the limited field surveying time. On the other hand, Secondary data were abundantly collected from the regional water bureau and other appropriate offices that includes: borehole history and physico-chemical analyses although they have poor quality and at the same time not completed. Therefore, this research work is produced mostly based on the secondary data. Most of the secondary data on physico-chemical analysis obtained from regional water bureau were analyzed with in last two years thus it is believed that they represent the actual condition of the area and groundwater flow system.

The appropriate software like Global Mapper, Surfer, Arc GIS, Arc View, and Aqua hem were fully used to produce the result from the existing data that was very crucial to approaching the methodology and determining: Ground water level contouring, three dimensional view of the groundwater flow, mapping of Geology, Structure, Hydrogeology, TDS, pH, EC, Cl, Na, HCO_3, F, determine recharge and discharge zones and plotting of the major ions in the studied area.

Concerning the geology of the area, the lake Awassa area, as it is part of the MER, is characterized by various volcanic activities such as formation of complex Awassa caldera with nested Corbetti one on the north of the study corridor. In this caldera there are many volcanic products like rhyolitic domes, scoria cones and manifestation of high temperature thermal springs. The floor of caldera is covered by volcano-lacustrine and fluvio-lacustrine deposits. Whereas the south eastern and western parts of the study corridor are mostly covered by welded tuff and pyroclastic deposits including others, respectively.

The geological formations found in the study area are generally good aquifer especially around the lake region; however, there is water quality problem at the lake and it's vicinity due to high fluoride concentration. In spite of this, from pre-knowledge of the area that the pyroclalstic deposit exposed on the western margin of the study area, west of Yirba town has a poor water holding capacity.

The study corridor is rich in surface water bodies and has high drainage system. Accordingly, the hydrology of the area includes lakes, many perennial and intermittent streams and swamp areas. The lakes are: Awassa, which is one of the rift lakes and Cheleleka that is already converted into swampy area. They are connected by the perennial Tikurwuha River which is the only inlet for Lake Awassa. Gidabo River is the major river that found in the southern part of the study corridor .There is also many tributaries for Gidabo and Tikurwuha Rivers in their catchment areas. Gidabo River has a potential for both drinking and irrigation water supplies.

Among these surface water bodies there are no as such significant developments have been done for consumption, irrigation and mini hydropower generation purposes though they have good potential. However, Kedo and Gidabo Rivers were being developed for Awassa and Yirgalem towns as water supply sources. Gidabo River is also used for irrigation in a very limited potential.

Moreover, a wide swampy area (Cheleleka) exists in the eastern part of Awassa Lake. Marsh areas are also found at central and western part of the study area. Many shallow wells and some deep wells (Jermancho BH, which is found out of the corridor in the south west) are located in these areas have good yield, however , their water holding capacity varies from place to place. These all have their own contribution in groundwater recharge and circulation in the study area.

The hydrologic cycle comprises precipitation, ET from water bodies, vegetations and bare soil those account all hydrologic and hydrogeologic parameters .These are highly interconnected together. Hydrogeology encompasses the interrelationships of geologic materials and processes with water which is characterized by porosity and permeability.

Based on the permeability of the aquifer formations in the area the hydrogeologic units are classified as very high to high (High potential Intergranular aquifer of lacustrine and alluvial sediments), High to Moderate (potential intergranular aquifer of dominantly lacustrine sediment), Moderate(potential fractured ignimbrite aquifer), Low to moderate (potential aquifer of welded tuff and lacustrine sediment), Low (potential aquifer of predominantly volcanic ash, pumice and basalt) and Aquiclude, this comprising mainly rhyolite and trychite.

The aquifer distributions in the studied area are of two types: shallow and deep aquifer system identified through studying the lithologic log and depths of the existing wells in the corridor. The shallow aquifer system ranged from 9 to 50 m and the formation included: Lacustrine sediments (sand and Gravel), volcanic sand and ash, weathered volcanic rock, quartz sand and welded ignimbrites and tuff. The deep aquifer system is encountered at the depth range of 56 to 224 metres and the types of aquifer observed are lacustrine sediments, volcanic sands and gravels, pyroclastic deposit, fractured rhyolitic ignimbrites and weathered ignimbrite and tuff

Based on these aquifer formations, and the existence of subsurface water, groundwater flow system has been investigated. For this study different methodology were used like collecting secondary data and field static water level inventory for some of shallow and deep aquifer to determine groundwater level contouring; using the water sampling analysis result to get hydrochemical evolution of Cl, Na, HCO_3 and others along with using the appropriate software like Surfer and Arc GIS for analysis purpose of the flow system.

In the previous studies by Kedir Yasin, (2002) and Tamiru Alemayehu, (2006) the following suggestions were proposed:

According to KedirYasin, 2002) there is groundwater out flow in the northern part of the catchement, especially north of Leku and Yirba, to the adjacent catchment (Lake Awassa) following the fault lines. He determined the presence of groundwater outflow by using groundwater contour map and quantifying the amount of out flow to be less than 1mcm per year by considering one of the springs (Gemeto spring) that is located at the floor of the rift near to Wondogenet ridge. Tamiru Alemayehu, (2006) was also suggested that the presence of numerous springs in the southern periphery of Awassa closed basin shows the recharging role of Upper Gidabo basin

Hence the current study output is also agreed with that of the above suggestions using the groundwater flow contour lines and physico-chemical trend analysis presented accordingly as follows:

In figure 6.5, flow system with in the deep aquifer system shows that especially groundwater flows take place from south eastern high plateau area to that of north western and western parts of the study corridor. As it is observed from the groundwater contour, frequency and magnitude of vectors, the high flow is encountered at north east where high yield wells, cold and hot springs are concentrated in those areas. This is strongly supported by the spatial distribution of Na, Cl and HCO_3 in the flow system which is increasing towards the north (Lake Region). Their ions concentrations have low and high in the south and south east, and northern parts of the study corridor, respectively which increase, keeping the same trend towards the north.

Flow system in the shallow aquifers happened entirely in the same manner with that of the deep aquifer system (Figure 6.3). According to the previous work and the current study, it is confirmed that the Lake Awassa basin is receiving water from Upper Gidabo basin mainly via north eastern part of the study corridor along the fault lines (Figure 3.2). The high yield cold springs including Gemeto those concentrated along the foot of Wondogenet ridge and at Loke palace are controlled by the structures and have sources or recharge from the upper Gidabo River basin.

As they are portrayed on map in the figure 6.2, one groundwater divide is found at the eastern part of the lake which is very localized due to fault structure whereas the other is located at the center of the study area near to Boricha ridge. Based on groundwater flow line determination, it is believed that this groundwater divide has no lateral extension towards the eastern part of the study area.

Water that originated from these groundwater flow system can also be determined in the laboratory to observe the hydrochemistry part, which is partly significant to determine water type, to show high concentration of fluoride, to determine major ionic distribution by using different graphical methods like Box and Whisker(7.4) for Major ions chemistry distribution for groundwater and surface water, and Piper diagram permit the cations and anions composition of many samples to be represented on a single(Figure 7.5 to7.11) graph to indicate water types

The water types in the studied area are of Na-Ca-HCO_3 and Ca-Mg-HCO_3. For both surface and groundwater the dominant cations and anions are Na and HCO_3 and it is possible to conclude that the general water type of the area is Na-HCO_3. Water types for different source are also determined that lake and Hot spring waters fall in Na–HCO_3 type, boreholes, HDW and rivers show Na–HCO_3 and Ca-Mg-HCO_3 type, while cold spring water has Na-Ca- HCO_3 type. On the other hand, safe drinking water needs special consideration for the concentration of major ions on the basis of WHO guideline, 2004.

The spatial distribution of Na and fluoride ions concentrations are obtained from using surfer and ArcGIS softwares and plotted on the figures (Fig.7.13) and (Figure 7.14), respectively. Accordingly, Na ion concentration varies from 0 to740Mg/l (for Bela hot spring). Based on this figure there is high concentration of fluoride at the vicinity of Lake Awassa and in Awassa town. The fluoride ion concentration of these areas is found to be > 4 mg/l that is far beyond WHO standard for fluoride optimal level of 1.5 mg/l, 2004 for safe drinking water. Like the sodium ions, this is also highly concentrated in hot spring waters.

The highest value is encountered in Shallo hot spring (28 mg/l). While the rest of eastern and central areas of the study corridor have fluoride value at safe limit, except for one borehole, which is located at Konsore Arke(429409E and 763401N) with 2.37 mg/l. High concentration of fluoride causes the known problems of dental and skeletal fluorosis. This was the main problem of the inhabitants of Awassa town two decades ago, before using drinking water supply from other source (surface water like river).

To make all water potable for human consumption it is better to pass in defluoridation techniques. There are different methods of defluoridation techniques and the most common, suitable, available types are Nalgonda (lime & alum). (Abiyu Kebede, 2007) and/or using other alternative sources.

Generally, objective of this study is to determine flow direction and comparative water chemistry. Both of which are investigated, the flow system determined with different methodologies stated above and their output is agreed with that of Kedir Yasin,(2002) and Tamiru Alemayehu,(2006) that confirmed the groundwater flows takes place from the south eastern part to the north west of the study corridor. From groundwater contour lines and vectors; the fault orientations and hydrochemical evolution trend maps, groundwater flow direction is determined that there is groundwater flow from eastern part towards north west and to the east .There is also flows from central and south western parts to the lake region. In the comparative Water chemistry part, water types of different source, evolution of major ions and their significant for water movement, fluoride concentration, and its mapping is investigated and analyzed.

As long as the amounts of groundwater flows from upper Gidabo River basin to Lake Awassa basin is quantified by using flow amounts of high yield springs those are found along the foot of Wondogenet ridge and considering Loke Palace spring. To do so, first, the catchments of the springs were delineated individually and as well as in group, from topographic map and total area is obtained. Then, by considering the annual recharge which is 211mm (Dessie Nedaw, 1997) and the catchment area, discharge of all springs were computed. On the other hand, considering the present yield of the springs, the annual discharge is also calculated. Finally, the difference between the two amounts was assumed to be the amount of groundwater flowing from upper Gidabo River catchment to the Awassa Lake catchemnt.

CHAPTER NINE

CONCLUSIONS and RECOMMENDATIONS

The secondary data collection was supported by field well inventory to take the UTM location and measuring some of the physical parameters on site, and hydrochemical techniques were applied to understand the groundwater flow system. The hydrochemical data were thoroughly analyzed through graphical and chemical analyses which in turn are interpreted based on the analyses results. On the other hand, results from analysis of flow system in the area are basically showed the hydrodynamics. From this approach the following conclusions have been drawn.

◘Aquifers in the study area have two systems, the shallow and the deep. The shallow aquifer system is mainly composed of lacustrine and alluvial sediments and pyroclastic materials such as fractured Ignimbrite and its weathering product. From the lithologic log of some shallow wells, it is observed that the range of aquifer depth is 9 to 50 meters. Groundwater generally exists in an unconfined or semi-confined condition, the low permeability paleosols that are present between the successive eruptions and flows acting as semi-confining layers.

◘For the deep aquifer system, the depth of the aquifers ranges from 49 to 174 meters. This shows it's being deep confined aquifers with regional lateral extension. The aquifer is mainly composed of lacustrine and alluvium sediments, fractured rhyolitic ignimbrites, pyroclastic deposits and welded tuff with lacustrine sediment and volcanic ash, pumice and basalt. Based on the hydrogeologic map and the permeabilities of rocks, the aquifers shows variation and classified as high, high to moderate, moderate, low to moderate, and low respectively.

◘According to lithologic logs described under chapter five and by understanding that the area is affected by the volcanic processes like eruption of volcanoes, it is possible to say that there is similarity among lithologies in the study corridor. From this and by studying the structures in the area, generally, it can be concluded that the groundwater circulation is controlled by both by lithologies and structures.

- In general it can be said that there is deep and shallow circulation of groundwater giving different aquifer systems and various high and low yield springs. Groundwater in the study corridor is of good yield in low relief areas along the major structures mainly at the foot of the eastern escarpments (Wondogenet ridge) of the rift. However, the quality of water should take a great concern particularly in terms of fluoride ions.

- Some of the high discharge structurally controlled springs those emanate from the foot and neck of the Wondogenet ridge are Kikie, Melgewondo (Elfora), Borja, Bash, Wkondogenet, Isawa, Arulma Chemo,Gemeto and Loke Palace are believed to get recharge internally from eastern highlands (Upper Gidabo-basin).

- As the studied area is parts of the Main Ethiopian Rift (MER), tectonic and volcanic activities (processes) are highly reworked in the area. Based on the existed manifestation of volcanic and tectonic structures like caldera, cinder cones, rhyolitic domes, and normal faults and fractures, respectively; presence of high temperature springs (Gemeto) with characteristic features of geyser, and together with Tamiru Alemayehu(2006) findings it is possibly concluded that there is geothermal energy potential at lake Awassa and Wondogenet areas especially at Gemeto sub-area.

- The groundwater flow systems from both shallow and deep aquifers have exactly the same flow trends (Fig.6.3 and 6.5). After having high amounts of recharge from eastern high plateau, groundwater moves both towards north western (Lake Awassa sub-basin) and western parts following Gidabo River flow direction within the study corridor. However, when the magnitude of the flow is concerned, high flow is observed in the north western part. There is also some localized source(recharge) from west of the central part where Boricha ridge (Yirba area) is located and groundwater flows from this area towards the lake. As it is indicated on the figure 6.1 the main discharge areas are the rift floor in the north and at the south western part of the study corridor where Gidabo River leaving the corridor.

- The estimated groundwater flowing amount from the upper Gidabo river basin to the Lake Awassa catchment is calculated to be $4.97x10^6m^3$ (4.97mcm). Including the Gemeto spring flow amount, the total estimated amount is found to be $5.81x10^6m^6$ (5.81mcm). However, when the detail investigation on the area is made, the amounts will be quite more.

- The field measurements of pH values of the studied area ranges between 6 to 8.4 and therefore, pH values of water in the area can consider as neutral. The spatial distribution of the pH values are increasing from south towards the northern part of the studied areas (Fig. 7.1) that, reflecting the direction of groundwater flows towards the lake region.

- Electrical conductivity values show significant variations with the different sources of water. Generally as it is seen from Fig.7.3 there is a gradual increment in EC from south eastern part (Upper Gidabo River sub-basin) towards the north western (Lake Awassa) part of the corridor and at the time the highest EC value 1228µS/cm is found at Mulete area(426369E & 778520N) where there is a frequent ground crack.
- TDS, the concentrations of dissolved solids have entirely the same trend with that of EC. It increases from south east towards northwest part of the study area and also concentrated (has a highest value) at the same location which is mentioned above that is also coincided with groundwater flow direction. This is may be due to high rock-water interaction at the course of long groundwater flow and has long residence time.
- Na and Ca, and HCO_3 are the dominant cations and anions respectively for both surface and ground water in the studied corridor (Fig. 7.7)
- The water types in the studied area are of Na-Ca-HCO_3 and Ca-Mg-HCO_3. As mentioned, for both surface and groundwater the dominant cations and anions are

Na and Ca, and Bicarbonate and it is possible to conclude that the general water type of the area is Na-HCO_3.

- Water types for different source are also determined, Boreholes, Hand dug wells and rivers have the same water type as Na– HCO_3 and Ca-Mg-HCO_3, Lake and Hot springs also possess the same types of water composition as Na–HCO_3 .Whereas cold springs fall on Na-Ca-HCO_3 type in the study area.

- **Chlorine (Cl), Sodium (Na), Fluorine (F), and Bicarbonate (HCO_3)** distributions in the studied area also investigated in a separate way so as to observe their evolution and confirm whether the water fits WHO guideline, 2004.
- In the study area, Cl ion concentration shows three spatial distribution trends. Generally it increases from south to north of the study corridor. On the other hand within the lake region, it radially increases at the water point of borehole (Jara Dado) with GPS location 430456E & 773897N in south west and hot spring of Bela (456965E & 786018N) north east of the Awassa Lake. The highest values from these areas are observed that concentration values found to be 163mg/l and 156 mg/l respectively. The ranges of the chloride ions in the study corridor are in between 4 to 163. According to WHO guidelines for drinking water quality 2004, the concentration of Cl has to be less than or equal to 250mg/L. As of these, in terms of Chloride, almost all parts of the area are safe for the drinking water quality.
- Na concentrations vary from 0 to740mg/l (for Bela hot spring). Generally hot springs and hand dug wells found around the lake, lake water and all water bodies located at south and south eastern part of the study corridor have high(>300mg/l,) medium(150mg/l) and low(<100mg/l) of Na ion concentrations respectively. Cold springs around the lake area especially at the eastern part of the Awassa Lake along the foot of Wondogenet ridge, have also low Na ion concentration. According to WHO guidelines for drinking water quality 2004, the concentration of Na has to be less than or equal to 200mg/L. As of these, in terms of sodium, the areas where there is high Na concentration is encountered are not safe for the drinking water quality.

◙Bicarbonate ions have exactly the same spatial distribution trend in the study corridor with that of Sodium ions. They are increasing from Upper Gidabo River sub-basin to Lake Awassa sub-basin, which also shows the presence of groundwater interaction between the two basins. The higher bicarbonate ion concentrations are found at north east and south west of the lake. HCO3 varies from 0 to1553 mg/l (for Bela hot spring). Generally hot springs and hand dug wells found around the lake, have higher HCO_3 ion concentrations.

◙The fluoride ion concentration of Lake Awassa and its vicinity is greater than 4 mg/l that is far beyond WHO standard for fluoride optimal level of 1.5 mg/l, 2003 for safe drinking water. Like the sodium ions, this is also highly concentrated in hot spring waters. The highest value is encountered in Shallo hot spring (28 mg/l). Where as the rest of areas have fluoride value at safe limit, except for one borehole, which is located at Konsore Arke(429409E and 763401N) with 2.37 mg/l. High concentration of fluoride causes the known problems of dental and skeletal fluorosis. This was obviously observed on the inhabitants of Awassa town two decades ago, before using drinking water supply from other source (surface water like river).

♣**Based on the findings obtained so far from this research work the following recommendations have been given.**

♣Data base organization about well history, physico-chemical analysis, pump testing etc., should be done well for newly construction water schemes.

♣On the other hand, collecting and documenting data for the old wells from the concerning offices, drilling companies and organizations should be done.

♣Observation pipes should be installed in the existing and newly constructed boreholes for that almost of all wells exit in the area do not have such pipes.

♣For the existing boreholes static water levels, depths if possible and hydrochemical analysis have to be carried out and well documented.

- ♣ Further quantification of the groundwater flow amounts should be done with detail investigation methods through systematic sampling and measurements of all springs those are found along Wondogenet ridge and around Loke Palace.
- ♣According to this study there are two aquifer systems, concerning the groundwater flow direction both of them showed the same trend? This is also left for further verification through detail shallow, hand dug and deep wells inventory, depth, and lithologic log characterization
- ♣Other methodology like isotopes should be employed in future works for analysis of groundwater flow system along the corridor to confirm the out put of this work.
- ♣Regional major ions evolution (including the study area) needs to be conducted to observe variation of water types which strongly indicated groundwater flow direction.
- ♣Lateral distribution of fluoride and iron should be assessed and mapped especially around Gemeto well field and in the vicinity of the lake for F^{-1} and including entire study corridor for Fe with detail hyddrochemical trend analysis approaches. As it has been observed from fluoride distribution map above, this area has high fluoride concentration that is beyond WHO's guideline, 2004 (1.5mg/l); therefore, the other alternatives should be searched out with detail studies. Conversely, the higher iron ion concentrations are encountered from well data, at the central and plateau areas.
- ♣Appropriate environmental protection measures should be done on the eastern rift escarpment (upper parts of the Wondogenet ridge) and on the central part of the study corridor along which there are high groundwater flow is expected.

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ANNEXES

Hydrochemistry of all water sources																
ID	Name	GPS Location			Date				Major Cations and Anions							
		X	Y	Z		Na	K	Ca	Mg	Cl	F	HCO3	NO3	CO3	SO4	Fe+2
BH1	Mulete	426900	778488	1692	23.03.06	248.00	16.25	28.00	22.00	1.00	4.00	793.00	18.92	28.80	2.60	0.06
BH2	MitteAwas	445394	770695	1728	28.05.97	36.43	6.40	24.00	19.20	10.00	1.34	244.00	11.88	0.00	0.30	0.60
BH3	AbelaWondo	445692	770852	1720	26.05.98	42.28	7.10	40.00	14.40	5.00	0.39	280.60	7.92	0.00	33.30	5.90
BH4	AbelaWondo	446490	771490	1723	26.05.98	41.12	8.40	28.00	14.40	10.00	0.46	244.00	16.72	0.00	1.80	0.02
BH5	AbelaWondo	447560	769845	1765	26.05.98	15.35	9.20	28.00	14.40	8.00	0.38	158.60	15.40	24.00	1.50	0.03
BH6	Wijigra	451697	766560	2170	28.06.97	42.00	3.15	44.00	12.00	7.50	0.85	292.80	4.40	0.00	7.00	2.96
BH7	Mesenkela#	431250	752170	1800	06.04.00	15.00	5.00	11.00	2.00	3.00	0.00	104.00	1.00	0.00	1.00	0.00
BH8	Chume	435598	752687	1800	06.04.00	16.00	5.00	14.00	2.00	10.00	0.00	109.00	1.00	0.00	1.00	0.00
BH9	Kerbo	428744	760825	1840	17.05.98	38.15	7.50	18.40	3.36	2.00	0.70	170.80	8.80	0.00	1.00	0.10
BH10	KonsoreArke	429409	763401	1954	05.01.98	52.23	1.00	16.00	9.60	1.50	2.37	224.48	6.60	0.00	0.00	0.50
BH11	Buko	432478	760906	1840	22.01.98	42.26	1.60	22.40	1.92	2.50	0.61	150.00	3.20	0.00	0.00	0.09
BH12	Dobe Dena	439289	763826	1920	05.02.98	43.75	3.50	6.40	9.60	2.50	0.83	170.80	8.80	0.00	2.20	
BH13	TaramesaSi	439688	758825	1824	01.09.98	46.30	1.60	22.40	5.76	2.50	0.27	190.00	33.88	0.00	1.00	1.20
BH14	TelamoKera	442481	754518		01.09.98	25.87	1.20	8.00	2	2.50	0.00	85.40	13.64	2.10	0.60	0.20
BH15	NureDulecha	438570	769845	1747	02.02.98	40.12	7.30	20.00	9.60	17.50	0.44	170.80	18.00	0.00	10.60	0.21
BH16	GoboHebish	445875	760540	2014	10.05.06	32.11	1.00	18.40	8.16	5.00	0.41	158.60	14.52	0.00	1.00	0.33
BH17	Awassa She	444260	778935	1734	28.08.97	188.30	2.00	32.00	16.80	7.50	3.50	622.00	7.92	0.00	24.40	0.00
BH18	TaramesaAv	440704	756025	1856	01.09.98	21.69	1.30	7.20	2.88	6.00	0.00	78.08	14.08	0.00	2.80	0.56
BH19	DilaGumbe	435947	757536	1839	01.09.98	32.67	1.70	16.00	7.20	2.50	0.00	158.60	13.20	0.00	0.00	0.18
BH20	Gonowa Gal	442898	757337	1884	02.09.98	47.71	0.30	16.00	7.20	0.02	0.08	202.52	8.36	0.00	1.50	0.27
BH21	DiramoAfera	430871	755256	1782	03.02.98	33.82	5.80	16.00	9.60	12.50	0.56	164.70	4.40	0.00	2.50	0.11
BH22	Midregenet	434540	759693	1840	02.02.98	27	8.00	16.00	9.60	10.00	0.98	146.40	10.12	0.00	3.40	0.04
BH23	Yigalem	439510	745870	1800	15.06.98	5.89	5.50	20.00	12.00	7.50	0.18	119.56	9.68	0.00	3.70	0.43
BH24	Leku New	439541	760203	1843	02.02.98	121.75	8.40	8.00	48.00	20.00	0.47	164.70	33.88	0.00	120.00	0.55
BH25	DulechaTebe	437033	767515	1862	02.02.98	51.54	9.60	16.00	9.60	12.50	0.75	213.50	11.44	0.00	0.00	0.07
BH26	Yirba#1	429989	763353	1957	12.04.00	37.00	6.00	19.00	4.00	4.00	0.00	198.00	1.00	0.00	0.00	0.00
BH27	AwassaSOS	442800	782150	1695	26.08.97	249.92	2.60	36.00	12.00	10.00	4.00	805.00	2.20	0.00	3.50	0.30
BH28	Alamura	441459	770953	1758	18.02.99	44.00	7.00	10.00	5.00	4.00	2.00	236.00	0.00	0.00	0.00	0.00
BH29	MorochoSho	436649	763919	1864	10.05.06	56.14	1.50	16.00	7.20	2.50	1.11	219.60	10.12	0.00	0.00	0.26
BH30	AwassaTrea	447592	768985	1771	04.06.97	21.52	3.00	20.00	9.60	15.00	0.11	97.60	20.68	0.00	21.00	0.07
BH31	ChipwoodF	444996	777032	1728	30.02.99	27.73	3.50	33.00	16.80	5.00	4.20	183.00	19.80	0.00	27.00	0.09
BH33	South RA	443800	780200	1700	29.09.98	213.23	2.00	38.40	15.36	10.00	5.60	644.16	20.68	31.20	0.00	0.21
BH34	Wondokosha	433187	790000	1720	13.01.01	314.00	12.00	17	6.00	23.00	15.00	889.00	0.00	0.00	4.00	0.00
BH35	DelaAndfera	435611	758560	1852	01.09.98	52.39	1.70	12.00	4.80	3.50	0.00	134.20	10.12	0.00	1.60	0.33
BH36	Fura Koyo	436770	756366	1819	19.01.98	0.54	1.40	20.00	12.00	13.00	0.00	91.50	10.12	0.00	3.00	0.53
BH37	Moenco	443961	780365	1706	12.12.95	157.93	10.50	30.40	12.96	7.50	2.06	492.88	10.56	33.60	1.00	0.03
BH38	SedekaSher	438799	755843	1820	11.05.06	31.44	1.80	20.00	7.20	35.50	0.00	78.08	50.60	0.00	0.90	0.00
BH39	SedekaSere	439506	765702	1858	11.05.06	23.84	1.20	8.00	4.80	9.00	0.00	82.96	14.96	0.00	0.70	0.00
BH40	AbelaLida	441358	765820	1953	02.09.98	61.45	1.10	4.00	2.40	2.00	0.51	170.80	12.32	0.00	1.30	0.00
BH41	AbelaCeffe	442014	765157	1963	02.09.98	49	1.10	19.20	5.76	2.50	0.51	202.52	8.35	0.00	0.00	0.13
BH42	GaragaloCat	449274	763908	2165	10.05.06	26.23	1.20	16.00	3.84	5.00	0.25	107.36	22.44	0.00	0.40	0.13
BH43	TaramesaSe	439367	757255	1834	13.05.06	13.26	1.50	9.60	11.04	8.00	0.62	73.20	31.68	0.00	1.90	0.24
BH44	Fura boreKo	437218	755867	1844	10.05.06	6.00	27.68	2.20	12.00	2.88	2.50	1.05	122.00	3.96	0.00	0.70
BH45	WijigraKelifo	452500	766100	2190	21.09.97	0.00	0.00	80.00	11.52	40.00	0.10	189.00	46.20	0.00	10.00	0.45
BH46	TelamoTown	443096	755562	1912	09.05.06	10.31	1.80	12.00	7.20	0.30	0.04	68.32	36.52	0.00	0.00	0.05
HDW1	Fura/Abecho	435914	755202	1818	01.09.98	27.84	1.40	16.00	5.76	2.50	0.18	134.20	14.96	0.00	0.00	0.07
HDW2	Fura/bongod	436558	755447	1794	01.09.98	38.24	1.10	12.80	2.40	4.50	0.22	134.20	8.36	0.00	2.90	0.09
HDW3	Fura/Bungud	436742	755262	1850	(10/05/06	4.57	1.70	11.20	12.48	0.40	0.00	85.40	24.64	0.00	2.80	0.00
HDW4	DiramoAnfra	432384	755452	1812	02.09.98	40.50	1.70	18.40	5.28	5.00	0.00	170.80	11.88	0.00	2.00	0.01
HDW5	Diramo Anfra	433612	755635	1790	2/9/98	27.46	1.50	22.40	1.44	5.00	0.00	112.24	28.60	0.00	2.30	0.00
HDW6	DiramoAnfra	432261	754991	1819	2/9/98	47.52	1.40	16.00	4.80	2.50	0.63	192.76	3.96	0.00	0.00	0.73
HDW7	DelaAnfrara/	432570	756833	1790	1/9/98	72.34	1.90	56.00	7.20	5.50	0.64	353.80	14.08	0.00	19.50	0.30
HDW8	DelaAnfrara/	432998	756034	1853	1/9/98	36.28	1.20	12.00	4.80	2.00	0.27	148.84	7.92	0.00	1.00	0.40
HDW9	DilaAferar/O	434104	756309	1796	19/04/98	44.69	10.00	20.00	7.20	5.00	0.90	148.84	18.04	0.00	41.10	0.14
HDW10	DelaAferara/	433766	755634	1772	26/04/98	0.00	7.50	1.20	19.20	7.50	0.65	91.50	1.76	0.00	7.50	1.22
HDW11	DilaAferar/K.	433061	756710		(09/05/06	55.33	0.90	32.00	0.00	0.00	1.10	192.64	29.48	0.00	14.40	0.09
HDW12	MuranchoGu	447766	760194	2075	18/04/98	12.07	22.50	12.00	12.00	7.50	1.95	122.00	20.68	0.00	0.60	0.22
HDW13	MuranchoGu	448595	760040	2132	18/04/98	1.71	32.00	12.00	9.60	5.00	0.00	114.68	16.72	0.00	0.00	0.22
HDW14	Sedeka/She	456264	755580	1611	19/04/98	14.72	7.50	12.80	9.12	5.00	0.54	107.36	6.60	0.00	14.60	2.83
HDW15	Remeda/Ge	439634	761676	1916	26/04/98	40.59	5.50	16.00	7.20	12.50	0.00	58.56	89.32	0.00	36.70	5.64
HDW16	Midiregenet/	437057	758700	1823	19/04/98	48.65	10.00	12.00	9.60	17.50	0.00	156.16	11.00	0.00	27.40	7.13
HDW17	Garagalo/Se	445623	764801	2003	19/04/98	19.91	8.00	25.60	11.04	12.50	0.00	170.80	7.04	0.00	3.50	1.25
HDW18	HaisaWita	451022	763015	2243	06.02.98	14.35	4.75	8.00	3.36	7.50	0.19	29.28	47.52	0.00	0.60	0.73
HDW19	SkonsoreAn	433345	762974	1870	(12/05/06	111.01	1.80	12.00	4.80	30.00	0.00	244.00	55.88	0.00	15.00	*0.62
HDW20	Gergelo/Aro	448941	769312	2145	18/04/98	29.75	18.50	8.00	7.20	5.00	0.01	61.00	14.08	0.00	67.00	0.05
HDW21	Midiregenet	437392	759253	1836	14/03/98	130.29	25.00	36.00	7.20	10.00	0.00	244.00	2.64	120.00	22.00	0.36
HDW22	AlawaAno/G	432019	760064	1830	(03/03/05	53.53	10.00	12.00	12.00	12.50	0.00	219.60	11.88	0.00	2.50	0.05
HDW23	Hobolso/Go	441657	759279	1883	(09/05/06	6.99	1.80	8.00	4.80	0.75	0.18	53.68	25.52	0.00	12.50	2.41
HDW24	Dikicha/Bor.	432471	763273	1957	21/07/97	0.03	7.50	24.00	4.80	30.00		97.60	24.20	0.00	0.00	0.12
HDW25	Wome/Bor.	431854	721768	1920	21/07/97	8.62	9.60	16.00	16.00	32.50		141.52	9.68	0.00	25.00	2.61
HDW26	Gemeso/Ke	459580	757850	2710	18/04/98	6.87	20.00	24.00	7.20	20.00	0.00	61.00	64.24	0.00	0.00	0.16
HDW27	Gemeso/Ke	459764	758188	2697	2/9/98	14.69	1.00	9.60	3.84	7.50	0.27	61.00	10.56	0.00	2.90	0.01
HDW28	Halabano/G	432050	758216	1842	2/9/98	81.80	1.60	15.20	3.36	5.00	0.80	219.60	33.88	0.00	15.70	0.01
HDW29	Busa/Schoo	454445	775117	1721	(03/03/05	64.99	7.60	32.00	14.40	40.00	0.34	195.20	62.92	0.00	21.00	0.09
HDW30	Busa/Shafar	453549	777841	1698	(03/03/05	326.00	11.20	64.00	12.96	17.50	0.08	878.40	51.04	0.00	0.90	2.30
HDW31	Busa/Dire	453822	774321	1691	(03/03/05	46.11	8.40	20.80	9.12	15.00	1.01	207.40	7.48	0.00	0.20	0.04
HDW32	Busa/SisoLo	458601	790000	1700	(03/03/05	87.55	9.60	33.60	8.64	35.00	1.34	287.92	8.36	0.00	22.50	0.10
HDW33	Dipito/Yuho	449740	770724	1711	14/03/98	279.67	0.05	14.40	17.76	6.00	6.28	729.56	15.84	22.80	41.20	0.03
HDW34	Ado/Aroja	451523	773762	1696	18/04/98	81.77	35.00	48.00	14.40	5.00	0.69	488.00	9.24	0.00	0.00	0.25
HDW35	Ado/Abaye	451614	773209	1696	18/04/98	125.44	29.00	60.00	7.20	20.00	0.58	463.60	9.68	0.00	77.20	0.29
HDW36	Wijigira/Afro	451795	766515	2192	(03/03/05	17.46	8.50	32.00	9.60	15.00	0.00	183.00	6.60	0.00	0.40	2.79
HDW37	Futo K/Gerg	457683	765865	2464	19/04/98	13.99	13.00	4.00	4.80	12.50	0.00	43.92	32.56	0.00	5.00	1.06
HDW38	Awassa Tow	443459	778713	1757	05.05.98	206.46	12.25	36.00	21.60	24.00	*3.6	683.20	12.32	0.00	31.30	0.10
HDW39	Fute/Katamu	456044	765833	2396	(03/03/05	1.82	7.50	16.00	9.60	10.00	0.00	85.40	8.36	0.00	1.90	0.15
HDW40	Fute/Katamu	456045	766201	2538	(03/03/05	17.48	6.50	16.00	4.80	15.00	0.00	97.60	0.00	0.00	5.20	0.08
HDW41	Yubo/ Dareb	449793	771881	1706	(03/03/05	278.00	8.80	52.00	24.00	37.50	1.48	805.20	22.44	0.00	104.00	0.08
HDW42	Wondo wes	457255	782872	1720	01.11.99	33.00	9.00	9.00	2.00	10.00	0.00	107.00	18.00		9.00	
HDW43	Wondogenet	457004	779044	1740	15.01.99	19.00	10.00	8.00	2.00	8.00	1.00	92.00	9.00		3.00	
HDW44	Busa	454686	775165	1706	23.01.01	25.00	14.00	15.00	3.00	7.00	1.00	140.00	4.00		4.00	
HDW45	Edol School	452744	772218	1707	14.01.99	69.00	30.00	46.00	8.00	21.00	1.00	331.00	0.00		19.00	
HDW46	Edol	452000	773211	1686	19.10.98	94.00	15.00	56.00	10.00	28.00	3.00	464.00	1.00		12.00	
HDW47		439509	772724	1684	26.10.98	354.00	33.00	18.00	6.00	51.00	10.00	949.00	3.00		6.00	

HDW37	Futo K/Gerge	457683	765865	2464	19/04/98	13.99	13.00	4.00	4.80	12.50	0.00	43.92	32.56	0.00	5.00	1.06
HDW38	Awassa Tow	443459	778713	1757	05.05.98	206.46	12.25	36.00	21.60	24.00	*3.6	683.20	12.32	0.00	31.30	0.10
HDW39	Fute/Katamu	456044	765833	2396	(03/03/05	1.82	7.50	16.00	9.60	10.00	0.00	85.40	8.36	0.00	1.90	0.15
HDW40	Fute/Katamu	456045	766201	2538	(03/03/05	17.48	6.50	16.00	4.80	15.00	0.00	97.60	0.00	0.00	5.20	0.08
HDW41	Yubo/ Dareb	449793	771881	1706	(03/03/05	278.00	8.80	52.00	24.00	37.50	1.48	805.20	22.44	0.00	#####	0.08
HDW42	Wondo wesh	457255	782872	1720	01.11.99	33.00	9.00	9.00	2.00	10.00	0.00	107.00	18.00		9.00	
HDW43	Wondogenet	457004	779044	1740	15.01.99	19.00	10.00	8.00	2.00	8.00	1.00	92.00	9.00		3.00	
HDW44	Busa	454686	775165	1706	23.01.01	25.00	14.00	15.00	3.00	7.00	1.00	140.00	4.00		4.00	
HDW45	Edol School	452744	772218	1707	14.01.99	69.00	30.00	46.00	8.00	21.00	1.00	331.00	0.00		19.00	
HDW46	Edol	452000	773211	1686	19.10.98	94.00	15.00	56.00	10.00	28.00	3.00	464.00	1.00		12.00	
HDW47		439509	772724	1684	26.10.98	354.00	33.00	18.00	6.00	51.00	10.00	949.00	3.00		6.00	
HDW48	Loke Village	440863	774376	1687	19.10.98	268.00	47.00	12.00	6.00	38.00	15.00	748.00	0.00		8.00	
HDW49	Central hote	441086	778907	1689	21.01.00	375.00	30.00	13.00	23.00	66.00	10.00	858.00	0.00	96.00	27.00	
HDW50	Chefe Kuto .	446254	779830	1693	26.01.00	236.00	20.00	26.00	10.00	7.00	7.00	697.00	15.00		26.00	
HDW51	ShiferawHot	443037	782227	1692	17.01.00	328.00	9.00	18.00	2.00	49.00	17.00	755.00	20.00		19.00	
HDW52	Dato	443429	783712	1692	18.01.99	328.00	20.00	12.00	6.00	30.00	16.00	775.00	8.00	17.00	44.00	
HDW53	Tikurwoha	442636	785021	1693	15.02.99	398.00	25.00	4.00	2.00	61.00	15.00	928.00	1.00	12.00	30.00	
HDW54	Kagamo	431531	783983	1730	18.02.99	304.00	10.00	8.00	2.00	37.00	9.00	713.00	5.00		23.00	
HDW55	Wondotika	432378	783143	1714	22.10.98	338.00	11.00	4.00	1.00	43.00	11.00	832.00	4.00		5.00	
HDW56	Udo	430971	782021	1710	18.02.99	310.00	13.00	10.00	3.00	48.00	9.00	728.00	7.00		33.00	
HDW57	Galoargisa	432993	781279	1695	19.02.99	470.00	29.00	8.00	2.00	70.00	16.00	1032.00	3.00		82.00	
HDW58		426882	778994	1705	25.04.00	286.00	13.00	20.00	4.00	37.00	6.00	795.00	3.00		25.00	
HDW59	Durabafano	429445	777840	1715	22.02.99	350.00	15.00	8.00	1.00	59.00	7.00	852.00	5.00		43.00	
HDW60	Wondotika	431402	778053	1690	12.04.00	324.00	11.00	11.00	3.00	48.00	10.00	834.00	0.00		3.00	
HDW61		427174	774333	1720	06.04.00	282.00	15.00	12.00	6.00	37.00	7.00	723.00	3.00		23.00	
HDW62	Jaradado	430456	773897	1715	10.04.00	475.00	25.00	15.00	8.00	####	10.00	931.00	62.00		74.00	
HDW63		431664	770968	1740	06.04.00	280.00	15.00	20.00	20.00	39.00	8.00	859.00	4.00		3.00	
HDW64	Jara Hinsa	434741	771816	1693	10.04.00	420.00	34.00	88.00	30.00	####	8.00	1262.00	11.00		82.00	
HDW65	Dela	434955	748998	1780	13.03.01	12.00	8.00	12.00	1.00	3.00	0.00	107.00	3.00		3.00	
CS1	Medo	455746	788356	2020	25.02.99	40.00	7.00	7.00	2.00	13.00	0.00	41.00	70.00		15.00	
CS2	Tutu (Big)	451992	785880	1700	25.02.99	25.00	5.00	9.00	3.00	7.00	1.00	81.00	10.00		11.00	
CS3	Abaro	461987	787362	2312	25.02.99	16.00	7.00	22.00	4.00	9.00	0.00	59.00	59.00		16.00	
CS4	Abaro-Lajo	461555	786954	2380	03.07.01	10.00	2.00	2.00	1.00	5.00	0.00	22.00	9.00		9.00	
CS5	Abaro	462876	786900	2340	25.02.99	11.00	5.00	13.00	2.00	10.00	0.00	50.00	22.00		5.00	
CS6	Wondo G.F.(	460747	784454	2110	06.03.00	12.00	4.00	10.00	2.00	9.00	0.00	55.00	8.00		3.00	
CS7	Wosha&Soy	461406	783250	2041	16.03.99	13.17	2.30	20.00	9.60	5.00	0.45	122.00	15.84	0.00	0.00	0.00
CS8	Cheko	458776	781867	1830	13.03.00	22.00	5.00	13.00	4.00	6.00	1.00	134.00	1.00		4.00	
CS9	Wondowesha	460084	782090	1980	13.03.00	17.00	5.00	12.00	4.00	8.00	0.00	99.00	8.00		3.00	
CS10	Watera-Wor	457323	780700	1720	02.04.00	22.00	13.00	18.00	4.00	16.00	0.00	82.00	21.00		17.00	
CS11	Watera hich	456608	779956	1713	28.03.00	16.00	8.00	7.00	2.00	6.00	0.00	73.00	1.00		6.00	
CS12	Ketanketa	457343	777517	1760	17.02.87	18.00	6.00	22.00	3.00	7.00	1.00	92.00	3.00		5.00	
CS13	BashaWondo	458592	776758	1920	23.06.87	24.00	8.00	11.00	4.00	7.00	1.00	113.00	7.00		4.00	
CS14	Melga wondo	456186	776054	1713	18.01.00	23.00	17.00	20.00	6.00	25.00	1.00	93.00	35.00		7.00	
CS15	Girebe	462037	765283	2640	18.01.00	4.00	2.00	3.00	1.00	3.00	0.00	20.00	7.00		1.00	
CS16	Borja	451238	769452	1780	10.03.00	14.00	5.00	17.00	9.00	6.00	0.00	149.00	10.00		3.00	
CS17	Mete	445646	770671	1712	13.01.00	0.00	0.00	18.00	11.00	8.00	0.00	12.00	5.00	0.00	0.00	
CS18	Abella Wonc	445381	770562	1715	18.01.00	27.00	6.00	15.00	7.00	4.00	1.00	156.00	9.00		8.00	
CS19	Gemeto	444676	770823	1707	23.09.97	2.00	5.00	28.00	7.20	5.00	0.60	189.00	15.40	0.00	2.00	0.18
CS20	Loke Palace	436985	771887	1690	01.02.00	36.00	5.00	9.00	3.00	5.00	1.00	131.00	1.00		5.00	
CS21	Galko Haro	443002	760888	1940	26.02.99	7.00	6.00	6.00	1.00	6.00	0.00	49.00	13.00		3.00	
CS22	Dubiye	448464	765928	2040	06.02.00	12.00	6.00	8.00	2.00	7.00	0.00	61.00	13.00		1.00	
CS23	Haisa weta	451888	762462	2240	08.03.00	6.00	4.00	3.00	1.00	3.00	0.00	40.00	1.00		1.00	
CS24	Dobe Dena	456852	761450	2504	07.01.98	14.90	1.20	4.00	4.80	4.50	0.00	61.00	10.12	0.00	0.00	
CS25	GemesoKene	459858	759538	2639	12.05.06	17.06	1.80	13.60	1.93	5.00	0.00	68.32	23.76	0.00	2.00	0.70
CS26	Hogiso	464996	757168	2700	27.02.99	6.00	6.00	4.00	1.00	6.00	0.00	32.00	12.00		2.00	
CS27	Meke Catho	438672	750022	1780	26.01.00	13.00	6.00	7.00	2.00	7.00	0.00	83.00	5.00		2.00	
CS28	Debub-Meser	432014	750919	1720	19.01.00	28.00	10.00	5.00	2.00	9.00	1.00	104.00	1.00		3.00	
CS29	Bokola	430472	758306	1960	29.02.99	29.00	6.00	6.00	2.00	19.00	0.00	63.00	31.00		5.00	
CS30	Dobe Bute	461517	761932	2658	07.02.98	23.94	1.80	6.40	2.88	2.50	0.00	36.60	10.12	0.00	0.06	0.43
CS31	Wome Buna	451202	758778	2244	10.05.06	12.29	1.80	17.60	1.44	0.00	0.26	56.12	32.56	0.00	7.40	0.03
CS32	Harbe Shisho	448561	757491	2131	10.05.06	21.07	1.90	8.00	3.84	14.00	0.00	36.60	36.52	0.00	4.60	0.05
CS33	Harbe Shisho	447179	756172	1975	24.09.98	29.39	1.60	10.40	2.40	0.03	0.00	82.96	23.32	0.00	15.70	0.15
CS34	GonowaGon(	447764	757922	2031	24.09.98	12.86	0.90	4.00	4.32	5.00	0.00	39.76	23.76	0.00	0.00	0.11
CS35	Hobolso	441565	758481	1875	01.09.98	38.52	1.00	8.00	4.80	6.00	0.00	112.00	20.68	0.00	10.00	0.90
CS36	Haisa wita	456514	761568	2325	12.05.06	18.71	0.70	6.40	3.36	4.00	0.00	48.80	29.48	0.00	2.70	0.51
CS37	FaychoGojar	462586	756066	2707	13.05.06	6.43	0.60	4.00	7.20	4.00	0.00	36.60	19.80	0.00	4.60	0.43
CS38	Telame Kan	443310	755101	1896	01.09.98	12.78	1.10	28.00	7.20	0.02	0.19	146.40	13.64	0.00	2.60	1.20
CS39	Wondogenet	458350	779900	1740	01.10.97	0.00	0.00	12.00	4.80	8.50	0.90	164.70	21.12	0.00	0.00	0.15

CS26	Hogiso	464996	757168	2700	27.02.99	6.00	6.00	4.00	1.00	6.00	0.00	32.00	12.00		2.00	
CS27	Meke Catho	438672	750022	1780	26.01.00	13.00	6.00	7.00	2.00	7.00	0.00	83.00	5.00		2.00	
CS28	Debub-Meser	432014	750919	1720	19.01.00	28.00	10.00	5.00	2.00	9.00	1.00	104.00	1.00		3.00	
CS29	Bokola	430472	758306	1960	29.02.99	29.00	6.00	6.00	2.00	19.00	0.00	63.00	31.00		5.00	
CS30	Dobe Bute	461517	761932	2658	07.02.98	23.94	1.80	6.40	2.88	2.50	0.00	36.60	10.12	0.00	0.06	0.43
CS31	Wome Buna	451202	758778	2244	10.05.06	12.29	1.80	17.60	1.44	0.00	0.26	56.12	32.56	0.00	7.40	0.03
CS32	Harbe Shisho	448561	757491	2131	10.05.06	21.07	1.90	8.00	3.84	14.00	0.00	36.60	36.52	0.00	4.60	0.05
CS33	Harbe Shisho	447179	756172	1975	24.09.98	29.39	1.60	10.40	2.40	0.03	0.00	82.96	23.32	0.00	15.70	0.15
CS34	GonowaGon(	447764	757922	2031	24.09.98	12.86	0.90	4.00	4.32	5.00	0.00	39.76	23.76	0.00	0.00	0.11
CS35	Hobolso	441565	758481	1875	01.09.98	38.52	1.00	8.00	4.80	6.00	0.00	112.00	20.68	0.00	10.00	0.90
CS36	Haisa wita	456514	761568	2325	12.05.06	18.71	0.70	6.40	3.36	4.00	0.00	48.80	29.48	0.00	2.70	0.51
CS37	FaychoGojar	462586	756066	2707	13.05.06	6.43	0.60	4.00	7.20	4.00	0.00	36.60	19.80	0.00	4.60	0.43
CS38	Telame Kan	443310	755101	1896	01.09.98	12.78	1.10	28.00	7.20	0.02	0.19	146.40	13.64	0.00	2.60	1.20
CS39	Wondogenet	458350	779900	1740	01.10.97	0.00	0.00	12.00	4.80	8.50	0.90	164.70	21.12	0.00	0.00	0.15
HS1	Shalo hot sp	452526	785341	1700	24.01.00	450.00	27.00	5.00	0.00	93.00	28.00	778.00	0.00	71.00	70.00	
HS2	Bela hot spri	456965	786018	1760	28.01.00	740.00	40.00	34.00	5.00	####	8.00	1553.00	0.00		#####	
HS3	Wondogenet	459944	782463	1880	28.01.00	182.00	41.00	6.00	3.00	26.00	1.00	564.00	1.00		0.00	
HS4	Soyema Hot	460642	781786	2060	29.02.99	170.00	42.00	11.00	4.00	25.00	1.00	541.00	1.00		2.00	
HS5	Gerariketa H	447156	772809	1707	12.01.00	196.00	15.00	8.00	5.00	38.00	5.00	467.00	0.00		37.00	
HS6	Gerariketa H	447189	772574	1703	30.02.99	380.00	25.00	10.00	3.00	60.00	10.00	854.00	0.00		90.00	
HS7	Yirgalem Ho	432212	746480	1670	03.01.01	57.00	6.00	4.00	1.00	6.00	2.00	211.00	0.00		2.00	
LK1	Lake Awassa	441388	785594	1681	05.03.99	151.00	25.00	10.00	5.00	29.00	6.00	412.00	3.00	12.00	1.00	
LK1	Lake Awassa	439907	779806	0	11.03.99	150.00	24.00	9.00	6.00	30.00	6.00	363.00	3.00	38.00	3.00	
LK2	Lake Awassa	441060	779619	0	11.03.99	151.00	25.00	10.00	6.00	33.00	6.00	414.00	3.00	12.00	0.00	
LK3	Lake Awassa	439731	778581	0	13.02.99	152.00	25.00	11.00	6.00	28.00	6.00	373.00	2.00	24.00	0.00	
LK4	Lake Awassa	432893	778614	0	15.03.99	157.00	30.00	10.00	5.00	32.00	7.00	364.00	5.00		22.00	
LK5	Lake Awassa	436137	783475	0	18.03.99	158.00	3.00	10.00	5.00	30.00	7.00	400.00	6.00		24.00	
RV1	Wesha Raww	458869	783694	0	18.03.99	19.00	5.00	9.00	3.00	4.00	0.00	118.00	1.00		2.00	

Annex I Hydrochemical data

ID	Name	X	Y	Z(m)	Depth(m	SWL(m	GW Elev	DWL(m	Q(l/s)	pH	Conduct (µS/cm)	TDS(mg	Temp. °	Eh
BH1	Bushulo H	439500	772100	1692	56	8	1684	8	5	8	1633	1143		
BH2	MitteAwas	445394	770695	1728	70	6	1722	13	17	8	280	140	22	
BH3	AbelaWond	445692	770852	1720	50	10	1710	12	7	7	389	195	28	
BH4	AbelaWond	446490	771490	1723	56	25	1698	38	6	7	400	201	23	
BH5	AbelaWond	447560	769845	1765	62	38	1727	40	6	7	322	161		
BH6	Wijigra	451697	766560	2170	110	41	2129	57	6	6	256	155	25	
BH7	Mesenkela#	431250	752170	1800	121	10	1790	80	7	6	163	98		
BH8	AlawoArke#	429256	761374	1960	220	64	1896	99	6	7	330	167	22	
BH9	Kerbo	428744	760825	1840	120	48	1793	60	4	7	220	111	27	
BH10	KonsoreArl	429409	763401	1954	204	95	1859	173	4	7	330	167	22	
BH11	Buko	432478	760906	1840	192	73	1767	118	5	7	260	130	23	
BH12	Jermancho	421586	744115	1640	165	17	1623	40	4	8	330	238		
BH13	Wicho	433643	739043	1846	214	114	1732	114	4	8	154	74		
BH14	SodoSimita	424424	738819	1748	153	43	1705	46	3	8	226	109		
BH15	Aletawondo	436140	732217	1892	146	57	1835	73	7					
BH16	GoboHebis	445875	760540	2014	177	93	1922	108	6	7	210	105	23	
BH17	Hobolso#1	441586	757533	1886	147	23	1864	27	7	8	190	85		
BH18	GoboHebis	446335	760059	2008	120	58	1950	94	3					
BH19	Hobolso#2	440687	757533	1878	150	50	1829	99	6					
BH20	Gonowa Ga	442898	757337	1884	150	33	1851	69	6	6	200	100	24	
BH21	DiramoAfer	430871	755256	1782	78	19	1763	64	3	7	170	102	30	
BH22	Midregenet	434540	759693	1840	224	43	1797		5	7	216	130	26	
BH23	AbelaLidaM	442014	765157	1912	165	63	1849		1	7	220	110	24	
BH24	Leku New	440280	760414	1864	154	60	1803	95	6	7	259	156	20	
BH25	DeraraGorb	421535	755179	1883	307	244	1639		5					
BH26	Yirba#1	429989	763353	1957	150	83	1875		5	7	306	184		
BH27	Yirba#2	430000	765500	2010	200	143	1867		1					
BH28	Alamura	441459	770953	1758	110	52	1706			7	285	171	26	20
BH29	MorochoSh	436649	763919	1864	170	43	1821			7	264	132	22	
BH30	AwassaTre	447592	768985	1771	107	56	1715	66	8	7	178	89	24	
BH31	Bash#1	455727	776557	1725	78	0	1725	0						
BH32	AbelaLida	435563	769021	1890	128	54	1836		2					
BH33	Sedine	439456	770917	1740	119	56	1684	78					26	
BH34	Mulate Fala	426369	778520	1715	66	46	1669	52	3	8	1228	737	26	-37
BH35	Melegewon	456003	775232	1730	75	12	1718	16.4	8.33		320		21.5	
BH36	TobacoM	444867	775396	1735	82	54	1681		4	7	1076	646	24.5	-3
BH37	Ceramix2	442940	781079	1700	70	26	1674							
BH38	Soft Drink	445009	777028	1731	80	41	1690	40.71	4.4	8.34	1095	531		
BH39	Soft Drink	445540	777450	1735	82	44	1691	44.36	7.6	7.79	1120	544		
BH40	Wenenata	429933	743188	1772	125	80	1692							
BH41	Telamo K4	444010	756200	1960	80	60.1	1900		1					
BH42	Ceramix2	442940	781079	1700	70	26	1674							
SP1	Aruma	451283	769680	1764		0	1765		6					
SP21	Finchawa	450435	768623	1897		0	1898		1.5					
SP3	Isawa	451158	770262	1703		0	1704		7					
SP4	Gemeto	444763	771042	1716		0	1717		40					
SP5	Tute Big	451992	785880	1700		0	1700			6	181	109	30	49
SP6	Abaro	461987	787362	2314		0	2314			6	254	152.4	16	25
SP7	Wondogen	460747	784454	2110		0	2110		1.5	6	135	81	18	57
SP8	Melegewon	455285	775356	1700		0	1700		7	6.55	315	207.9	21.1	63
SP9	Wondogen	458592	776758	1920		0	1920		12	6	208	124.8	23	66
SP10	Borja	451283	769680	1780		0	1780		20	7	242	145.2	23	48
SP11	Loke Palac	436994	772114	1683		0	1683		30	6.98	228	136.8	27	38
SP12	Basha	458823	774168	2130		0	2130		4	6.85	274	181	22.6	
SP13	Bokala	430472	758306	1960		0	1960			6	205	123	21	96
SP144	Kike	461355	783109						200					

Annex II *Borehole and Some High yield cold springs*

DECLARATION

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

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

Mulugeta Mussie

Signature ______________________________

Place and date of submission: School of Graduate Studies, Addis Ababa University, July, 2007

Dedication

This thesis is dedicated to:

My dad Mussie Mehari and mom Gete Gebremedihin

And

My currently born (two month old) baby daughter, Piritskila and my beloved wife,

Yodit Tilahun