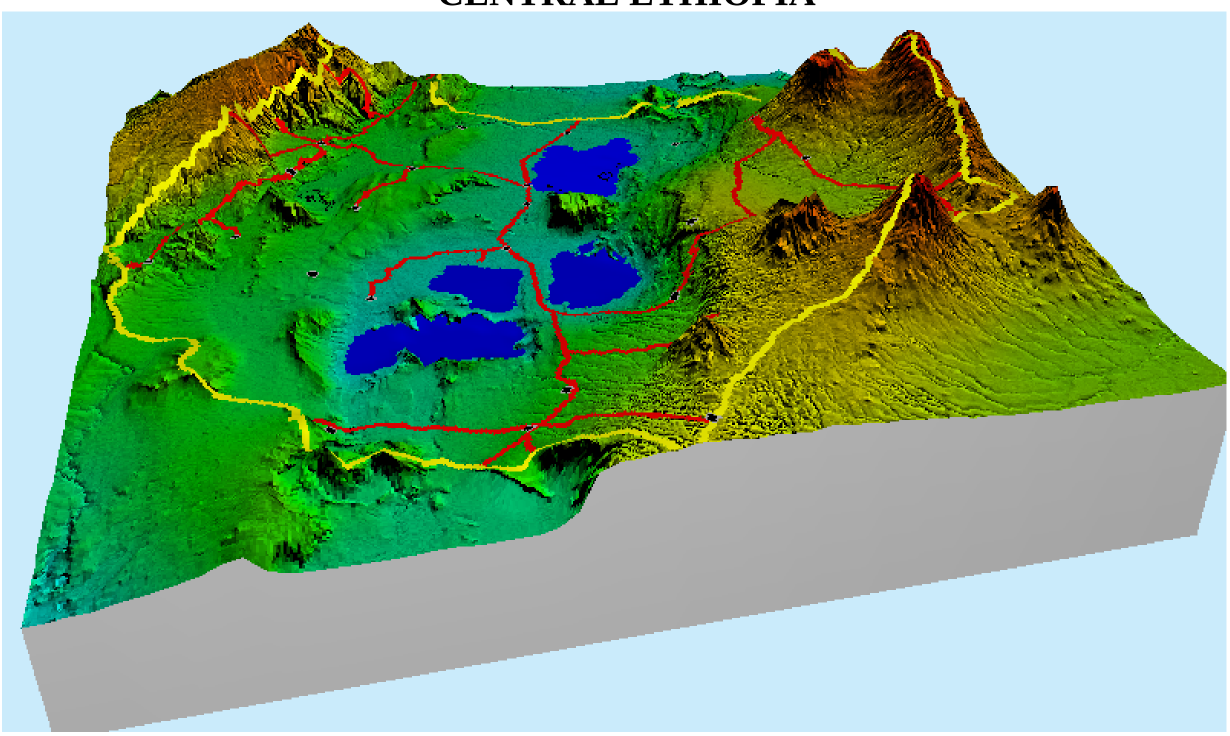
ADDIS ABABA UNIVERSITY

SCHOOL OF GRADUATE STUDIES

DEPARTMENT OF EARTH SCIENCES

HYDROGEOLOGICAL SYSTEM ANALYSIS IN ZIWAY–SHALA LAKES AREA USING HYDROCHEMISTRY AND ISOTOPE TECHNIQUES, CENTRAL ETHIOPIA



A THESIS SUBMITTED TO THE SCHOOL OF GRADUATE STUDIES OF ADDIS ABABA UNIVERSITY IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN HYDROGEOLOGY

By
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June, 2006

Addis Ababa

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

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ACKNOWLEDGEMENTS

First of all I would like to thank Dr. Tenalem Ayenew, my advisor and initiator of this work. His pleasant working atmosphere and way of guiding creates me a hardworking environment, which I am glad I was able to use. Further more I would like to thank him for sharing his knowledge; providing all laboratory facilities, giving me reference materials and arranging my field trip, I appreciated that a lot. I would also like to acknowledge the Department of Earth Sciences, AAU and its staff members for their help during the two years stay in the university.

All the organizations and individuals, who directly or indirectly involved in this study, deserve special appreciations. First Earth Sciences Department, which let me to use hydrochemistry and isotope laboratory, International Atomic Energy Agency (IAEA) for the background knowledge I gained on high-tech laboratory instruments, Geological Survey of Ethiopia, which allows me to use their data, Ministry of Water Resources, National Meteorological Service Agency and Region-4 Water Resources Bureau are greatly acknowledged for their data source.

My deepest heart felt thank goes to my family. My father Fikre Weldesenbet, I would like to appreciate him for his endless support up to now. My mother, Amakelech Getachew, who is my source of strength in every aspects of life, her caring and love, which brought me to this day, I thank you. I would also like to appreciate the remaining part of my family for their help in every day life.

I would like to express my gratitude to my colleagues Ms. Eleni Mulugeta for her suffering, together with me, in the extensive laboratory analysis and Mr. Alemu Diribsa for providing me field vehicle. All friends in and outside the University, especially Martha Nigussie that we share all the academic and social life together in the two years stay during this study are appreciated. Last but not least I offer my special thanks for those involve directly or indirectly in this study and their names are not listed are greatly acknowledged.

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ABSTRACT

In this work, hydrochemical and isotopic study has been carried out in order to conceptualize the groundwater circulation and to evaluate the subsurface hydraulic connection between the lakes in the Ziway-Shala lakes basin, located 190km south of Addis Ababa in the central sector of the Main Ethiopian Rift and covers a large portion of the lakes district in Ethiopia. Lacustrine sediments and volcano-clasitic succession (in the floor), volcanics (on the highlands and escarpment) are the main geological units in the area. The area is highly affected by rift structures and recent tectonic features.

The hydraulic characteristics of the aquifers in the area show high spatial variability, which is the result of the complex nature of the lacustrine sediments and the degree of fracturing of the volcanic rocks. The most permeable unit is the basalts and local ignimbrites with hydraulic conductivity grater than 40m/day, where as the least are those rift volcanoes and volcanic ridges having less than 1m/day. The others volcanic rocks lie in between depending on the degree of weathering, fracturing or faulting.

The hydrochemical and isotopic analysis of δ^2H, $\delta^{18}O$ & ^3H result signifies that groundwater of the floor, escarpment and highland is found in different flow regime. 75% of the total groundwater samples collected in the area has concentration range of sodium (the dominant cation) and range of bicarbonate (the dominant anion) between 60-300 mg/l and between 200-600 mg/l respectively. These high ionic variabilities show the presence of different groundwater flow systems.

Groundwater in the recharge area evolves from a dilute Na -Ca– HCO_3 type water (statistically determined Subgroup-1: average TDS is ~332 mg/l) to a fresh Na–HCO3 type water (Subgroup-2: average TDS is ~475 mg/l) to a more concentrated Na–HCO3 type water (Subgroup-3: average TDS is ~1184 mg/l) to a brackish Na–HCO_3-Cl type water (Subgroup-4: average TDS is ~6538 mg/l) along the topographic flowpath Overall, the waters from the area can be classified as recharge area waters (Subgroup-1), transition zone waters (Subgroup-2) and discharge area waters (Subgroup-3 and Subgroup-4).

Hydrochemical and Isotope concentrations of groundwater and surface water samples between the lakes help to study the subsurface interconnection between the lakes. ^{18}O and ^{2}H signatures in relation with the hydrochemistry of waters from the highlands, escarpments and rift valley helps to conceptualize the groundwater flow system in the area.

CHAPTER ONE

INTRODUCTION

1.1. General information

The Ethiopian Rift System, which represents the northern half of the East African Rift System (EARS), consists of three major rift zones with distinct volcanic and tectonic characteristics that are at different stages of rifting. These are the broadly rifted zone of southwestern Ethiopia, the Main Ethiopian Rift (MER) of central Ethiopia, and the Afar Rift Systems. The width of the MER increases from the southern (30-60 km) to the central (65-80 km) and the northern (80-120 km) sectors, and is more than 200-km wide in the southern part of the Afar Rift.

In MER numerous lakes fed by streams from the adjacent rift shoulders and highlands occupy the rift floor in the geologic past (Gasse & Street 1978, Gasse et at. 1980). The present day lakes (e.g., Awassa, Shala, and the Langano-Abiyata-Ziway basin) within the central sector filled ancestral depressions of Plio-Pleistocene calderas. They vary significantly in size, depth, hydrochemistry and hydrogeological settings.

The basin studied here is part of MER which consists of a number of rift lakes that are filled with both fresh and saline, alkaline water (e.g., Lake Shala).It also contains abundant and diverse natural resources. Volcanic and tectonic processes are responsible for creating scenic topographic features and fertile regions, as is the case with the MER. Apart from the presence of rich volcanic soil with great agricultural potential; the basin contains abundant resources of industrial minerals, geothermal energy, and surface and groundwater. Although most of the farmers in the rift floor depend on seasonal rains, irrigation techniques are being developed to cultivate farmlands close to some of these lakes.

The scope of applying hydrochemistry and isotope hydrology has broadened dramatically over the past few decades. Although the problems of chemical water quality to be of important and relevance for the security of the community and for socioeconomic development, many applied problems relating to the wider role of hydrochemistry and isotope techniques have come into focus. There has been a growing need to study, understand and quantify the water resources using these techniques.

Information on spatial and temporal variability of chemical and isotopic composition of natural water is valuable to understand the different hydrological and hydrogeological processes in the basin. The concentrations in water samples reflect their source path, flow directions, surface water - groundwater interactions, travel time and age of groundwater, hydraulic connection of the lakes, and ultimately for water management practices.

The chemical composition of natural waters and the amount of its ionic species depend on several factors: type of soil and rock through which the water passes, the degree of weathering and solubility of the mineral components of the rocks and soils, the extent and duration of the contact with rocks and soils, the temperature conditions, the type of dissolved and suspended solutes that falls with precipitation.

Climatic pattern, which produces characteristics plant communities and soil types governing biochemical processes in the hydrosphere, play also important role. The process of rock weathering is strongly influenced by temperature and the amount and distribution of precipitation. Aside from the recharge and discharge conditions related to precipitation; the evaporation of open water bodies influence the amount of the total ionic concentrations. Climatic patterns tend to produce characteristics plant communities and soil types, and the composition of waters of streams draining such areas could be influenced by the ecological balance. Bicarbonate, for example, tends to predominate in water in areas where vegetation grows profusely.

A major impact of the environmental factors influencing the composition of water may also come from human activities. Solutes may be directly added to water by disposal of municipal and industrial wastes and from application of fertilizers.

The number of major dissolved constituents in water is quite few, and the natural variations are not as great as might be expected from a study of the various minerals and organic materials through which the water has passed. More than ninety percent of the dissolved solids in groundwater can be attributed to eight ions: sodium (Na), calcium (Ca), potassium (K), magnesium (Mg), sulfate (SO_4), chloride (Cl), bicarbonate (HCO_3) and carbonate (CO_3) (Freeze and Cherry, 1979). These ions are usually present at concentrations greater than 1 milligram per litre (mg/l). Silica (SiO_2), a non-ionic species and nitrate (NO_3) are also typically present at concentrations greater than 1 mg/l. There are, however, many naturally occurring ions as minor and trace constituents usually present at concentrations of less than 0.1 mg/l. Some of the common ones at times contribute to major ions include fluoride (F), boron (B), iron (Fe), strontium (St), etc. These ions and other trace elements are important indicators of the origin and movement of surface water and groundwater systems. Many other inorganic constituents are valuable from a standpoint of water quality.

Although all elements present in hydrogeological systems have a number of isotopes, only a few are of practical importance to hydrogeology. The environmental isotopes are the naturally occurring isotopes of elements found in abundance in our environment: H, C, N, O and S. The environmental stable isotopes of these elements (deuterium (^2H) and oxygen (^{18}O)) serve as tracers of groundwater, recharge process, subsurface process, geochemical reactions and reaction rates. The radioactive environmental isotopes (tritium (^3H) and carbon (^{14}C)) can be used to estimate the age or circulation of groundwater. The environmental isotopes (N and S) provide information on the groundwater quality.

The relationship of a variety of global scale and local scale processes can influence the isotope regime of Ethiopian meteoric waters. The temporal and the spatial variation in the $\delta^{18}O$ and δD composition of natural water bodies and rainfalls influenced by temperature, subsurface rock-water interactions, basin topography, seasonal changes associated with moisture sources and moisture from continental evapotranspiration. These variations can provide characteristics that are preserved in the groundwater and useful for tracing. A measure of time from the decay of environmental radioactive isotopes (^3H and ^{14}C) is useful to estimate the age of groundwater. Tritium is produced naturally by cosmic radiation, although much greater production accompanied the atmospheric testing of thermonuclear bombs between 1951 and 1980.

1.2. Previous works

Groundwater well drilling programs have been initiated over the last decades, but groundwater provision is often unsuccessful because of poor groundwater productivity of wells, difficult drilling conditions, drying of wells and springs after prolonged drought, or sometimes due to poor quality. This is hampered by lack of understanding of groundwater systems. Information on groundwater recharge, storage, circulation, and chemical evolution is barely known. Groundwater development is being conducted without a good understanding of its role in the hydrology of the basin. Some of the lakes have reduced in size (Znabu G/Mariam, 1989) and changes in the chemistry of the lake water have been observed, but it is largely unknown whether the ecosystem has been affected (HALCROW.1989)

Some hydrogeochemical researches have been conducted in the Ethiopian Rift System. The presence of many lakes, lacustrine deposits, heat flow owing to Rifting and accompanied thinning of the crust in the East African Rift System (EARS) have attracted major geoscientific investigations since the second half of the 20th century. Many of the geochemical investigations (Craig et al., 1977; Darling, 1996; Darling et al., 1996; Gizaw, 1996; Chernet et al., 2001; Reimann et al., 2003) showed the role of water–rock interaction in influencing the water quality, salinity and flouride composition of groundwaters and thermal systems of the EARS. In many instances the water–rock interaction is induced by volatile gases from the mantle and by the high heat flow beneath the EARS. Groundwater circulation patterns, groundwater recharge source identifications and interactions between lakes and groundwaters have also been the subject of many important studies in the EARS (Schoell and Faber, 1976; Craig et al., 1977; Darling et al., 1996; Ayenew, 1998; McKenzie et al., 2001). Many of these studies show riftward groundwater flow from adjacent highlands.

Hydrochemical survey to study the spatial variation of the major ions composition of the surface and groundwater systems in the Ethiopian volcanic terrain and associated Plio-Quaternary sediments has carried out by Tenalem Ayenew, (2005).He has also studied the application of ^{2}H and ^{18}O isotopes for the study of the hydrogeological system of some Ethiopian rift lakes. The major ion composition, total ionic concentration and salinity of the various lakes in relation to the hydrogeological and physiographic setting of the Ethiopian Rift Valley Lakes were reported by Tamiru Alemayehu et al., (2005).

In all studies conducted so far, there is limited consideration of the detailed hydrochemistry and isotopic compositions of the groundwaters between and around the lakes in the basin to confirm the interconnection of the lakes and the groundwater flow system in the area. Moreover, the current study considers hydrochemistry and isotopes of water in the area to critically understand the hydraulic connection of the lakes and groundwater flow patterns.Understanding of the interconnection of the lakes and groundwater flow system after incorporating recent data to the existing ones and assessment of recent changes in hydrogeology of the area are new works that supplement the existing ones to provide useful information for Policy makers and general public to manage the resource on sustainable basis.

1.3. Objectives

The main objectives of the research are:-

- ✓ To apply hydrochemistry and isotope techniques to conceptualize the groundwater flow system in the catchment.
- ✓ To investigate the subsurface hydraulic connection of the lakes using the chemical and isotopic composition of waters.
- ✓ To apply statistical analysis techniques for classification of chemistry and isotope data
- ✓ To investigate the correspondence between spatial locations and statistical groups.

The specific objectives are:-

- ❖ To understand the rock –water interactions and the resulting impact on the natural water compositions.
- ❖ To assess surface water- groundwater interactions in the lake watershed system.
- ❖ To study local & sub-regional groundwater flow system based on hydrochemistry and isotope hydrology.

- To discriminate the origins of different water bodies.
- To conceptualize the role of geological structures on the type and movement of groundwater.
- To produce hydrogeological and hydrochemical maps, plots, bars and diagrams for the different water bodies and water types.
- To build-up the chemical and isotopic database needed for future research.

1.4. Methodology and materials

➢ Sampling and laboratory analysis

A total of 82 water samples were collected from groundwater wells, springs, lakes and rivers between November 2005 and April 2005 and kept in polyethylene sample bottles and completely filled and tightened with plastic caps. Of the total; 38 samples were analysed for major ions, 13 for radioactive isotope and 66 samples for fluorine. TDS, Conductivity, salinity and pH of waters were measured in situ using the appropriate field kits. Locations of the sampling points are recorded during the fieldworks using Global Positioning System (GPS).

129 water chemical and isotopic data points from a previous study (UN 1973; Scripps 1977; Chernet, 1982, Gizaw 1996; Tenalem Ayenew 1998) were included in the database. Some of the previous data that were compiled in this work do not have a geographic coordinate. For the spatial physical, chemical and isotopic plots and maps the geographic coordinates were needed. In absence of this information, this work tried to find the closest possible coordinate from maps and localities indicated in the various reports. The Locations of sampling sites are shown in Fig 5.1 and Fig 5.15. The results of the analyses, including data from earlier work and water quality variables measured in the field, are presented in Appendix3, Appendix4 and Appendix 7.

For the majority of the samples were analyzed for their major ion concentrations as well as selected representative samples were analyzed for radioactive isotope content (^3H) using the methods as can be seen in table1. Chemical analyses were carried out at the Laboratory of Hydrochemistry and Isotope hydrology, Addis Ababa University and The Central Chemical Laboratory of the Geological Survey of Ethiopia while isotope compositions were measured at the former laboratory. Chemical concentrations are reported in meq/l and Tritium concentrations are reported in tritium units (TU).

Table 1.1 Methods applied for water Samples analysis

Parameter	Instrument/Analysis Method
Major Anions	Dionex Ion Chromatography equipped with automatic sampler
Major Cations	Atomic Absorption Flame Spectrophotometer
Isotope (Tritium)	Electrolytic Enrichment and Liquid Scintillation Counter
Carbonate and Bicarbonate	Acid Titration
PH ,EH and Temperature	Field PH meter
TDS , Conductivity and salinity	Field EC Meter

- **Database**

In this study a database is compiled using most of the previously collected raw data and the field data (chemical and isotopic data of spring, surface, and well water). It was used for classification of waters into hydrochemical facies, also known as 'water types' or 'water groups'. The database has also helped a lot to decipher the flow and hydrochemical evolution of the study area which also used to show the hydraulic connection of the four lakes in the basin.

The data have been evaluated for errors and used for preparing plots, graphs, maps and tables for interpretation. The softwares XLSTAT Pro7.5.2, AquaChem4.0, Arcview 3.3a, Surfer8, Global Mapper 6, Ulead photo Express3.0SE, and Microsoft offices are used to analyse the data.

- **Physicochemical and isotope analysis**

Major ions, TDS and electrical conductivity of waters are used to conceptualize the groundwater flow system, groundwater residence time and rock-water interactions. Piper plots, hydrochemical map, EC map, Semilog-box plot, and Collins bar diagram are used to present the different hydrochemical distributions and analyse the groundwater flow.

Isotope data are analysed using ^{18}O versus ^{2}H plot for samples from the different water bodies (that is lakes, rivers, cold springs, hot springs, cold wells and geothermal wells) by comparing with the Local Meteoric Water Line (LMWL) and Global Meteoric Water Line (GMWL).

Scatter plots and maps were also prepared to relate the isotopes and hydrochemistry for flow analysis and hydrodynamics of the lake.

➢ Statistical cluster analysis

Q-mode statistical cluster analysis was used to determine if the samples can be grouped into distinct populations (hydrochemical groups) that may be significant in the hydrogeologic context. Comparisons based on multiple parameters from different samples are made and the samples grouped according to their ‘similarity’ to each other. In this study Q-mode hierarchical cluster analysis (HCA) is used to classify water composition into hydrochemical facies and to understand groundwater geochemical evolution among the different groups or subgroups. A Microsoft EXCEL add-in module XLSTAT5.2 was used to conduct the HCA

HCA is a statistical technique used to classify water samples in to groups or subgroups that have similar chemical and physical characteristics and distinct from the other groups (Alther, 1979; Williams, 1982; Farnham et al., 2000; Alberto et al., 2001; Meng and Maynard, 2001). The characteristics of the groups or sub groups are not pre determined but can be obtained after the classification. The advantage of HCA is that many variables such as physical, chemical or isotopic composition can be used to classify waters because a single parameter may not be sufficient to distinguish between different water types. The ability of HCA to classify groundwater chemistry into coherent groups that may be distinguished in terms of flow system, subsurface residence time and degree of human impact on water chemistry provides a good opportunity to understand groundwater geochemical evolution among the different groups or subgroups A detailed description of the advantages and uses of the HCA in hydrogeochemistry and the mathematical formulation behind HCA is thoroughly discussed in Gu¨ ler et al. (2002).

CHAPTER TWO

2. STUDY SITE DESCRIPTION

2.1. Location , accessibility and aerial extent

The Ziway–Shala lake basin system is located in central Ethiopia some 190km south of the capital Addis Ababa .It is bounded with in the limits of 7^{0}00'–8º30'N latitude or 446200-471200 UTM (Adindan) and 38º07'–39º30' E longitude or 859900-866300 UTM (Adindan) (Fig 2.1).

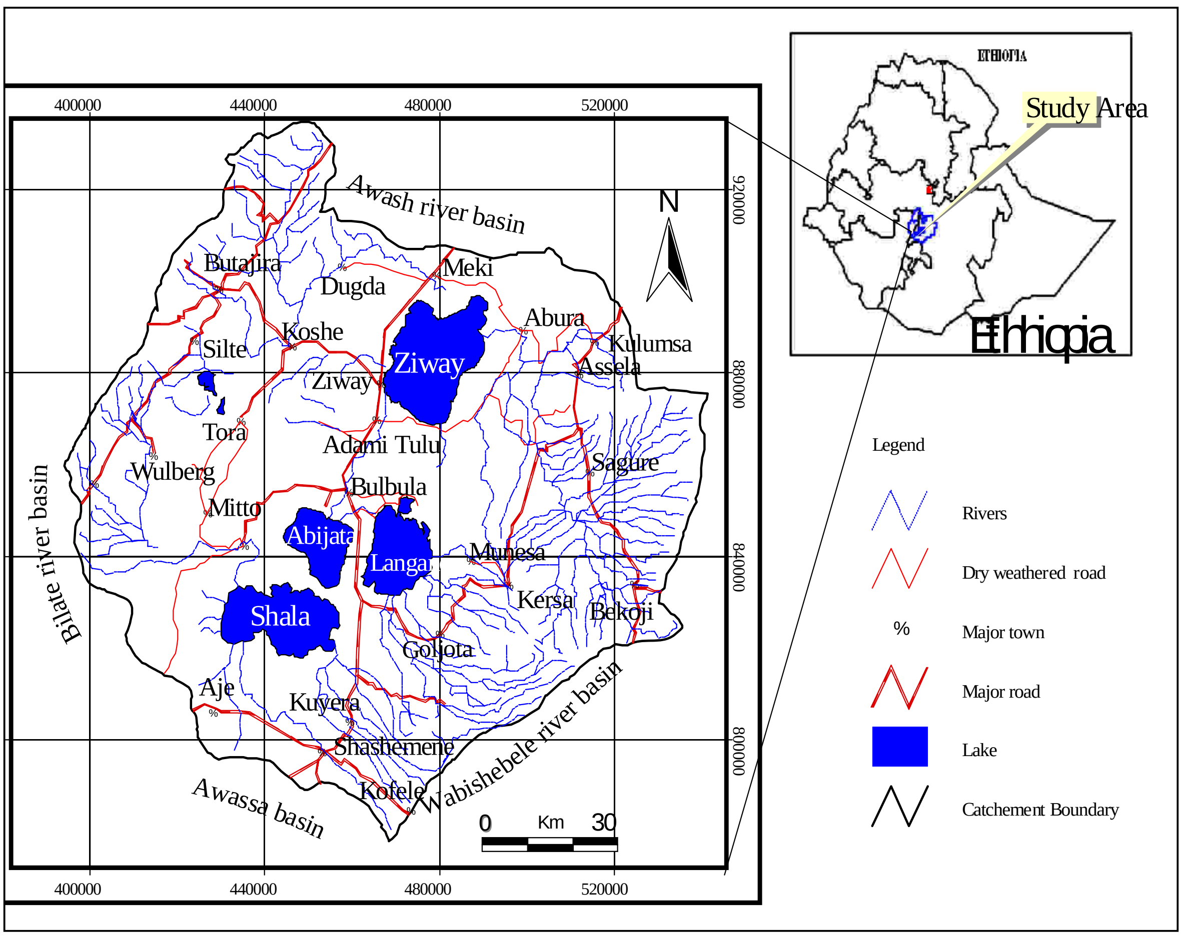


Figure 2.1Location Map of the Study Area

A large portion of the basin is part of the NNE-trending Main Ethiopian Rift, or what is commonly called the lakes district. The area is accessible through an Asphalt road, which goes from Addis Ababa to the border town of Moyale. There are all weather and seasonal gravel roads, which go from major town to different direction in the study area.

Table 2.1 Lakes systems of the studied basin

Lake Systems	Drainage Area(km^2)	Lakes Area as % of basin area
Ziway-Abiyata-Langano	10700	8
Shala	2300	16

The lakes in the basin are set in two drainage systems isolated from each other by volcanic hills and ridges (table2).The total catchment area of the basin is 13,000 km^2, of which 1,443 km^2 is covered with natural, permanent open water bodies.

2.2. Topography

Large-scale normal block faulting has disrupted the volcanic rocks and formed step-faults and horst and graben topography. The basin can be divided into three physiographic regions: the rift floor, the transitional escarpment and the highlands. Rift escarpment faults have undergone a long period of erosion while those of the rift floor are mostly recent. The rift floor consists mainly of extensive flat lands (Chernet, 1982).

The middle part of the basin is the rift floor bounded to the east and west by the southeastern plateau and shewan plateau respectively. It rises to 1550–1750 m above mean sea level (m.a.s.l.). There is a large topography difference between the rift floor and the plateau. The altitude ranges from a little over 2700m.a.s.l.in most parts of the surface water divide in the plateaux to 1600 m.a.s.l. around the large rift lakes. The lowest elevation is the level of lake Shala (1550 m.a.s.l) and the highest is Kaka mountain (4245 m.a.s.l.). The large Pliocene trachytic shield volcanoes of Mount Chilalo (4006 m), Mount Badda (4170 m), Mount Kubsa (3760 m) overlook the Ziway–Shala lake basin system from the east. Several dormant silicic caldera volcanoes rise above the rift floor: Mount Bora (2293 m), the Alutu Caldera (2328 m), the O’a Caldera (1960 m), and the Corbetti Caldera (2320 m).The eastern rift margin is marked by deep gorges and canyons due to the existence of large regional marginal fault system. The average altitude of the rift is about 1700 m.a.s.l. The shewan platue ranges in altitude from 2000-3000m.a.s.l.

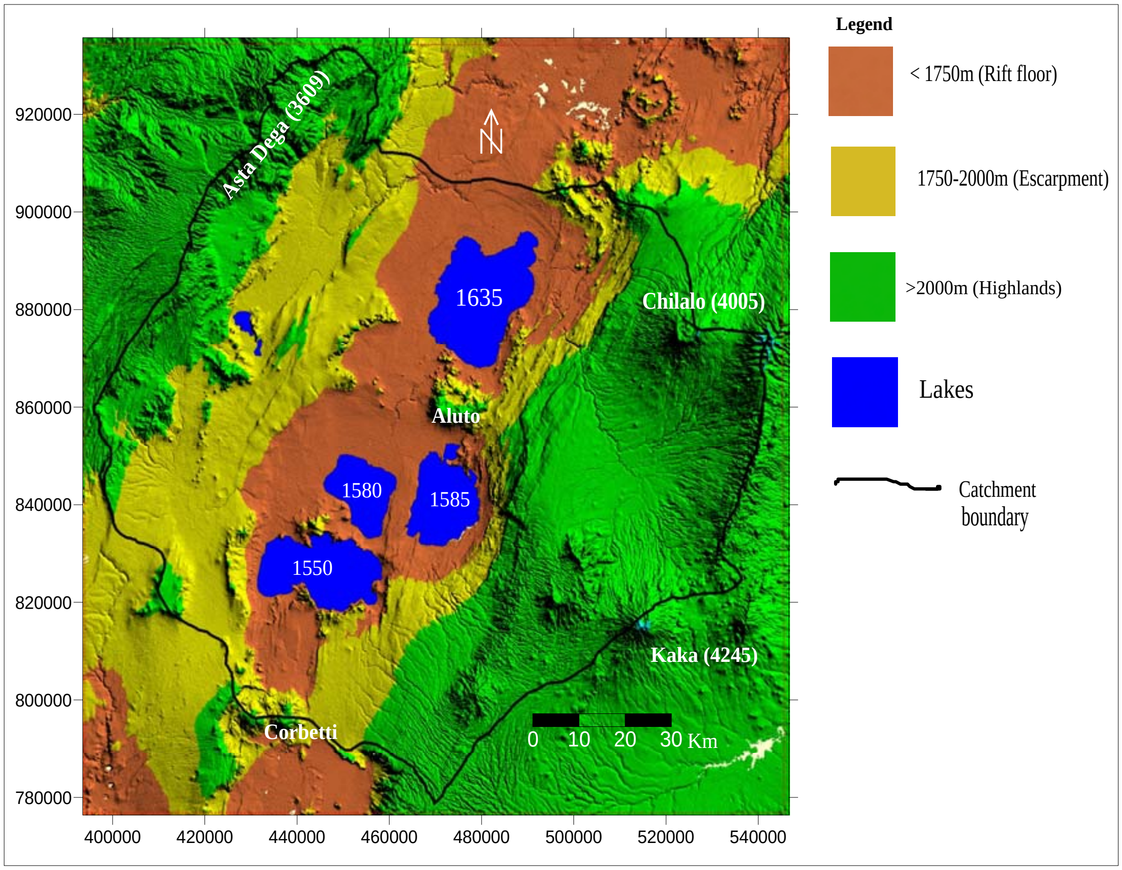


Figure 2.2Topographic map and the geomorphic features

The basin has a closed surface water drainage system .It is bordered by the Awassa lake basin to the south, the Bilate river basin to the West, the Awash river basin to the north and the Wabishebelle river basin to the east (Fig 2.1). The drainage divide is characterized by elongated volcanic ridges to the east and west and in other places by isolated volcanic mountains. The four main lakes of, Ziway, Abiyata, Langano and Shala are believed to have been formed by volcano-tectonic processes (Street, 1979).The first three lakes have an elongate shape parallel to the main trend of the MER and can be defined as tectonically controlled lakes. Unlike the other three lakes; Shala occupies a large caldera. The western part of the lake lies in a tectonically controlled depression. Thus, lake Shala can be classified as a volcanically–tectonically controlled lake .As a result of differences in the geomorphologic setting they vary considerably in depth, shape and size. (Caroline Le Turdu et.al., 1998)

2.3. Climate

The climate is humid to sub-humid in the highlands and semi-arid in the rift valley. The modern climate of the Ziway–Shala region varies markedly over quite short distances. It is mainly characterized by alternating wet and dry seasons following the annual movements of the Intertropical Convergence Zone (ITCZ) which separates the air streams of the northeast and southeast monsoons (Nicholson, 1996). The mean annual rainfall is no more than 600 mm in the vicinity of lake Ziway, and rises to a maximum of 1200 mm at the high margins (3000m contour) of the MER. Mean annual temperature is less than 15ºCin the highlands and more than 20ºC in the lowlands. Evaporation ranges from more than 2500mm on the rift floor to less than 1000mm in the highlands. (Caroline Le Turdu et.al., 1998)

2.4. Soil and Vegetation

The central parts of weakly developed soils are associated with lacustrine sediments, river alluvium and pumice. Unconsolidated sediments are common below the rift shoulder slopes and at the foot of volcanic mountains .Many areas bordering the rift bear well developed soils overlying weathered ignimbrite, pumice and basalt. Infiltration test on these deposits shows that many profiles on unconsolidated deposits are highly permeable and likely to generate little surface runoff (Street, 1979).On the contrary, profiles measured on west of Ziway showed abundant clay layers or nodules of carbonate at depth. The presence of clay rich horizons and calcrete in this area considerably restricts percolation.

The soils of the plains have well developed horizons at higher altitudes .The distribution of these thick soils closely mirrors the former extent of weathering .They occur widely on both escarpment and foothills of the Arsi mountains, but are best developed on rolling terrain underlain by basaltic parent materials .Poorly drained clays or less permeable soils on the Arsi volcanoes grade into locally well-drained mountain soils. These soils are thin occupying steep slopes of the large volcanic mountains.

The present vegetation ranges from open woodland to bushed grassland on the rift floor. Rift escarpments are characterized by bushed grassland, then remnants of dry, mountain forest and, from 3200 to 3500 m, ericaceous scrub and Afro alpine moorland (Makin et al., 1975).

2.5. Water quality changes and links to human interaction

The exponential growth of human populations and the attendant agricultural development (which demands more clearing of forests, irrigation, fertilizers, and pesticides) and industrialization are the main causes of water quality deterioration on all scales. Such impacts of human activities on freshwater lakes have existed for quite some time in Ethiopia and have contributed to the continuous degradation of their pristine qualities (Zinabu and Elias, 1989).

❖ **Land use and modification**

Human activities in drainage areas are potential causes of pollution of lakes. Even without human interference, lakes change over time because natural factors, such as soil erosion, sediment loading, deposition of animal and plant debris, solution of minerals in the basin, and so on, are always at work. Human activities in the catchment areas of the lakes in the basin like land use and modification greatly accelerate some of these changes.

❖ **Irrigation**

Irrigation is the most obvious response to water scarcity in agricultural areas, which explains why a lot of effort is being made to use irrigation in Ethiopia. The irrigation scheme that is being used for farms around lake Ziway has had a considerable effect on the water level. Since the irrigation in this area is a year-round process, its effect on the water level is magnified, especially during times of low precipitation and high evaporation (Zinabu and Elias, 1989). Several rivers that flow into one or more of the rift-valley lakes have been diverted for irrigation. The rivers Meki and Katar and the Bulbula and Gogessa rivers, which flow into lake Ziway and lake Abiyata, respectively, are being used for irrigation. This practice has caused water level subsidence in both lakes because of the reduced inflows.

❖ Industrial uses of water

The soda ash extraction plant on lake Abiyata is a good indicator of what can be brought about by industrial uses of water from the lakes. I have already mentioned that the water level of lake Abiyata has declined as a result of the diversion of its inflows for irrigation. This loss of water from lake Abiyata has been exacerbated by certain activities of the soda ash extraction plant, such as pumping of water from the lake or the discharge of effluents. The relatively shallow depth and terminal position in the drainage area make lake Abiyata rather vulnerable.

The above impacts of human activities on the lakes in the basin can be revealed by considering the terminal lake Abiyata. It has shown a considerable increase in ionic concentration since 1961. Although the soda ash extraction plant on lake Abiyata may have increased the evaporation rate of the lake water in the last 10 years or so, diversion of the inflows for irrigation purposes and flushing from deforested and heavily grazed catchment may also have contributed to the decrease in the water level and the increase in the concentrations of ions (Zinabu and Elias, 1989).

Another study on the Ethiopian rift-valley lakes indicated that three different trends in the salinity of the basin lakes have occurred in the last three decades. According to the study Ziway and Shala have maintained the same salinity they had in the 1960s, Langano has become more dilute, and the salinity of the soda lake Abiyata has increased over the last 30 years. The changes that have taken place in the conductivity of the lakes in the last three decades suggest a similar trend. Although these changes in salinity can take place due to evapotranspiration and/or solute inputs, the intensity of the human activity in their catchments must have contributed to the contrasting trends in their salinity. In the catchment areas of the lakes that have become more saline, human activity has been much more intense than in those that have not. Thus it is possible to conclude that human interference in the lakes in the basin is a major cause of water quality changes in the lakes (Zinabu, 1989).

CHAPTER THREE

3. GEOLOGY

3.1. Regional geology

Limited outcrops of Precambrian gneiss, covered by Early Mesozoic fluvial sandstones, marine shales and limestones, occur in a complex horst structure on the western margin (Kela horst, Woldegabriel et al., 1990; Di Paola et al., 1993).The Early Mesozoic sediment accumulation over the Precambrian basement rocks is due to spreading of a shallow sea over much of Ethiopia as a result of land subsidence. The geology and morphology of the study area is the result of Cenozoic volcano-tectonic and sedimentation processes that took place in the part of the eastern Africa and Ethiopia.

Following the regression of the Mesozoic sea to the southeast a major uplift occurred, which is known as the Arabo-Ethiopian Swell. The upraised and up arched land mass fissuring under tension permitted the accentuations of voluminous basaltic magma to form the Ethiopian flood basalt province (Mengesha et al., 1996). This was followed by the development of full symmetrical grabens and rift-in-rift structures (Di Paola, 1972; Woldegabriel et al., 1990; Le Turdu et al., 1999).Superimposed on the uplifted swell, part of the great East African Rift System started in the Miocene. The uplift, subsequent rifting and volcanism in the rift and outside the rift resulted into the formation of the present physiography of Ethiopia. Large Volcano-tectonic collapse in the MER formed the Ziway-Shala basin.

The present symmetrical graben morphology formed before the voluminous ignimbrite eruption at 3.5 Ma, resulting in the formation of the major ‘Munesa Caldera’ now buried beneath the Ziway– Shala lake basin system (Appendix 2), and other calderas located further south and west (Awassa Caldera; Wagebeta Caldera Complex) (WoldeGabriel et al., 1990).

The highlands flanking the Rift Valley and the Rift itself are dominantly composed of volcanic rocks (lavas and ashes, mainly of Tertiary and younger age), associated with the evolution of the Rift system. In the southern part of the Rift, the lakes District which includes the project area, the volcanic rocks are dominantly acidic (silica-rich), including much ash and pumice. The volcanic rocks in these areas are often inter-bedded with sediments.

The youngest volcanics are associated with obsidian flows, ignimbrite, pumice deposits with rhyolitic flows and domes, pyroclastic surge deposits, basaltic lava flows and spatter cones which mostly outcrop in the rift. From early Pleistocene to the present, tectonic and volcanic activity was concentrated along the Wonji Fault Belt (WFB), and successively along the Silte- Debrezeit Fault Zone (SDFZ).

The Plio-Quaternary sediments are alluvial, lacustrine, elluvial and colluvial deposits. Alluvial plains are filled up grabens and large stretches of flat land in the rift valley and along the whole length of the western boarder of the country (Tesfaye Chernet, 1993). Thin strips of alluvium along rivers occur in most places both in the highlands and the lowlands. The lacustrine deposits are of purely lake or swamp and volcano-lacustrine deposits. Extensive lacustrine sediments are located around existing lakes in the basin. Elluvials occur extensively within the metamorphic terrain in southern Ethiopia and in the basement rocks of northwestern Ethiopia. The eluvial lateritic crust consists of clay, silt and fine sand; but it has dominantly silt and fine sand. Small alluvial fans associated with colluvial deposits occur almost everywhere at the foot of mountainous areas and fault scarps. Late Quaternary fluvio-lacustrine sediments cover a large area of the central sector of the MER (Merla et al., 1979) which includes the basin studied. They were laid down in a very wide lake which, in the past, occupied most of the rift floor. The four present- day lakes (Ziway, Langano, Abiyata, and Shala) are the remnants of that ancient lacustrine basin (M. Benvenuti et al., 2002). Successively (late Pleistocene–Holocene) a fluvio-lacustrine basin occupied large areas of the MER floor (Di Paola, 1972; Laury and Albritton, 1975; Bigazzi et al., 1993) extending, in late Pleistocene, up to Mojo, 50 km north of lake Ziway.

3.2. Stratigraphic outlines of the area

The central sector and the shoulders of the MER which contains the study area are made of vulcanites and pyroclastic rocks, whereas large areas of the rift floor are covered by volcano-lacustrine and fluvio-lacustrine deposits. Limited outcrops of Precambrian rocks, covered by Early Mesozoic fluvial sandstones, marine shales and limestone, occur in a complex horst structure on the western margin (Kela horst, Woldegabriel et al., 1990; Di Paola et al., 1993).

The study area is basically composed of the volcanic & volcanicclastic rocks and sedimentary deposits. A Schematic geological map of the study basin, focusing on the Late Quaternary unconformity-bounded units and modified by the author is shown on Figure 3.1. A description of the stratigraphy and geochronology of the rocks indicated on the map is given starting from the oldest unit.

3.2.1. The volcanic & volcaniclastic rocks

These rocks include the following types based on chronology and lithostratigraphy

3.2.1.1. Late Eocene – Pliocene basalts, rhyolites and trachytes

The oldest volcanic rocks (Plateau Trap Series) are exposed in the western escarpment and consist of basaltic lava flows, with inter-bedded ignimbritic beds, topped by massive rhyolites and intervening tuffs and basalts. Middle Miocene to Pliocene (15–3 Ma) basalt flows, rhyolites and tuffs unconformably cap the Early Tertiary volcanic units (Merla et al., 1979; Woldegabriel et al., 1990).

The eastern plateau is covered by Pliocene to early Pleistocene (4.6–1.6 Ma) shield volcanoes (Chilalo, 4005m, Kecha, 4245 m Badda, 4170 m). These consist of trachytes with subordinate basalts and mugearites and of Miocene phonolites (Chike Mt) (Di Paola, 1972).

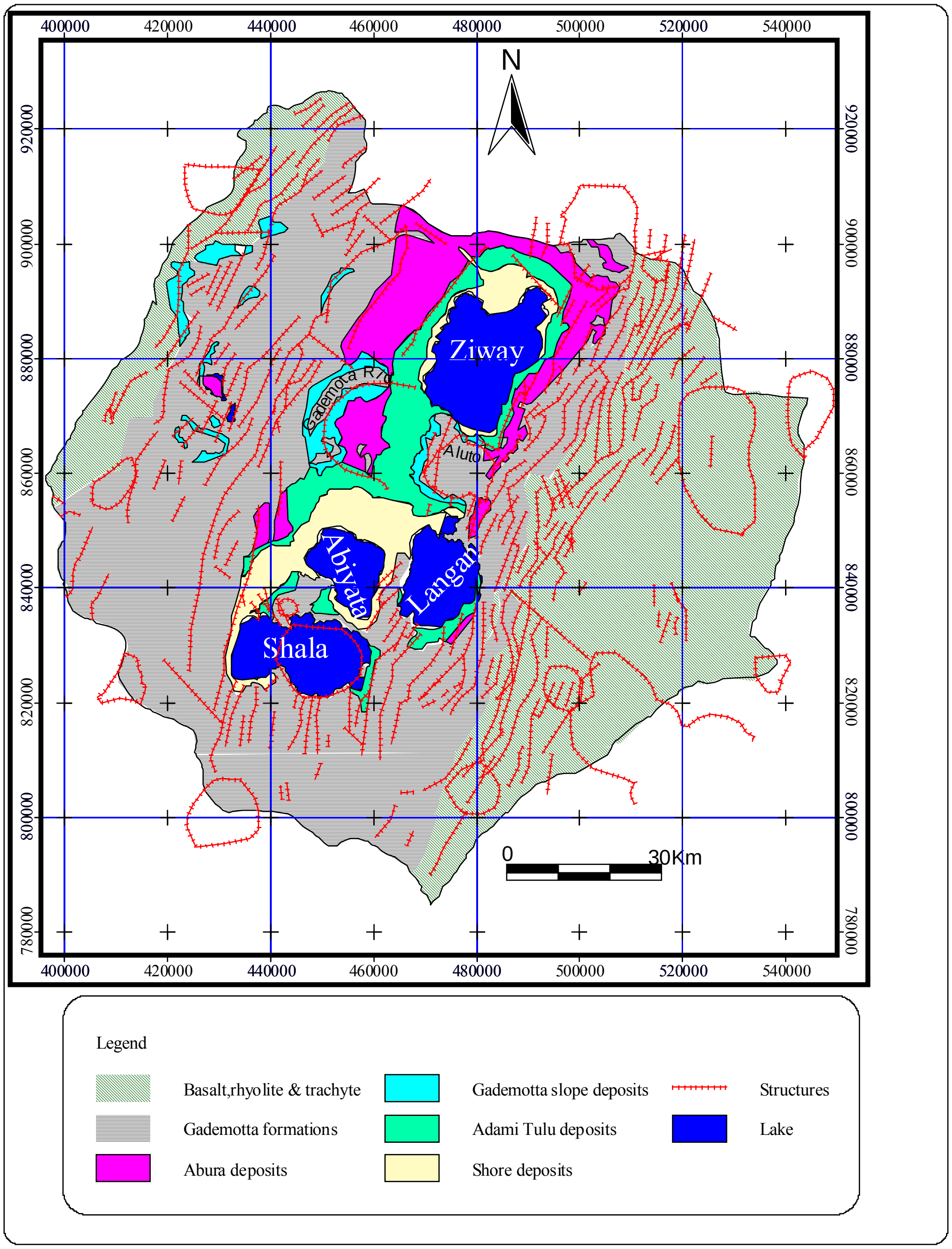


Figure 3.1.Geological map of the study area

3.2.1.2. Plio – pliestocene rhyolitic ignimbrites ,lava flows ,basalts & colluvial deposits (Gademotta formation)

Silicic pyroclastic materials cover most of the escarpments and the rift floor. They are mainly peralkaline rhyolitic ignimbrites, interlayered with basalts and tuffs (unit P_ρ on Appendix 1) and associated with layered, unwelded pumices. The thickness of the ignimbrites is not known, but outcrops and well data suggest it exceeds 500–600 m. (Mohr, 1962; Di Paola, 1972; Woldegabriel et al., 1990).

Alkaline and peralkaline rhyolitic lava flows and domes, associated with pumice and ash (unit P_{α} on Appendix 1) represent the late silicic volcanic events (Di Paola, 1972). These lavas were erupted from Late Pliocene to Middle Pleistocene and, in some places; crop out as remnants of large calderas. The Gademota ridge is one such remnant. It rises in an arc structure, 25–30 km in diameter, up to 400 m above the plain west of lake Ziway.

A more recent volcanic unit, (Q_{β} on Appendix 1), crops out along the SDFZ (Silte Debrezeit Fault Zone) and the WFB; it is made up of basaltic lava flows, associated with hyaloclastites and scoria cones. The thickness of this unit is only a few dozen meters; it is very recent, as testified by a radiometric age of 0.13 Ma (Woldegabriel et al., 1990).

Young volcanoes and calderas, such as the Bora– Bericcio complex, the Alutu volcano, the Ficke, O_a and Corbetti calderas, are made up of rhyolitic lava flows, unwelded pumice flows, pumice falls and ashes (units Q_{σ} and Q_{ω} on Appendix 1). Obsidian flows represent the final product of the volcanic activity (Di Paola, 1972; Mohr et al., 1980). These recent volcanoes started to be active from the Middle Pleistocene with intermittent Late Holocene activity and very recent ash deposits.

3.2.2. The sedimentary deposits

Late Quaternary fluvio-lacustrine sediments cover a large area of the rift floor. They were laid down in a very wide lake which, in the past, occupied most of the rift floor. The four present- day lakes (Ziway, Langano, Abiyata, and Shala) are the remnants of that ancient lacustrine basin (Merla et al., 1979).

A stratigraphic framework for the Late Quaternary sedimentary deposits is presented in Appendix 1, establishing four major unconformity-bounded units (i.e. Synthems; Salvador, 1987). The map on Fig 3.2 refers to the lithostratigraphic character of the deposits included within the synthems. The link between mapped units and synthems will be described in Appendix 1.

3.2.2.1. Synthem 1 (Abura deposits)

The oldest synthem is represented by colluvial (unit Q_u on Appendix 1), lacustrine, fluvio-deltaic, and volcaniclastic sediments (unit Ql_1), arranged in lesser unconformity bounded units. These deposits rests unconformably on surface S1 (Appendix 1), overlying Plio-Pleistocene volcanic rocks and older slope deposits (units Q_u and Q_{cg}) (Laury and Albritton, 1975, Le Turdu et al., 1999). They are bounded on top by erosive or non-depositional surfaces. On the whole, Synthem 1 is Late Pleistocene in age and composed of sands, laminated diatomaceous silts and marls, pumice.

3.2.2.2. Synthem 2 (Gademotta slope deposits)

The second synthem is composed of very thin alluvio-colluvial, volcaniclastic and fluvio-deltaic deposits (units Q_u and Q_c on Appendix 1), resting erosively on older deposits through surface S2. On the Gademotta slopes (Fig 3.2), this unit is represented by alluvial sands and gravels, overlain by alluvially reworked fine-grained greyish tuffs. In the Bulbula River Plain, 15–20 m thick subaerial pumice fall deposits, corresponding to the Abernosa Pumice Member, (Gasse and Street, 1978; Street, 1979), rest unconformably on synthem 1 deposit. Synthem 2 deposits also accumulated at the base of the Alutu Caldera.

3.2.2.3. Synthem 3 (Adami Tulu deposits)

The third synthem is made up of lacustrine, fluvio-deltaic, colluvial, and volcaniclastic sediments, with intervening buried soils (units Q_u, Q_c, Qf, Qdm, Qd, Qt_2, Ql_2 and Qs_2); these overlie older deposits through erosional surface S3 (Appendix 1).

In the Gademota area (Fig 3.2), synthem 3 deposits rest, through a high relief erosional surface (S3), on the deposits of Synthems 1 and 2; they are dominantly represented by alluvial and colluvial sands and silts, bearing a well developed Luvisol. Lacustrine deposits are represented by massive diatomites.

In the Bulbula Plain (Fig 3.2), Synthem 3 deposits unconformably overlie Synthem 2. Here, lacustrine deposits range from relatively open and deep lake diatomites and marls to sandy deposits, bearing shell beds.

In the East Shala outcrops (Fig 3.2) (Grove et al., 1975; Street, 1979; Gillespie et al., 1983), Synthem 3 deposits rest unconformably on the strongly deformed Middle Pleistocene volcaniclastic rocks and on Synthem 1 deposits. Alluvial or colluvial sands and silts at the base, overlain by marginal lake muds and sands.

3.2.2.4. Synthem 4 (Shore deposits)

The fourth synthem is represented by lacustrine, fluvio- deltaic and colluvial deposits (units Qu, Qc. Qf, Qdm, Qd, Qt3, Qb, Qs3 and Qp) unconformably overlying older deposits through surface S4 Appendix 1, and capped by a modern erosional–non-depositional surface. On the slopes of the Gademotta Ridge (Fig 3.2), this synthem is represented by alluvial–colluvial sediments, filling paleovalleys incised in the deposits of underlying units. The fills are characterized by basal alluvial gravelly sands, topped by fine-grained alluvial–colluvial.

In the west Shala Synthem 4 is represented by alluvial gravelly sands, overlain by low angle cross-stratified sands. Sands of the recessional stranded beach are visible close to the present lake Shala shore.

3.3. Geologic Structures

The study area has been confined to a NNE trending structure formed by a line of hundreds of young faults and volcanic centers along the rift floor close to the eastern escarpment, and arranged in en e´chelon fashion. This volcano-tectonic axis, named the Wonji Fault Belt (WFB), is considered to be the current axis of crustal extension (Meyer et al., 1975; Morton et al., 1979; WoldeGabriel et al., 1990).

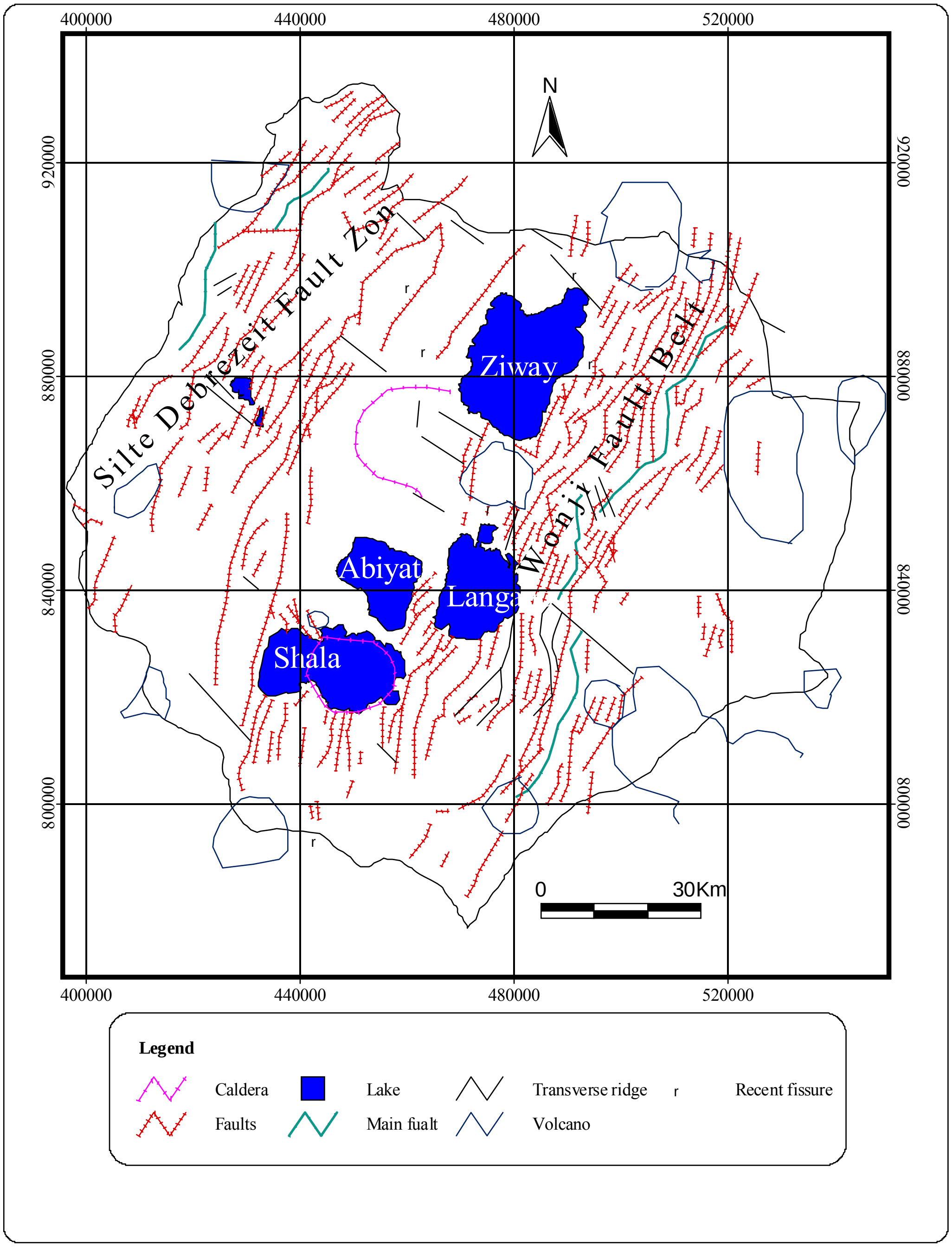


Figure 3.2. Structural map of the basin

Faults along this active zone form numerous minor horst and graben structures or “rift-in –rift” structures. Appendix 2 sows the WFB is dextrally offset into four en e´chelon rift-axis segments. From north to south, these are the Gadamsa–East Ziway, Ziway–Shala, Shala– Corbetti, and Duguna–Abaya segments (Mohr, 1960, 1967; Lloyd, 1977; Mohr et al., 1980; WoldeGabriel et al., 1990). Within the study region, the WFB formed along the eastern marginal graben. Caldera-topped shield volcanoes occur at each WFB offset: the Alutu Caldera between the Gadamsa–East Ziway and Ziway–Shala segments, the O'a Caldera (presently occupied by lake Shala) between the Ziway–Shala and Shala–Corbetti segments, and the Corbetti Caldera at the south end of the Shala–Corbetti segment. Figure 3.2 shows high fracture density to the east of lake Ziway and Langano and in areas between the two lakes along the WFB.

The western escarpment is primarily characterized by one major fault scrap. It shows a high throw in its north-eastern part, which progressively decreases and dies out to the southwest where it has been covered by volcanic products. However, in the western escarpment along the Guraghe Mountains, more than 1.5km thick flood basalt is displaced by several step faults that strike NNE. These faults are cut by north-west and west striking transverse fault (Figure 3.2). The Silte Debrezeit Fault Zone (SDFZ) of the western marginal graben is more than 100km long and 2-5km wide and converges at its southern end with the WFB. The SDFZ contains lacustrine sediments and tuff on which rest several nested scoria cones aligned parallel to the west escarpment (Tenalem Ayenew, 1998)

The central part of the basin is characterized by fresh faulting with variable displacements along the strike of the boundary faults .These margins are marked by high angle normal faults with large throws that comprise several step–faulted blocks. The faulted margins show right angle spurs (Moore & Davisdon, 1978). In places, the rift escarpment adjacent to the Quaternary silicic centres located aligning the rift axis (for example, Aluto, Shala and Corbetti) are generally subdued, in part due to pyroclastic accumulation along the rift margins.

3.4. Recent Tectonic Structures

Earth fissures are roughly aligned in the direction of local fault pattern indicating a possible relation between surface collapse, underground drainage and tectonic trend. The role of faults is established as a focus for fissure development and related subsidence.

In the Main Ethiopian Rift, ground fissuring is a basic hydrologic and geomorphic process which occurs in association with high intensity rains. In the study area, during unusually heavy rains, both new failures and renewed displacement on older ones occur. In degraded semiarid areas, fissuring is linked with reduced protection of soil by vegetation generating overland flow (Bryan and Jones, 1997).

The formation and propagation of fractures in this basin are determined by its rainfall, pre-existing structures and heterogeneous materials consisting of layers of clays and silts, sand, pumice and volcanic ash and hardpan calcrete. The contrasting physical and mechanical properties (such as permeability and compressibility) of this sequence evidence their different potential of deformation (Bekele et al., 2004).

All areas affected by subsidence and fissure development are characterized by very low drainage density. The flat topography does not allow the development of integrated surface drainage network which suggests the importance of underground drainage of intense storm water.

According to local reports, fissures formed in the Keyansho area (east of lake Zway) in March 1981 in coincidence with the highest monthly precipitation of 248.9 mm as recorded at the nearest station of Ziway. The same area was affected by ground failure in 1983 (Asfaw, 1998) and in 2005. Fissures are also formed in the Meki area and Siraro area in 2006 during heavy rains (unpublished report)(Fig 3.2).

Failure occurred on a half graben and consisted of a discontinuous fissure about 1.2 km long, with an average width of two meters and visible depth of up to 12 meters. Circular subsidence pits up to 15 meter in diameter formed along the fissure which truncates soil, volcanic ash, sandy and silty sediments of lacustrine and alluvial origin (Bekele et al., 2004). The fracture has a dominant NNE-SSW strike with short N30°W segments reflecting the fault geometry in the bedrock. Wall collapse and vegetation growth have partially obliterated the fissure.

Thus from early Pleistocene to the present, tectonic and volcanic activity was concentrated along the WFB, and successively along the SDZFZ. Present-day lake Shala occupies not only the O'a Caldera, but also a tectonic depression immediately west of the caldera belonging to the northern end of the Shala–Corbetti WFB segment (Mohr et al., 1980). The general shape of the depression has also been modified by recent regional faulting.

CHAPTER FOUR

4. SURFACE WATER HYDROLOGY AND HYDROGEOLOGY

4.1. Surface water hydrology

Several perennial rivers start from the highlands on both sides of the rift valley and they enter into a series of lakes which occupy the low lying middle part of the rift valley. The major rivers are Meki, Ketar, Bulbula, Horakelo, and Djido while the lakes are Ziway, Abiyata, Langano and Shala.

Fault systems associated with the rift have affected the drainage of the area both by determining the river courses and by impounding river water and causing some marshy areas such as Arata Swamp on the way from Kulumsa to Abura. The effect of faults on the courses of Katar and Meki Rivers is clearly seen on Figure 4.1.

The basin is heterogeneous in terms of surface runoff generation and total catchment yields. Rivers in the western half of the basin lose water in rift floor sediments and have rapid response to rainfall. The eastern highlands sustain baseflow due to high rainfall and aquifer storage capacity .In the eastern escarpment faults play an important role in both increasing and decreasing baseflows of rivers depending on the level of groundwater head with response to river bed elevation (Tenalem Ayenew, 1998).

In the area of lacustrine deposit among lake Ziway , Langano and Abiyata ,there is no drainage except Horakelo and Bulbula which increases it discharge downstream possibly groundwater migration from lake Ziway towards lake Abiyata and Langano. Similarly in the western Ziway area between Mito and Koshe lack drainage (Fig 2.1)

Table 4.1 The basic hydrologic data (Tenalem Ayenew, (1998***)***

Lake	Altitude (m.a.s.l.)	Lake area (km^2)	Catchment area (km^2)	Maximum Depth (m)	Main Depth(m)	Volume (mcm)
Abiyata	1580	180	10740	14.2	7.6	954
Langano	1585	230	2000	47.9	17	3800
Shala	1550	370	2300	266	8.6	37000
Ziway	1635	440	7380	8.9	2.5	1466

I. Lake Ziway

Lake Ziway is the largest lake in the basin. It lies in a shallow down faulted depression flanked in the east by a large basalt field. It is feed by the Meki and Katar and overflows to lake Abiyata via the Bulbula River.

The lake is relatively of low salinity and is the only lake used for irrigation purpose. The lake has a potential of irrigating 1700 ha but presently it is irrigating about 1000 ha (HALCROW, 1992). In addition to this the lake is used for fishing and has a potential of 3000 tone fish per year (Atkins & Partners, 1965).

The lake has a total average surface water inflow, including the direct precipitation, of 1028 mcm (million cubic meters) per year. The annual average water loss from the lake by evaporation, run off through Bulbula river and water loss for irrigation is amounts to 1102 mcm. But with this water balance the level of the lake remained constant indicating the inflow of groundwater to the lake (Tenalem Ayenew, 1998).

Lake Zway is 26 km. long and 18km, wide and several islands dot the surface of the largest of the five lakes in Ziway-Shala basin.

II. Lake Langano

Lake Langano occupies a large depression bounded by a well-defined major fault system. The eastern and western shores are bounded by a graben, whereas the northern part ends up as a small circular caldera in Oitu Bay and the southwestern and northeastern shores lap against the horst and grabens of the Wonji Fault Belt. The lake is fed by a number of small streams running from the highlands to the east and South of it in addition to the direct precipitation on the lake surface and hot springs, and discharge to lake Abiyata through Horakelo river. It has average annual surface water and precipitation inflow of 461 mcm and a combined annual average water loss from river run off and evaporation of 509 mcm. But regardless of the above water balance the lake level remains stable indicating the contribution of groundwater flow to the lake through springs and seepage through large faults (Tenalem Ayenew, 1998).

The lake water is distinctly colored brown due to fine suspended sediment (mainly colloidal clay) brought in by streams from the escarpments and highlands. The water is more alkaline than lake Ziway (Wood et. al., 1978).

Langano is serving as a recreational center. It is the most visited lake in the rift valley by tourists. The soft brown waters of Langano are set against the blue backdrop of the Arsi mountains soaring 4,000 meters high

III. Lake Abiyata

Lake Abiyata is a closed graben terminal lake. The main inputs of water to the lake come from direct precipitation and surface run off from rivers Horakelo and Bulbula and at times when the lake level is raised it overflows to lake Shala (Grove & Goudie, 1971). The average annual surface inflow and direct precipitation to the lake is 358 mcm and the out put components being evaporation and abstraction for soda ash production contributing to a total water loss of 385 mcm, however the lake level is stable indicating the contribution of groundwater flow to the lake. The lake level in lake Abiyata is affected by large scale water abstraction for the soda ash production and also by the abstraction of lake Ziway for irrigation in addition to the groundwater flux (Tenalem Ayenew, 1998).

The lake is currently being used for soda ash production by evaporation of the brine water and it has a reserve potential of 80 million tones but the present day annual production rate is 15,000 tones (HALCROW, 1992).

IV. Lake Shala

Lake Shala is a separate terminal lake and one of the deepest lakes in the Eastern African Rift system, occupying a major volcano-tectonic collapse modified by later regional faulting (Mohr, 1966; as cited in Di Bois, 1976). Although it is isolated from the other lakes at the present time it has probably received an inflow in the past from lake Abiyata at times when the water level in lake Abiyata was high (Wood et. al., 1978). The major inflow comes from precipitation, surface run off through rivers Dijo and Awade, and hot springs around the shore. It has an average annual surface inflow of 535 mcm and the only loss of water from the lake is through evaporation accounting to an average yearly total of 781 mcm. The stable lake level irrespective of the difference of the input and loss of water from the lake dictates the contribution of large amount of groundwater inflow (Tenalem Ayenew, 1998). Lake Shala is dominated by the countless hot springs, which pour boiling water into the lake.

The lake water is extremely saline and alkaline because of a prolonged stability and evaporation (Tudorancea et. al., 1989). According to Di Bois (1976) the lake has a total soda ash reserve potential of 740 million tones but Halcrow (1992) reported the reserve potential of soda ash to be 375 million tones.

V. Lake Chitu and other small lakes and swamps

In the Ziway Shala basin there is other small lakes right on the rift floor and on the western edge of the basin in wide plains and volcanic cones close to the Guraghe mountain range. The most notable in the rift floor is lake Chitu and that of the Guraghe Mountains is lake Abaya and the small circular crater lakes of Shetemata.

Lake Chitu is a circular small crater lake located southwest of lake Shala. It is the most saline lake in the basin. It is a highly saline lake having a total reserve potential of 1.2 million tones of soda ash (Di Bois, 1976). As most of the crater lakes the main source of inflow is groundwater and small surface run off and precipitation in the catchement. The lake is also fed by a number of low discharge hot-springs.

The other small lakes in the basin are fresh. The Shetemata swamp and the small crater lake Harro are flushed by both surface and groundwater from the highlands and rift valley fracture systems. These lakes play very important role in providing water supply for the rural community and for animal drinking. Around the alkaline lakes people and animals use only the hot-springs around the lakes or feeder rivers originating basically from the highland.

In the escarpment of the Guraghe mountains there are two important lakes: the crater lake Hara Shatan and the tectonic trough small lake Abaya. Lake Abaya is fed by the streams from the escarpment of Guraghe Mountains. Lake Hara Shatan is a crater lake located 140 km South of Addis Ababa. It is slightly elliptical crater in shape with an average diameter of 880 m and the lake lying about 125 m below the rim having a depth of at least 50 m (Wood & Dakin, 1975).

Arra Seitan lies farthest south in a row of craters and small volcanoes stretching from Butajira to Silte on the flank of the MER. On the way from Silte to Koshe, not far from Arra Seitan lake some 7 km from Silte, NW of the large Tuffa swamps, a terrain with fresh, nonweathered lava, with rough blocks and stones and with singularly rough surface features, pits, basins and ridges alternating without order, a kind of Gurghe replica to the fresh lava fields in the Fantale Methara area.

The surface hydrographic network of the Ziway–Shala lake basin system is particularly well developed to the north of the area, with the Meki and Katar rivers entering lake Ziway from the western and eastern escarpments respectively. Lake Langano is mainly maintained by five major rivers, Huluka, Lepis, Gedemso, Kersa and Jirma, flowing northwest then north from the south-eastern escarpment and characterized by weak, low water flow. Lake Abiyata receives flow at its northern end from the Bulbula and Horocallo rivers flowing from lake Ziway and lake Langano, respectively. The surface inflows to lake Shala come from two main sources, the perennial Adabar River which enters from the south-eastern rift escarpment, and the main branch of the Gidu River flowing from the western escarpment (Fig. 2.1).

4.2. Hydrogeology of the study area

In the basin the hydrogeological behaviour of the volcanic rocks deposits and the hydrochemical signature of natural waters are diversified and influenced by the:-

- Wide compositional, structural and textural variability of the volcanic rocks
- Complex spatial and temporal distribution of the volcanic rocks
- Different reciprocal stratigraphic relationships of the volcanic rocks with the Mesozoic and Precambrian rocks and recent plio-quaternary sediments
- Different level of weathering and variable topographic position of the volcanic rocks

Based on the hydraulic conductivity data collected from 17 wells (Appendix 6), the various formations in the area have been classified to three groups of High (greater than 40m/day), Moderate (1-40 m/ay) and Low (less than 1 m/day) permeabilities .As shown on Fig 4.1 there is a large variation in the permeability of rocks especially in the eastern escarpment (Fig 4.1) where there is high contrasting role of the rift faults (as conduits or barriers of groundwater) whereas most permeability of the rift floor falls in the moderate range(1-40 m/ay)

Large spatial variation in the permeability of rocks is a common feature of fractured volcanic terrain due to differences in the degree of fracturing .In contrast to geological bodies which are frequently determined by their stratigraphic characteristics and/or lithologic composition, spatial variation of hydrological bodies (aquifers and aquitard) can be partly or entirely independent of lithologic properties in a highly fractured environment (krasny, 1997).

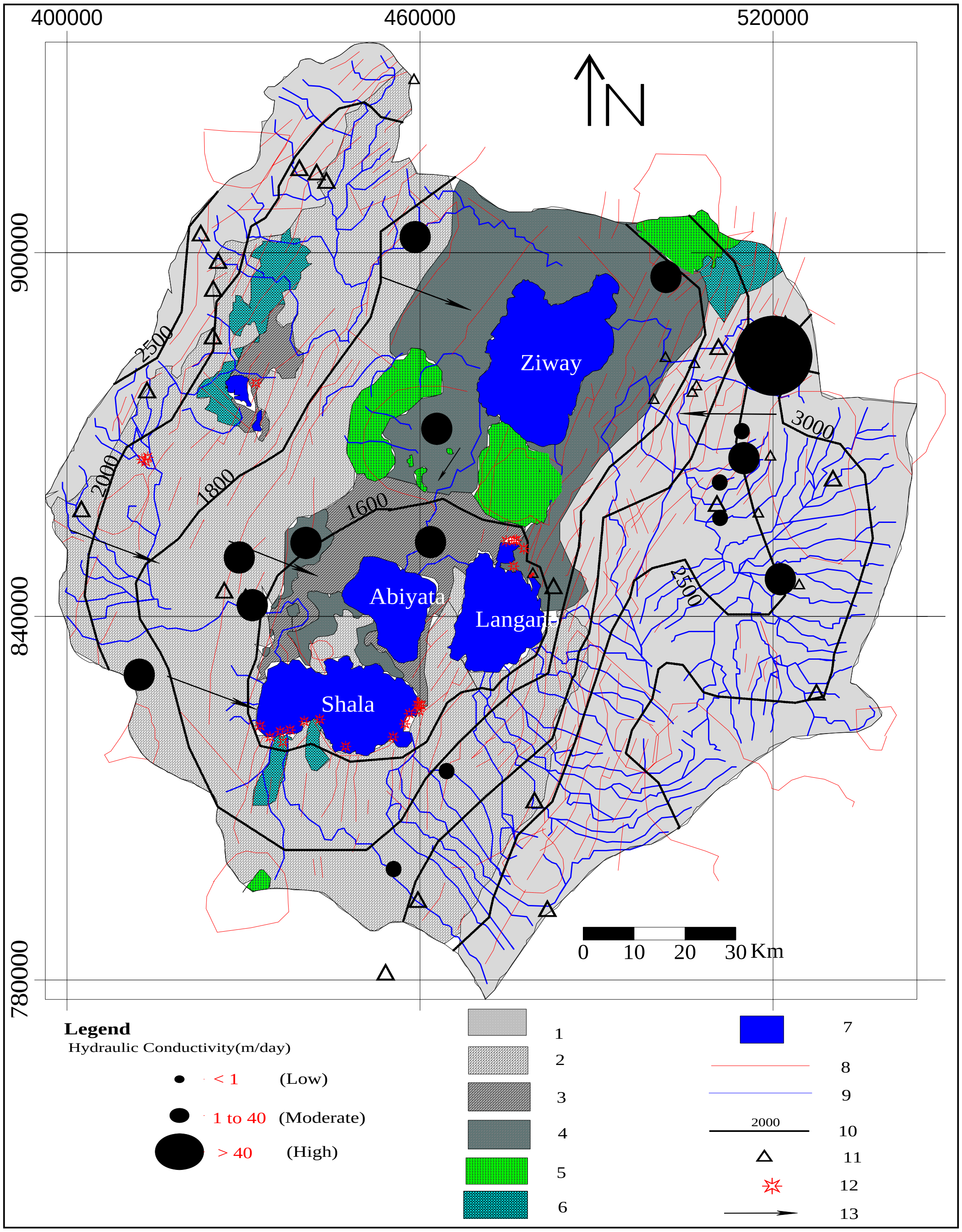
Depending on the characteristics of the different rock types mentioned in Chapter 3 and field investigation, the geological formations are put in six hydrostratigraphic units (modified after Tesfaye Chernet, 1982). The aquifer characteristics are described below:-

4.3. Major hydrogeologic units and aquifer characterstics

4.3.1. Ignimrite, tuff, local rhyolite

It is a unit covering most of the eastern highlands and some of the western highlands and it is best observed at the eastern fault scarps of the basin (Fig 4.1). These rocks are highly weathered and slightly fractured. The different hydrostratigraphic units are separated by different palaeosoils (mainly clay and silt). The density of faults in the highlands is quite low as compared to the rift valley. Much of the water-bearing zones in the highlands are within the upper few tens of meters in the weathered volcanic sequence and locally in inter-bedded river gravels and alluvial deposits. It has low to moderate permeability. It has high permeability where the dense Wonji Fault Belt cuts this rock.

Springs discharge at contacts of jointed and massive flows .Some of these springs are the starting points for perennial streams which flows down to the lake.



1= Ignimbrite, tuff, local rhyolite, ***2***= Ignimbrite, tuff, local basalt, ***3***= Ignimbrite covered with lacustrine soils, recent regression, ***4***= Ignimbrite covered with lacustrine deposit, ***5***= Rift volcanoes and volcanic ridges, ***6***= Basalt, local ignimbrite, ***7***= Lake, ***8***= Volcano-tectonic structures, ***9***= Drainage, ***10***=Groundwater level contour, ***11***=Cold spring, ***12***=Hot spring, ***13***=Groundwater flow direction, Circles represent the Hydraulic conductivity.

Figure 4.1.Simplified hydrogeological map

4.3.2. Ignimrite, tuff, local basalt

This rock is the most extensive unit covering the rift floor and most of the western highlands that contains various generations of the Trap series volcanics in the western highlands that is dominantly basaltic with inter-bedded ignimbrites. It has moderate permeability.

4.3.3. Ignimbrite covered with lacustrine soils, recent regression

This unit contains fluvio- lacustrine soils and recent depositional sediments due to lake level fluctuation over the rift floor ignimbrites. It covers the area north of lake Abiyata and the small lake on the western part of the basin. It has a moderate permeability.

4.3.4. Ignimbrite covered with lacustrine deposit

This unit consists of alternating fine and coarse beds overlying the ignimbrite, but they are predominantly fine to medium grained .It has a moderate permeability.Thickness of the lake sediments ranges from 40 meters to more than 200 meters and average they are 40-50 meters thick (Tesfaye Chernet , 1982).

4.3.5. Rift volcanoes and volcanic ridges

They were mapped partly in the mountains north of lake Ziway, at Aluto and Gademotta ridge. It has very law permeability.

4.3.6. Basalt , local ignimbrite

They form scoria cones along the major fault east of Butajira .Other area of basalt flows occur northern east of lake Ziway and south of lake Shala. It has moderate to high permeability.

4.4. Groundwater occurrence and movement

Groundwater in the basin moves towards lake Shala which has the lowest elevation in the area, 1550 meters above sea level. However it has been inferred that some groundwater flow from lake Awassa basin towards lake Shala (Tenalem Ayenew, 1998).Much of the water-bearing zones in the highlands are within the weathered volcanic sequence and locally in interbedded river gravels and alluvial deposits.

In the rift the localization of groundwater is strongly controlled by the rift faults. They have contrasting role in the movement and occurrence of groundwater. The majority of faults are conduits to groundwater flow. In places these open faults allow significant amount of preferential groundwater flow parallel and sub-parallel to the rift axis. 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 (Fig 4.1). It was found that these axial faults govern strongly the subsurface hydraulic connection of the rift lakes and the river-groundwater relations. Some rivers disappear in these open rift faults as in the case of rivers coming from the Arsi highlands feeding lakes Langano and Shala. The roles of faults on the subsurface connection of the lakes and groundwater flow are studied independently on Chapter 5 with the help Hydrchemical and isotope studies of waters in the basin.

In the rift floor, significant groundwater flows through local palaeochannels. An example to this is the palaeochannel along the Bulbula River, which connects lakes Ziway and Abiyata (Tesfaye Cherenet, 1982; Tenalem Ayenew, 1998). Isotopic and hydrochemical techniques (Chapter 5) of this study also supported the subsurface connection of these lakes.

In contrast to the high hydraulic conductivity of the rift fractured volcanics, 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. The typical examples are the Shetemata swamp east of Ziway. Large groundwater barrier zones exist west of the Gedamota ridge also southwest of lake Ziway. In these areas the groundwater reserve is extremely low, if present it is deep and with very low yield. Due to high groundwater residence time, the water has high total dissolved solids.

CHAPTER FIVE

5. HYDROGEOLOGICAL SYSTEM ANALYSIS USING HYDROCHEMISTRY AND ISOTOPE HYDROLOGY

5.1. HYDROCHEMISTRY

5.1.1. Introduction

Hydrochemical data are applicable for the conceptualization of groundwater flow pattern (dynamics) in various natural geological and hydrogeological systems. The natural chemical composition of water samples is valuable in identification of mixing, sources, flow path and the similarity and difference of subsurface waters.

Toth (1963) demonstrated the importance of hydrochemical analysis in hydrogeology along with simple two dimensional numerical groundwater flow model to conceptualize groundwater flow systems in small watersheds. Winter (1978a) presented the use of Groundwater flow models coupled with hydrochemical methods in understanding the groundwater-surface water interactions in lake watershed systems. A more comprehensive coverage of the study and interpretation of chemical characteristics of natural waters and their use in hydrological studies are has been provided by Hem (1970), Stumm & Morgan (1970) and Appeleo & Postman (1993).

In this study groundwater dynamics, hydrochemical evolution and the hydraulic relation of the rift lakes in the basin are the main objective of using hydrochemistry and isotope data. Isotope data in relation with the hydrochemistry data are presented using different scatter plots and maps and are interpreted for flow analysis.

Complete chemical analyses and physical measurements of waters from the study area are listed in Appendix 3 and Appendix 4.The locations of sampling sites are shown in Fig 5.1 .Sampling, and analytical techniques employed are described in Section 1.4.

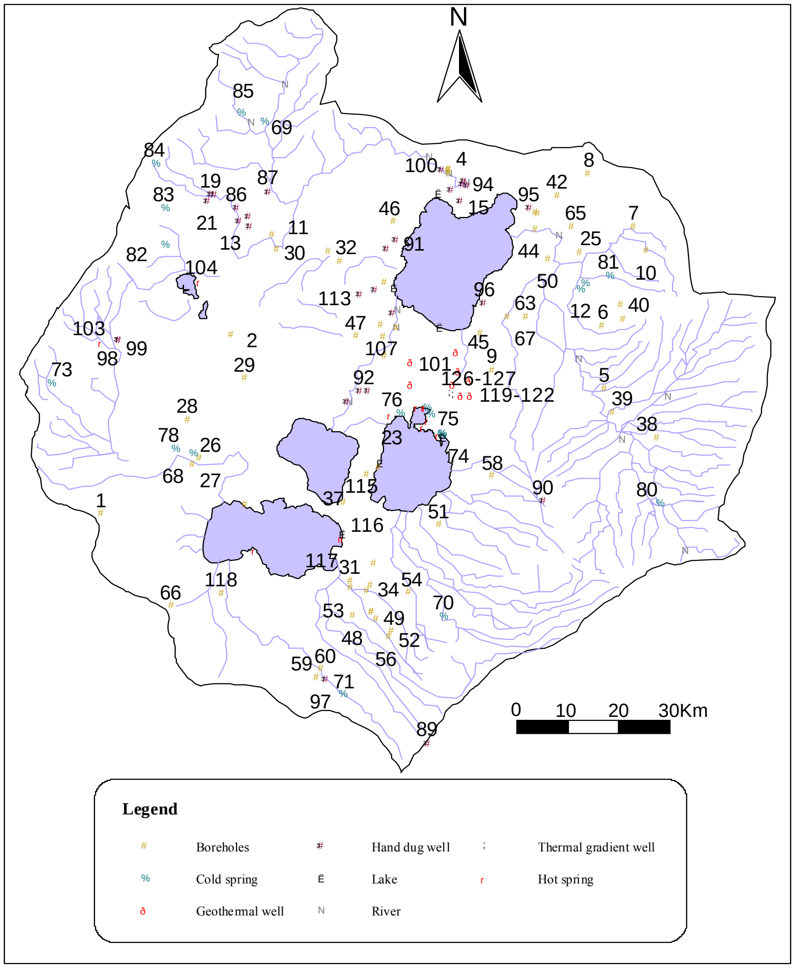
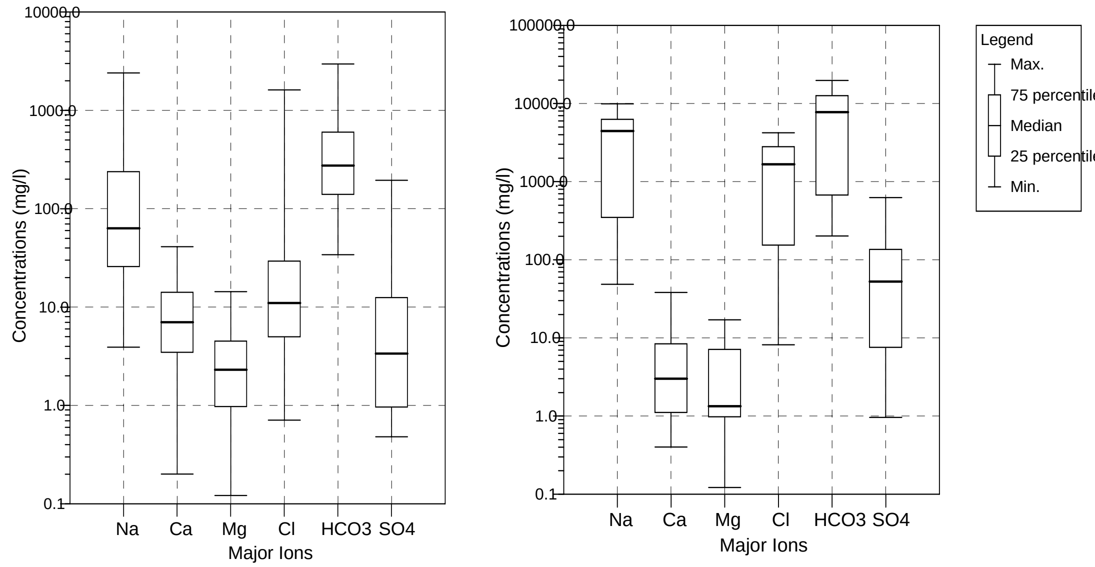


Figure 5.1. Water sampling sites

5.1.2. Chemical and physical analysis results of waters and their spatial variation

5.1.2.1. Major ions chemistry

Water is a naturally balanced system essentially containing a few dominant cations (Na^{+1}, K^{+1}, Ca^{+2}, Mg^{+2}) and anions (HCO_3^{-1}, Cl^{-1}, SO_4^{-2}). There is a large variability in the cations and anions of both groundwaters and surface waters as can be seen in Fig 5.2 .It is shown that the minimum, maximum and mean concentrations of the major cations and anions of groundwaters (from boreholes, cold springs, hot springs, dug wells and geothermal wells) and lake waters in the study area.



Groundwaters Lake waters

Figure 5.2. Semi-log plot of major ions concentration

In the case of groundwaters sodium is the dominant cations and bicarbonate followed by chlorine is the dominant anions. 75% of the total groundwater samples collected in the area have concentration range of sodium and range of bicarbonate between 60-300 mg/l and between 200-600 mg/l respectively (Fig 5.2). In the groundwater samples variations in the anion concentrations are larger than the variations in the cation concentrations.

In the case of lake waters sodium is the dominant cation, and bicarbonate and chlorine are the dominant anions.75% of the total lake water samples collected in the study area has sodium concentration between 3000-6000 mg/l, chloride concentration between 2000-3000 mg/l and bicarbonate concentration range of 9000-12000 mg/l.

The river waters have highly variable ionic composition. The particular feature of river waters is their uniformity of anions concentration (bicarbonate) and large variation in cations unlike that observed in the boreholes and lake waters .The magnesium concentration is not more than 30% of the total cations. (Na+K) and calcium is also always less than 80% of the total cation concentration .Large variations are found in the calcium and magnesium concentration (Tenalem Ayenew, 1998).

Therefore there is a high variation of dominant cation and anion species both in groundwater and surface water samples. This ionic variability reflects the existence of different hydrogeological regimes and helps to trace groundwater flow paths in the study area. The majority of the lake water samples show enrichments in dominant cation (sodium) and anion (bicarbonate) as compared to the large number of groundwaters in the area.

5.1.2.2. Water types and groundwater flow

Fig 5.3 shows the piper diagram for water type classification based on the concentrations of major cations and anions for samples of different water bodies: cold springs, hot springs, hand dug wells, cold boreholes, geothermal wells and lakes. The majority of the sample waters have cations distributed along a straight line which oriented down to right bottom apex of the small cation triangle and the anions are distributed along a horizontal line at the bottom of the small anion triangle.

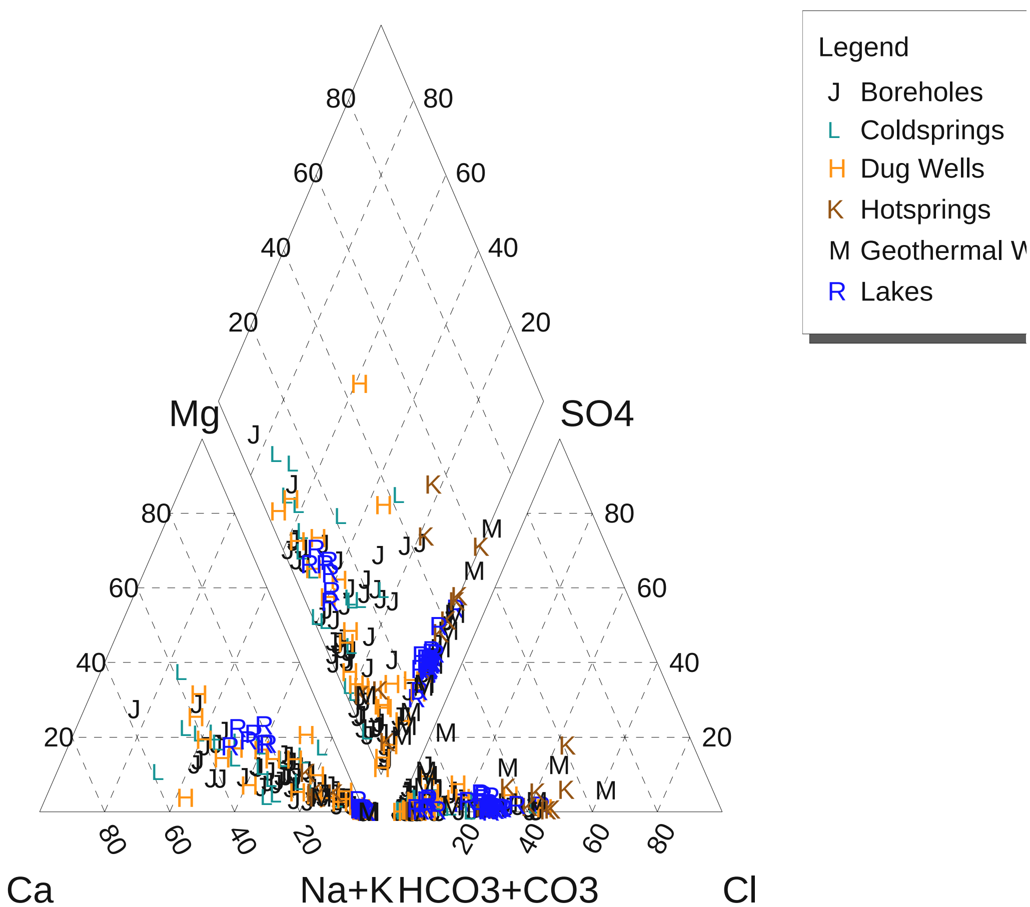


Figure 5.3. Piper plot of different water bodies (Relative % meq/l)

I.Highland and escarpment waters

The majority of the cold springs, dug wells and boreholes from the highlands and escarpments are Ca-Mg-HCO_3 type and Na-Ca –HCO_3 type in the piper plot and they are low TDS waters (Appendix 3). In the general groundwater chemical evolution model (Plummer et al., 1990; Adams et al., 2001; Edmunds and Smedley, 2000), these types of waters are often regarded as recharge area waters which are at their early stage of geochemical evolution. Rapidly circulating groundwaters which have not undergone a pronounced water–rock interaction may also have similar characteristics.

Unlike the rift floor hot springs, hot spring labeled 103 and 104 are located on the western highlands and are Na-HCO_3 type waters. These hot springs have similar chemical composition as the hand dug wells on the western highlands (number 19, 86, and 87) and boreholes and cold springs on the western escarpment (number 28 and 78 respectively).This shows that hot springs on the western highlands are recharged by shallow groundwaters. This is evidence to suggest that the geothermal system in this area is different from those of the rift.

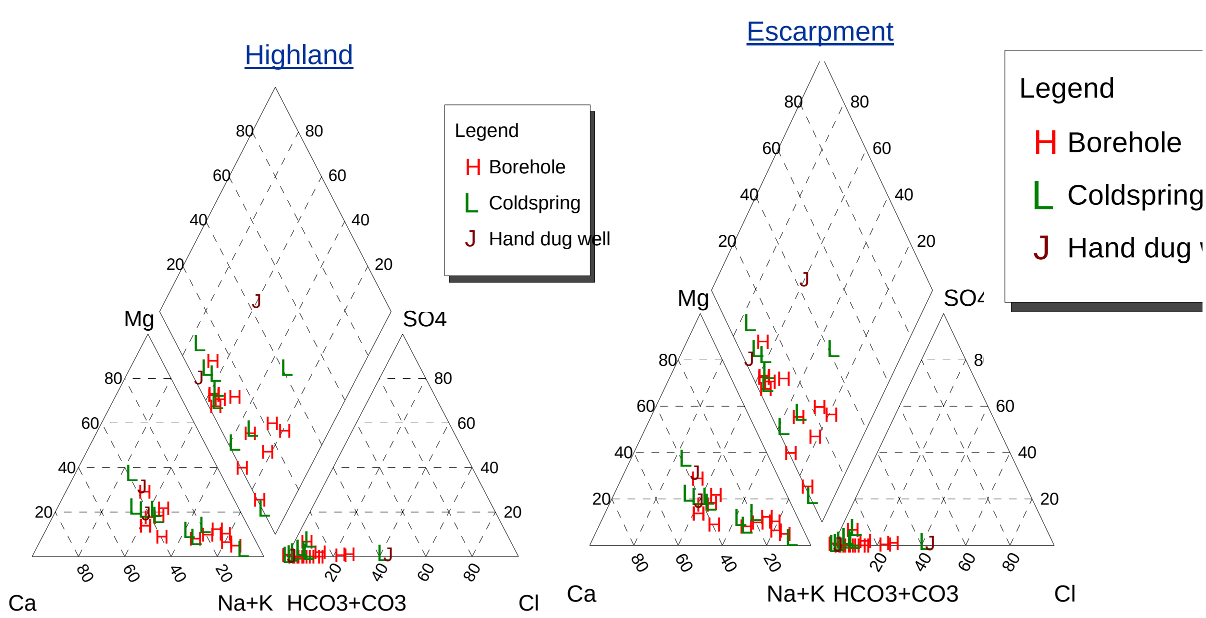


Figure 5.4. Piper plot of highland and escarpment waters

II.Rift floor lake waters and groundwaters

The lake waters are plotted in two separate positions on the piper plot (fig 5.3). The first group of lake sample positions on the piper plot represents the fresh lake Ziway waters. The dominant cation in lake Ziway waters is sodium followed by calcium and magnesium, and the dominant anion is bicarbonates. These lake waters fall in the Na–Ca-Mg-HCO_3 type in the Piper plot.

In the second position on the piper plot are lake Langano, lake Abiyata and lake Shala waters. In these waters the dominant cation is sodium and the dominant anion is bicarbonate followed by chlorine. They have relatively very high sodium concentration (more than 95%) and lower bicarbonate concentration as compared with lake Ziway waters. These types of waters are classified as Na-HCO_3-Cl type water.

In the majority of waters from the rift floor boreholes, cold spring and dug wells; sodium dominate their cation species and bicarbonate dominate their anions. These groundwaters fall in the Na–HCO_3 type in the Piper plot and most of them have moderately high TDS.

Some wells and cold springs show a similar hydrochemical signature to the nearby lake waters. Boreholes (number 46 and 4 on Fig 5.1) have similar chemical composition (have similar water type) as the lake Ziway waters. This shows that there is interconnection between the rift cold groundwaters and the lake waters.

The hydrochemical signature similarity is also evidence for the subsurface migration of lake waters and the subsurface interconnection between the lakes. Boreholes (number 9 and 67) and cold springs (75) have similar water types as the lake Ziway. This clearly indicates that there is a southward migration of waters from lake Ziway towards lake Abiyata and lake Langano parallel to Bulbula river. The chemical composition of borehole waters (number 37, 109 and 115) between lake Abiyata and Langano is similar for the nearby lake waters. This shows that there is flow of waters from lake Langano to lake Abiyata along the NE-SW trending fault. From this it is possible to conclude that the faults play role in groundwater flow between the lakes in the area and mixing of shallow groundwaters with the deep circulating thermal waters.

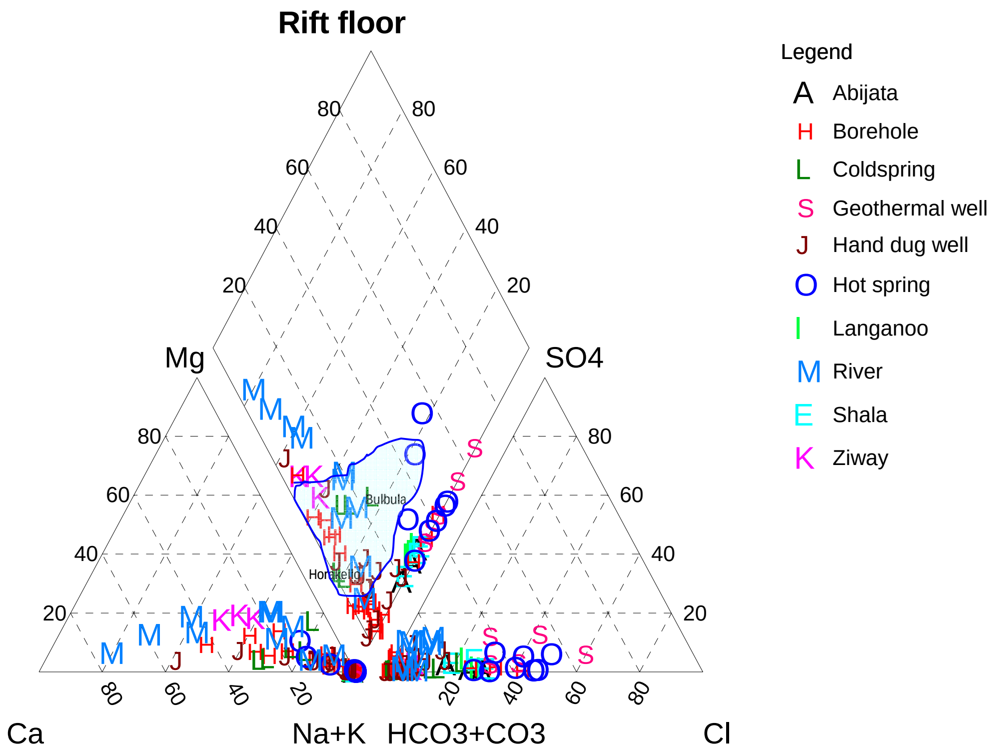


Figure 5.5. Piper plot of rift floor waters

(Closed area shows overlap of waters similar to highland and escarpment waters)

In all hot springs and geothermal well waters, sodium is the dominant cation (concentration more than 95%).In the majority of hot springs bicarbonate followed by chlorid are the dominant anions. These waters fall in Na-HCO_3-Cl type and are located in the rift floor near the lakes. The geothermal well north of lake Langano (number 101) has different chemical composition (water type) from the others. This is probably that the waters are mixed with shallow groundwaters through the fracture belt.

Classification of waters using the diagram shows the majority of surface water and groundwater samples have sodium and bicarbonate as dominant cation and dominant anion respectively. Sodium is usually derived from acidic volcanic sequences having high sodium feldspar (Hem, 1970). Fourinier & truesdell (1970) suggested that in geothermal systems most of the bicarbonate and part of the sodium and potassium are produced by the reaction of dissolved carbon dioxide with the rocks to produce mica or clay minerals and bicarbonate ions. Surface geochemical surveys of the Ethiopian rift (UN, 1973) also suggest a similar mechanism for the production of high bicarbonate concentration in waters according to the reaction:

$$CO_2 + H_2O + Na,K\text{ –silicates} \leftrightarrow HCO_3 + Na,K,\text{ H-silicate}$$

5.1.2.3. Spatial distributions of the major ions compositions

The wide spatial variations of the hydrochemistry of natural waters in this study has clearly demonstrated by preparing Stiff Pattern plots on the map using all scattered hydrochemical data in the study area (Fig 5.6). Stiff patterns visually allowing us to trace the flow paths on map (Stiff, 1995).

Fig 5.6 shows that there is clear systematic spatial variation in the major cations and anions concentrations of groundwaters (listed in Appendix 3) following the regional groundwater flow directions. The difference is due to the rock-water interactions (related to lithology and groundwater residence time), and the structural and geomorphologic settings.

The evidence that the systematic variations along the flow paths related to reactions between groundwater and the rock provides the hydrochemical evolution model for the area. In the area ionic composition of the water samples induces relatively variable chemical evolutions; waters are calcium, magnesium, sodium and bicarbonate dominated for the diluted waters on the highlands and the escarpment, and become sodium and bicarbonate dominated with a chloride increase for most concentrated waters in the rift valley (see the large symbols on the hydrochemical map). All the chemical evolution is towards a greater amount of sodium. The relative size of the stiff symbols on the highland and in the rift valley on the map demonstrates this evolutionary history (Fig 5.6).

On Fig 5.6 the sizes of the stiff symbol (which corresponds with the ionic concentration in the waters) is used to show the groundwater flow pattern in the area. The variation in the symbols size is related with the variations in the major ionic compositions of groundwaters. The increasing trend in the size of the symbol from the northwestern highland towards lake Ziway indicates the groundwater flow from the highland to the lake. The same trend also shows migration of groundwaters from the western and southwestern escarpments in to lake Abiyata and lake Shala respectively. The trend south of lake Shala in the rift may be due to the groundwater inflow from adjacent Awassa basin.

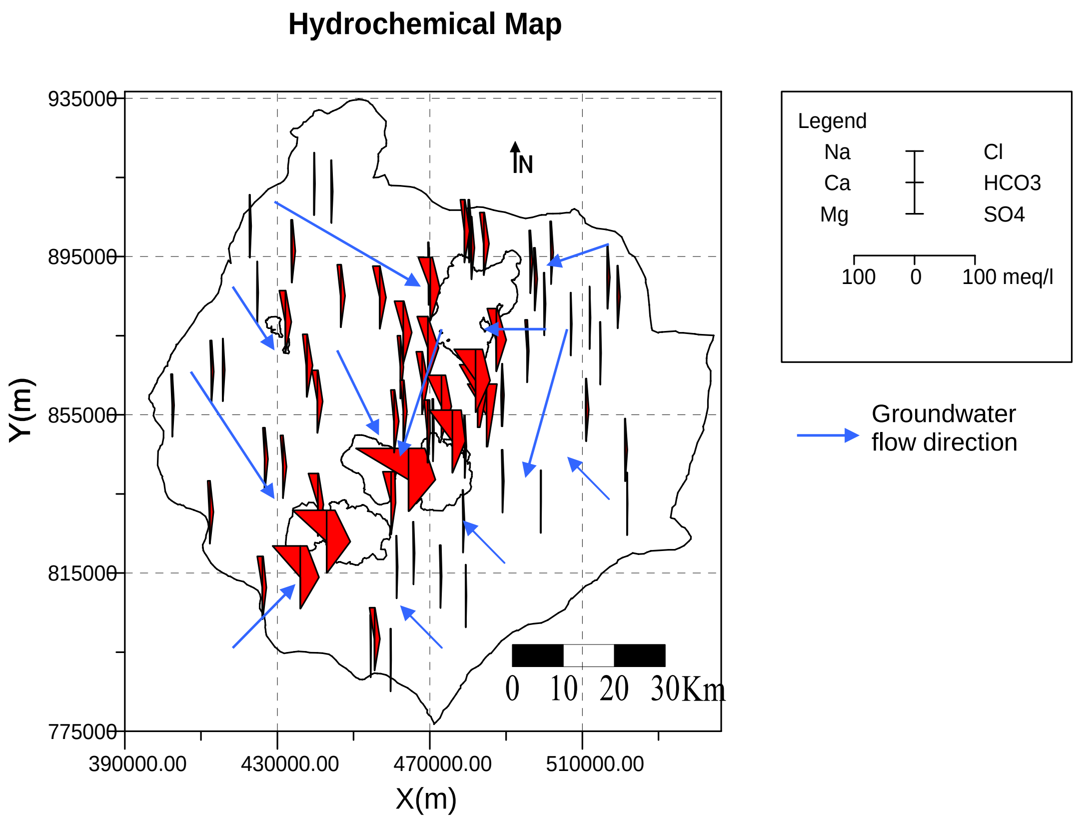


Figure 5.6. The distributions of major cations and anions in groundwaters

The sizes of the stiff symbols (Fig 5.6) are almost uniform on the eastern highlands & escarpments, and also in the rift east of Ziway unlike the sizes on the west and in the rift floor. This similarity is due to homogenous concentration of cations and anions species in a large number of samples from the eastern part of the area. These isoconcentration symbols in the eastern escarpments and in the rift east of Ziway shows that there is fast circulations of groundwater aligned parallel to the NNE-SSW and the N-S striking Wonji Fault Belt (Fig 5.6) possibly in to lake Langano and Shala and hot springs near Langano and Shala. This is evidenced in the major ion chemistry of section 5.1.2.3.

In the rift valley the symbols are relatively larger (Fig 5.6) this is due to the high residence time and high ionic concentration of the rift water (this is supported by the high EC values of rift groundwaters (see Fig 5.7). There is a general increasing pattern of the symbols aligned in NE-SW direction shows an increase in ionic concentration along the southward flow of groundwater in the rift. There is migration of groundwaters from the north in the area to lake Ziway. There is also a general subsurface interconnection of the rift lakes. Groundwaters flow from lake Ziway to Langano. Except in some places between Ziway and Abiyata (small symbols in the rift or low ionic concentration), there is subsurface flow from Ziway to Abiyata. The exception is due to groundwater flow through palaeochannels along Bulbula river which connects lakes Ziway and Abiyata (Tesfaye Cherenet, 1982; Tenalem Ayenew, 1998). There is also flow from Abiyata to Shala.

5.1.2.4. Electrical Conductivity

A map which shows the spatial variations of EC was prepared (Fig 5.7) based on point measurements of EC of river waters, lake water and groundwaters (Appendix 4).On the map generally, there are clear zonations in EC of natural waters following the rift ward direction. These zones correspond to the physiographic and geologic settings of the study area.

On Fig 5.7 the sharp increase in EC towards the rift implies that there is a general groundwater flow from the highlands towards the rift valley. The EC also varies within the rift waters which show the southward flow in the rift. The arrow symbols are vector maps prepared using surfer to show the regional groundwater flow from high EC to the lower. The regional flow system supports the results of major ion traced flow path.

Generally in the highlands and partly in the eastern transitional escarpments the EC of waters is less than 150 µS /cm. In the rift, waters from the lakes Shala and Abiyata, hot springs and other groundwater bodies have EC value more than 10,000 µS/cm.

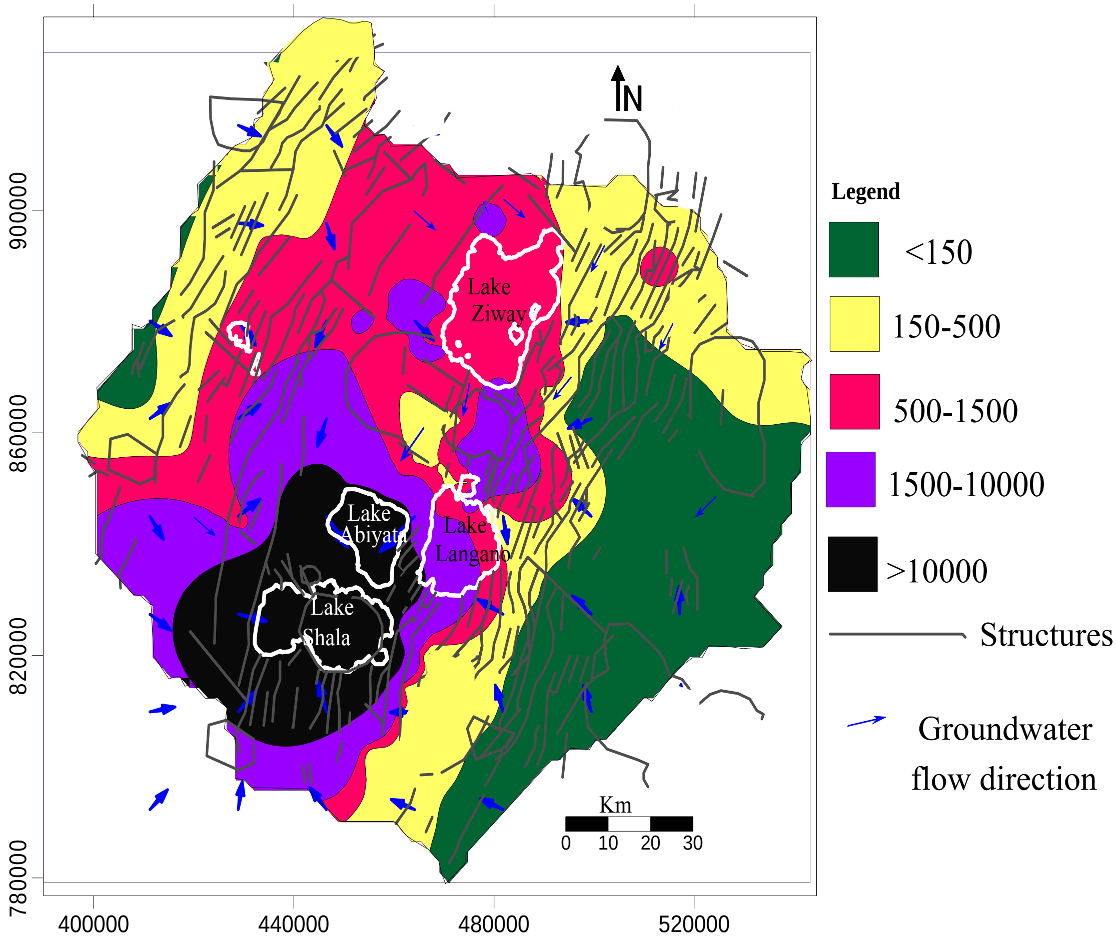


Figure 5.7. EC (µS/cm) distribution of surface waters and groundwater

The red dot on the north eastern rift floor is due to the locally high EC of deep borehole water (labeled f16 on fig 5.15).This is also supported by high depletion of tritium and 18O isotopes.

5.1.2.5. Fluoride

The inclusion of fluoride among the major solutes in natural water is arbitrary. Concentrations of fluoride are determined as a part of most water analyses, but concentrations present in most natural waters are small, generally less than 1.0 mg/l .In nature fluoride comes from chemical weathering products of igneous rocks, magmatic emission, atmospheric dust from continental sources and industrial pollution (Hem, 1970).

In the study area, the geothermal waters between lake Ziway and Langano show enrichment with fluoride this may be resulted from deep magmatic source. .The closed terminal lakes attain the highest fluoride concentration, salinity and alkalinity as a result of evaporation and the groundwater flux that comes from thermal wells.

The red circle on the north east of lake Ziway is due to locally high fluoride concentration of deep sourced boreholes. The relatively high fluoride on the western highland probably due to the mixing of cold spring (number 73 on Fig 5.1) with groundwaters circulating through the faults on the west escapement.

The spatial variations of fluoride prepared based on the existing and previous fluoride level in groundwaters and surface waters bodies (listed in Appendix 4) are illustrated by Fig 5.8.The figure shows that the rift valley waters are characterized by high fluoride which drastically increases as one goes down to the terminal lakes (for example 196 mg/l for lake Shala) The highland waters have relatively low fluoride content.

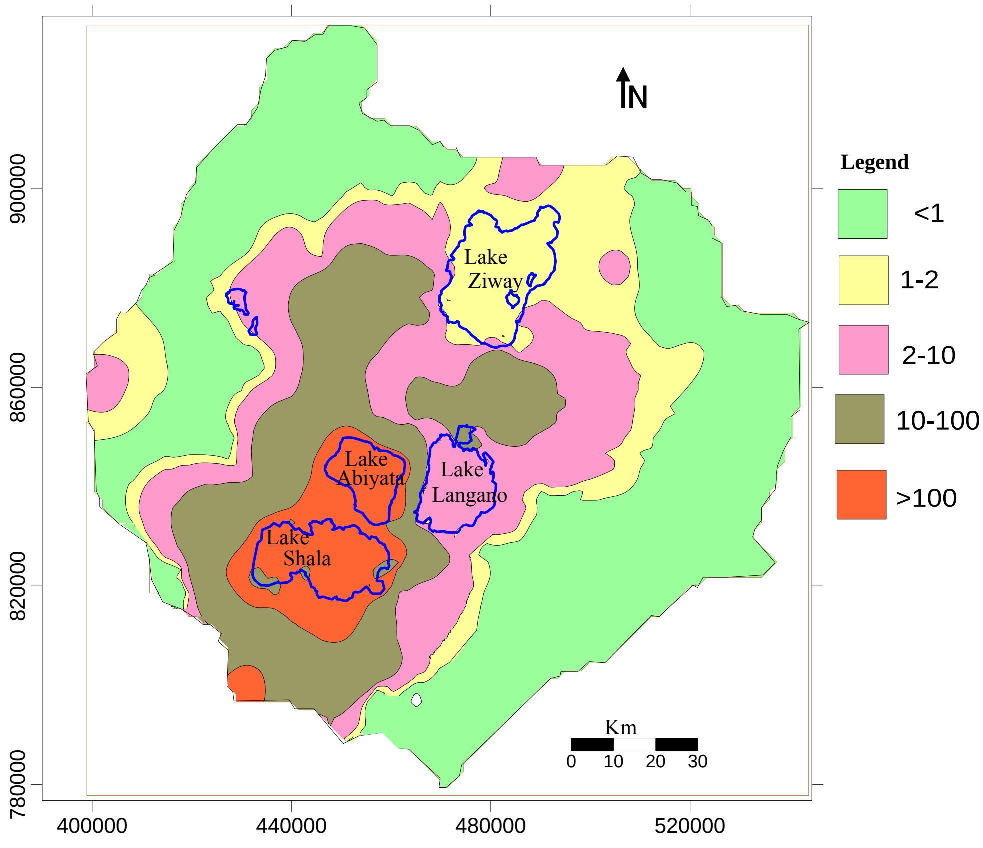


Figure 5.8. Fluoride Concentration map (mg/l)

Drinking water containing fluoride having a concentration of 1 ppm is considered ideal for dental health of children less than 10 years of age. The World Health Organization (WHO) guideline for fluoride in drinking water is 1.5 ppm. Concentrations above 2 ppm give permanently teeth a chalky-white appearance or mottled brown-satin coloration to children less than 10 years of age. Fluoride above 4 ppm in drinking water can cause a condition of dense and brittle bones, known as osteoporosis, or marble bones called skeleton fluorosis (WHO, 1984).

5.1.3. Statistical cluster analysis results and the spatial distributions of water types

5.1.3.1. Statistical clustering

To determine the different water types and their spatial variation associated with groundwater flow system 135 groundwater samples, of the total 211, are included for statistical classification of the hydrochemical data. The rest samples are excluded because they did not have full chemical analysis. Nine variables (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, HCO_3^{-1}, CO_3^{-2}, Cl^{-1}, $SO_4^{-\ 2}$, and TDS) were considered to classify the samples. Clustering the samples by using the Q-mode HCA technique resulted in a total of 2 major group and 7 subgroup waters which were selected visually from the dendrogram or tree diagram (Fig 5.9) which is the graphical output of the clustering. The subgroups were chosen from the dendrogram using an index of dissimilarity = 0.25 because at this index the 7 subgroups of waters that resulted were very clearly distinguishable in terms of their hydrogeological and hydrochemical variables.

The two major groups are distinguished by their TDS. Group-A waters have TDS less than 2000 mg/L. Group-B waters have TDS greater than 2000 mg/L. Group-A waters have 3 subgroups and Group-B waters have 4 subgroups. The seven subgroups have members from 91 wells, 19 cold springs, 12 hot springs, 5 thermal gradient wells and 7 geothermal wells (Appendix 3). Thermal gradient well water (TW6) was belonging to a single subgroup of one sample, which had an abnormally high calcium and sodium value, and was excluded from further analysis. It is also possible in HCA results that one single sample that does not belong to any of the groups or subgroups is placed in a group or subgroup by itself .This unusual sample is considered as residue (Gu¨ ler et al., 2002).

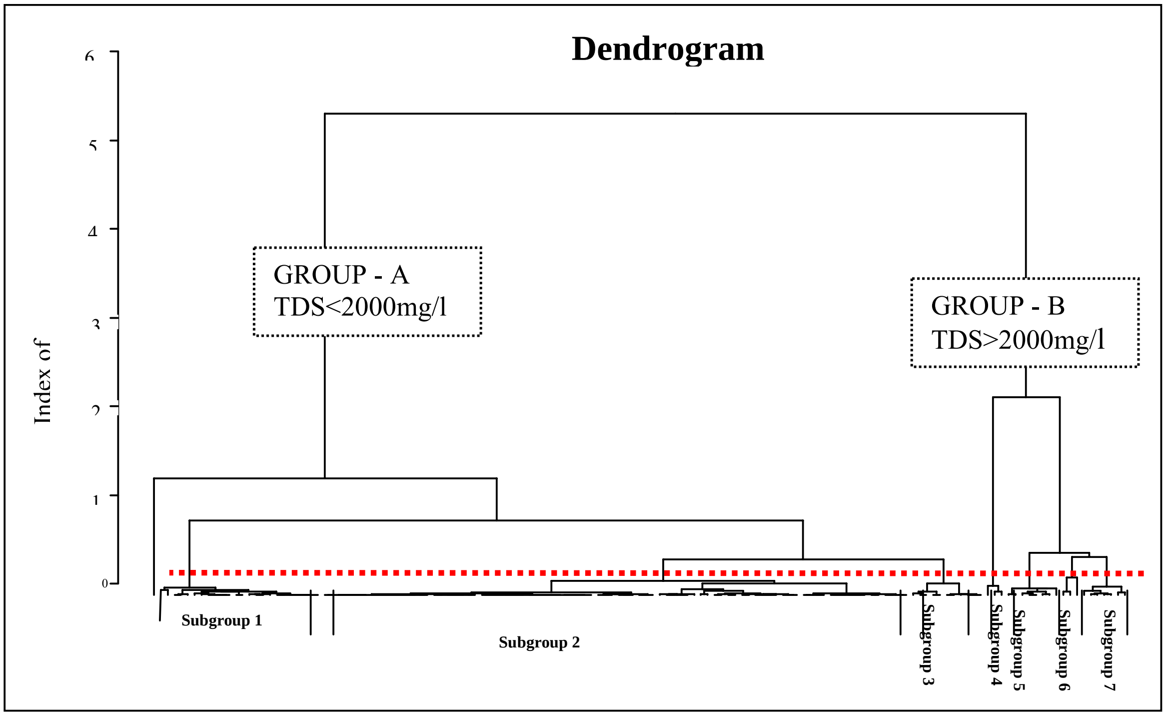


Figure 5.9. Dendrogram or tree diagram of the Q-mode hierarchical cluster analysis (HCA)

(The "phenon line" is chosen at dissimilarity index = 0.25 to select 7 Subgroups. The samples which belong to each subgroup are listed on Appendix_3).

The samples clustered under each subgroup and the average values for each of the physico-chemical composition for the 7 subgroups are presented in appendix 3 and Table4 respectively. The average values for each of the composition of the subgroups produced by the HCA analysis reveal trends between them and they are the basis for the distinction of the subgroups. Some of these trends show that there is a general trend of increment in Na value and decrement in Ca value as we go down in subgroups of group-A. For instance, subgroup-1 appears to be distinguished from subgroup-2 by the lower Na value (1.55 meq/l) and higher Ca value(0.98 meq/l) in turn Subgroup-2 differs from subgroup-3 by higher Na, K, Cl and TDS values and lower Ca value. Subgroups of group-B have almost nil Ca value and relatively high Na, HCO_3, and Cl values as compared to subgroups of group-A. These distinctions between subgroups are clearly shown on Figure 5.10. The good statistical coherence among mean values of the subgroups can be clearly explained in terms hydrochemical characterization of groundwater circulations, surfacewater-groundwater interactions and the human impact on water quality.

Table 5.1 Mean values (unit in meq/l) for groups and subgroups derived from HCA.
(Numbers in the superscript indicate the number of samples of the subgroup.TDS unit in mg/l.)

Group	Subgroup	Ca	Mg	Na	K	CO_3	HCO_3	Cl	SO_4	TDS
A	1^{27}	0.98	0.42	1.55	0.25	0.15	3.35	0.44	0.08	332
	2^{76}	0.43	0.26	3.86	0.31	0.07	4.57	0.49	0.09	475
	3^{11}	0.14	0.06	15.61	1.37	0.65	11.78	2.46	0.13	1184
B	4^{3}	0.03	0.03	97.51	1.02	6.74	44.48	38.75	0.70	6538
	5^{8}	0.06	0.03	40.88	2.05	0.12	25.91	13.16	0.76	3351
	6^{3}	0.07	0.15	43.60	4.31	1.08	22.18	13.09	3.71	3249
	7^{7}	0.06	0.02	28.27	1.11	0.26	21.47	2.48	2.99	2441

5.1.3.2. Discussion

1) Subgroup-1

This subgroup consists of waters from 8 boreholes, 12 cold springs, 5 handdug wells and 2 hot springs in the study area. The large number of members is located on the highlands and the transitional escarpments (Fig 5.12). They are low TDS, Na-Ca-HCO_3 type waters on the piper plot (Fig 5.11a). In this subgroup most of the highland cold springs have Ca dominates the other cations and they have very low TDS .In general groundwater evolution model ((Plummer et al., 1990;Adams et al., 2001; Edmunds and Smedley, 2000) these types of water represent early stage of geochemical evolution of young meteoric water or recharge areas water.

The two hot springs associated with faulted areas have high sodium and bicarbonate content but low TDS and they are plotted at the separate location on the subgroups piper (Fig 5.11).They also have relatively higher calcium comparing with the other hot spring. These hot springs are located in the rift valley at northern bay of lake Langano (Tuffa area). Hot spring labeled 22 has high chloride content probably mixing with deep geothermal waters. Hand dug wells north of lake Ziway which have very high calcium and magnesium are grouped in subgroup-1. The high content of calcium and magnesium is due to the recharge of the well which is composed of irrigation drainage waters. High calcium wells are found nearby the rivers in the area, which indicated that these wells probably get higher amount of recharge from the rivers (Haile Gashaw, 1999).

2) Subgroup-2

The majority of the samples used for analysis are members of this subgroup. They are collected from 49 boreholes, 7 cold springs, 15 shallow hand dug wells, 3 hotsprings, 1 geothermal and 1 thermal gradient wells. Samples of this subgroup are located in the rift valley and partially in the eastern escarpments with the exception of the hot springs which are located on the western escarpments. These groundwaters fall in the Na–HCO_3 water type in the Piper plot (Fig 5.11b). Subgroup-2 waters contain relatively high sodium content and very limited calcium and magnesium contents as compared to subgroup-1 waters. Fig 5.10 clearly shows the chemical distinction between subgroups. Previous study by Haile Gashaw, 1999 on the north part of the area around lake Ziway indicated that in the groundwater of the area sodium is the dominant cation due to high rock – water interaction, which is confirmed by higher values in wells within lacustrine sediments and lower values in welded ignimbrites and basalts. In this study the variations in sodium and calcium may show subgroup-2 waters have undergone chemical evolution as subgroup-1 waters flow through the geomedia.

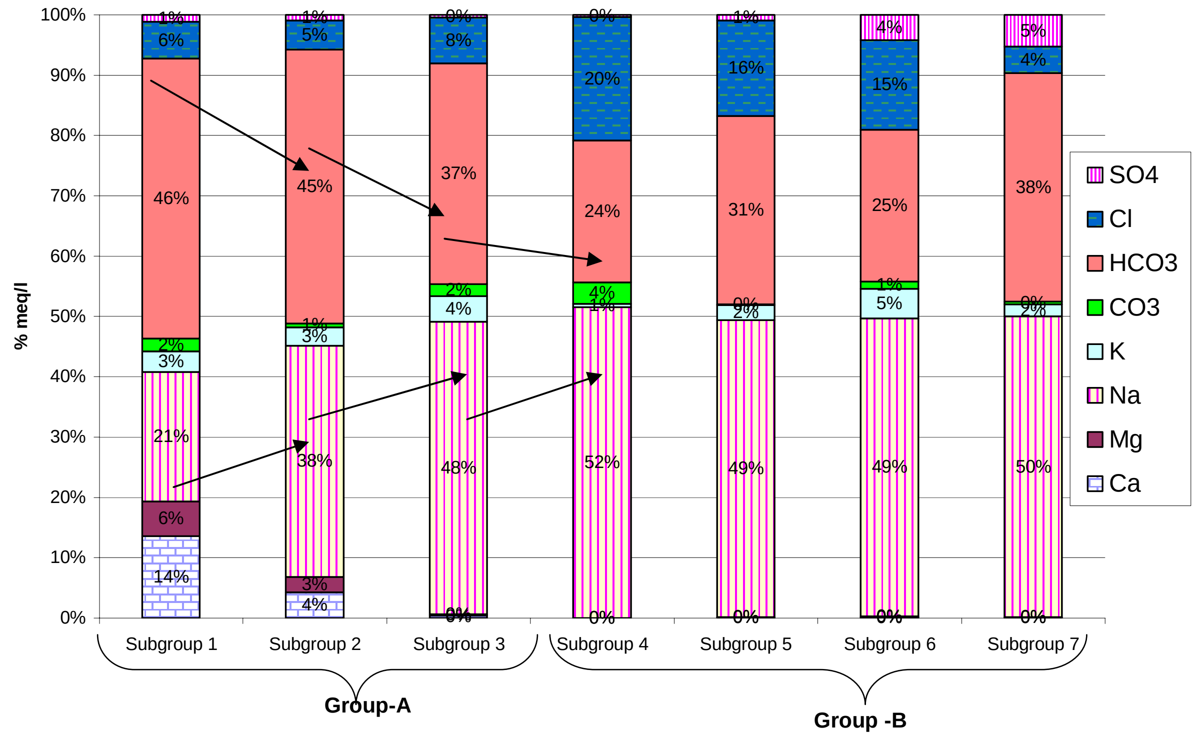


Figure 5.10. Collins bar diagram using subgroup mean defined by HCA
(The arrows indicate the chemical evolution or groundwater flow directions)

3) Subgroup-3

This subgroup contains 7 boreholes, 3 hand dug wells and 1 geothermal wells. They are located in the rift valley confined near the lakes and on the highly faulted areas. The high TDS groundwaters of this subgroup fall the more concentrated Na-HCO_3 type of water on the piper plot (Fig 5.11c).This is probably with further hydrolysis of silicate minerals by subgroup-2 waters, the concentration of Na and chloride increase but calcium becomes very low. The high TDS and the enrichment of sodium therefore testify that the thermal and the high TDS groundwaters have undergone a relatively pronounced degree of groundwater chemical evolution.

4) Subgroup-4

Members of this subgroup are a borehole south of lake Langano, and two hot springs at eastern side of lake shala. These waters are Na-HCO_3–Cl type waters on the piper plot (Fig 5.11d) and they can be classified as discharge area waters. The hydrochemical signature of these high TDS water (~6538 mg/l) is similar to that for many geothermal wells and hot springs this may indicate mixing in the course of their evolution.

5) Subgroup-5

Subgroup-5 waters contains 1 borehole south of lake Shala , 4 deep geothermal wells northern Langano, and 3 hot springs southwest of lake Shala and north of lake Langano. These waters are Na-HCO_3-Cl type waters on the piper plot (Fig 5.11e) and have very high chloride content. These waters can be from deep system. Ellis, 1970; Arnosson et al., 1978 indicate that high chloride concentrations are usually associated with high temperatures. However, high chloride can also be associated with seawater mixing, steam separation or evaporation. At depth, the chloride concentration generally increases with temperature.

6) Subgroup-6

Members of this subgroup waters are 2 geothermal wells and one hot springs located in north of lake Langano. Subgroup-6 waters fall in the Na-HCO_3-Cl type waters on the piper plot (Fig 5.11f).Thy have relatively high potassium and sulfate. These waters can be from deep system.

7) Subgroup-7

This subgroup contains 4 thermal gradient wells and 1 hot springs north of Langano, and two dug wells (labeled 129 and 130). Water type on the piper plot (Fig 5.11g) and spatial locations of the deep subgroup-7 waters have similarity to that of the deep thermal waters of subgroup-5 and 6.The difference is that subgroup-7 contains relatively high sodium and sulfate. The high sulfate content of subgroup-7 dug well waters is due to interaction of waters with the lacustrine sediments on Bulbula plain and southern west of lake Ziway. The high sulfate content may be partially due to the high bicarbonate content which depresses the calcium concentration .Calcium sulfate solubility is one of the factors controlling SO_4 content (UN, 1973).

5.1.3.3. Spatial Distributions of clusters (Water types)

The relationship between the statistically defined clusters of samples and geographic location was prepared by plotting subgroup values for each sample on the base map using ArcView GIS software (ESRI, 1999) (Fig 5.12). The seven subgroups are separated geographically, as well as physiographically with good correspondence between spatial locations and the statistical subgroups as determined by the HCA. Samples that belong to the same subgroup are located in close proximity to one another suggesting the same processes and/or flowpaths for this subgroup of samples. Subgroups which have small number of samples in an area are spatially located as a point data on the map (Fig 5.12).The high degree of spatial and statistical coherence suggests that the changes between the principal hydrochemical facies define the hydrochemical evolution of water in the region, this is testified by spatial distribution of major ions in the basin, section 5.1.2.3.

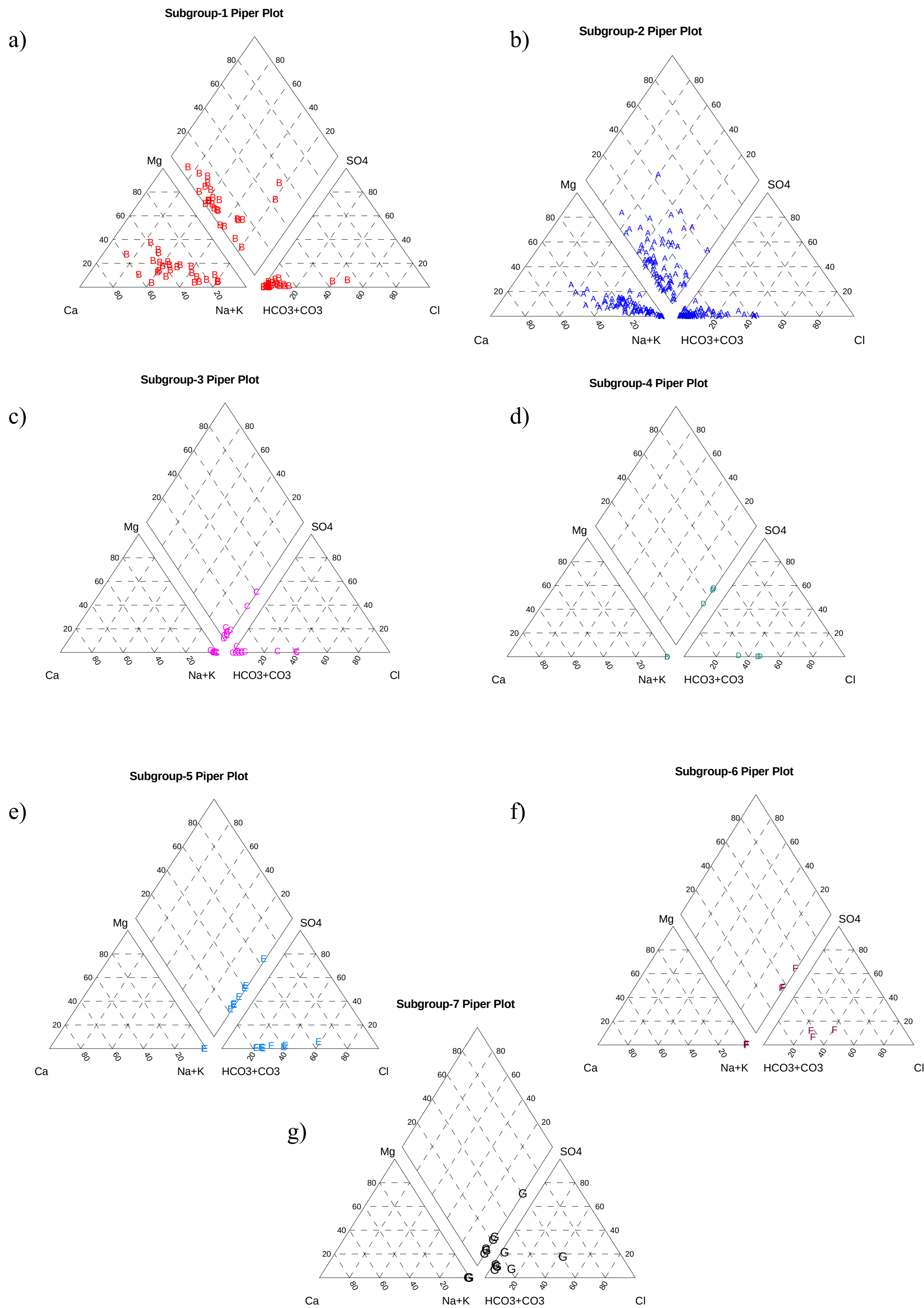


Figure 5.11. Piper Plots of the subgroups

The distinctions between the seven subgroup water samples and their water type are stated in discussion part, Section 5.1.3.2 and clearly shown on figure 5.10 and Fig 5.11. The seven principal hydrochemical facies are plotted on a Piper diagram to illustrate chemical differences between the subgroups and the geochemical changes along the topographic flowpaths (Fig 5.13).

Fig 5.12 shows that a large number of subgroup-1 water samples are clustered on the highlands and on the rift escarpments. Some samples of subgroup-1 are located on the densely faulted area north of lake Langano. The map also shows that the majority of subgroup-2 waters are located in the rift valley. Some members of this subgroup which have relatively higher TDS than subgroup-1 samples but spatially found on the eastern and western escarpment plotted as point data. The rest subgroup-3, subgroup-4, subgroup-5, subgroup-6 and subgroup-7 water samples are located within the rift valley

In fact, most of the samples composing subgroup-1 are above 1750 m. Subgroup-2 samples (transition zone waters) are mostly located below 1750 m in the rift valley. Sugroup-3 samples (discharge area waters) are all located on the rift floors, and specifically between subgroup-2 and subgroup-4.Subgroup-4 waters (discharge area waters) are sandwiched by subgroup-3 waters at the densely faulted area between lake Langano and Ziway and around the saline lake Shala. Subgroup-5, Subgroup-6 and Subgroup-7 samples are mainly situated where geothermal waters and hot springs are pronounced in the rift valley.

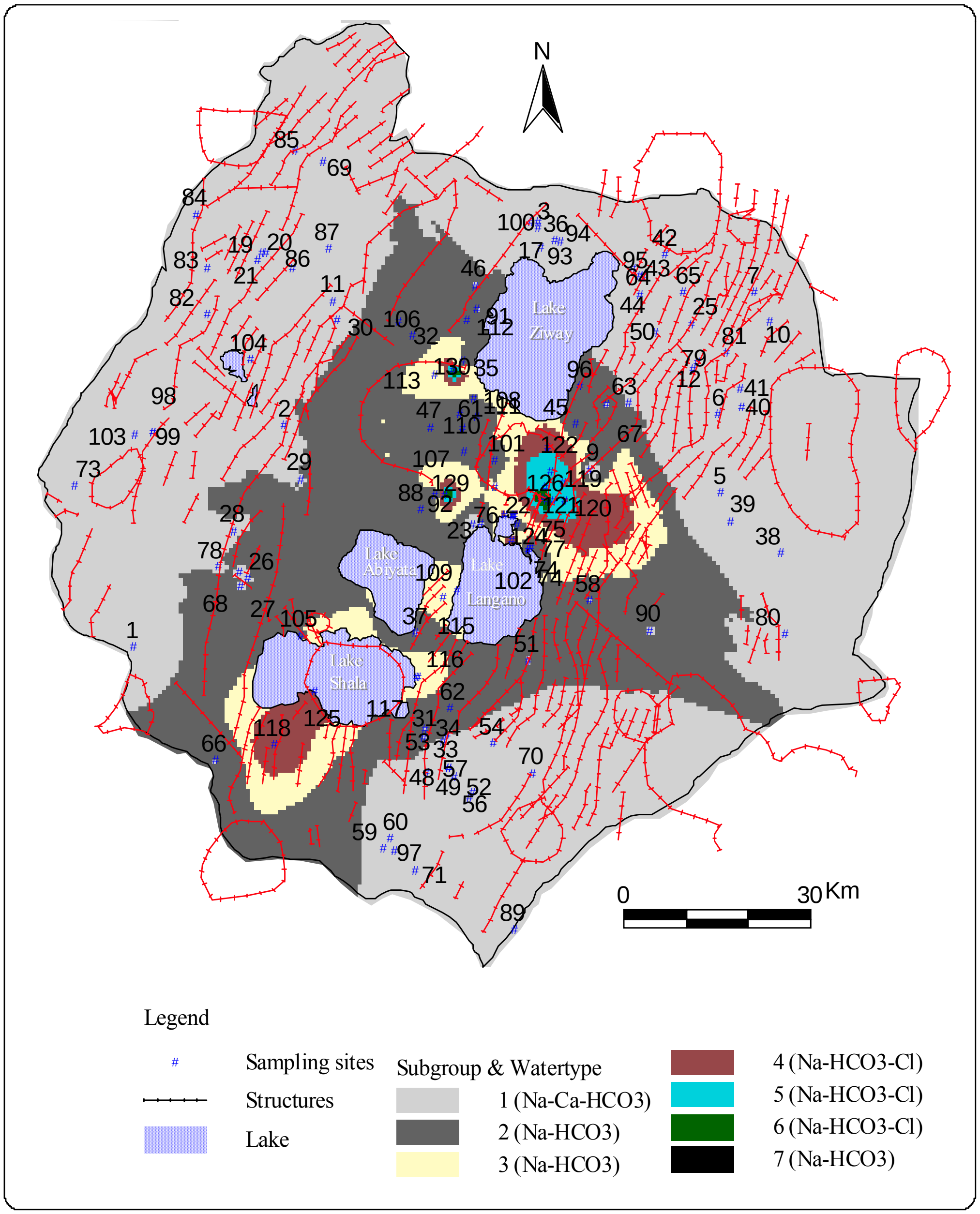


Figure 5.12. Spatial distribution of the HCA derived subgroups for groundwater

5.1.4. Hydrochemical evolution

The TDS of subgroup-1 waters are low which indicates that subgroup-1 waters are recharge area waters and increases as the water moves into the rift where subgroup-2 waters are situated. Subgroup-3 waters have high TDS (average~1184 mg/l) which increases to the highest TDS of all the subgroups (average ~6538 mg/l) as it moves to subgroup-4 waters are located which indicates that subgroup-3 and subgroup-4 waters are discharge area waters. Subgroup-2 waters are situated between the recharge area waters and the discharge area waters.

Groundwater in the recharge area evolves from a dilute Na -Ca– HCO_3 water (1: average TDS is ~332 mg/l) to a fresh Na–HCO3 water (2: average TDS is ~475 mg/l) to a more concentrated Na–HCO3 water (3: average TDS is ~1184 mg/l) to a brackish Na–HCO_3-Cl water (4: average TDS is ~6538 mg/l) along the topographic flowpath (Table 4 and Fig 5.12 and Fig 5.13. Overall, the waters from the area can be classified as recharge area waters (Subgroup-1), transition zone waters (Subgroup-2) and discharge area waters (Subgroup-3 and Subgroup-4).

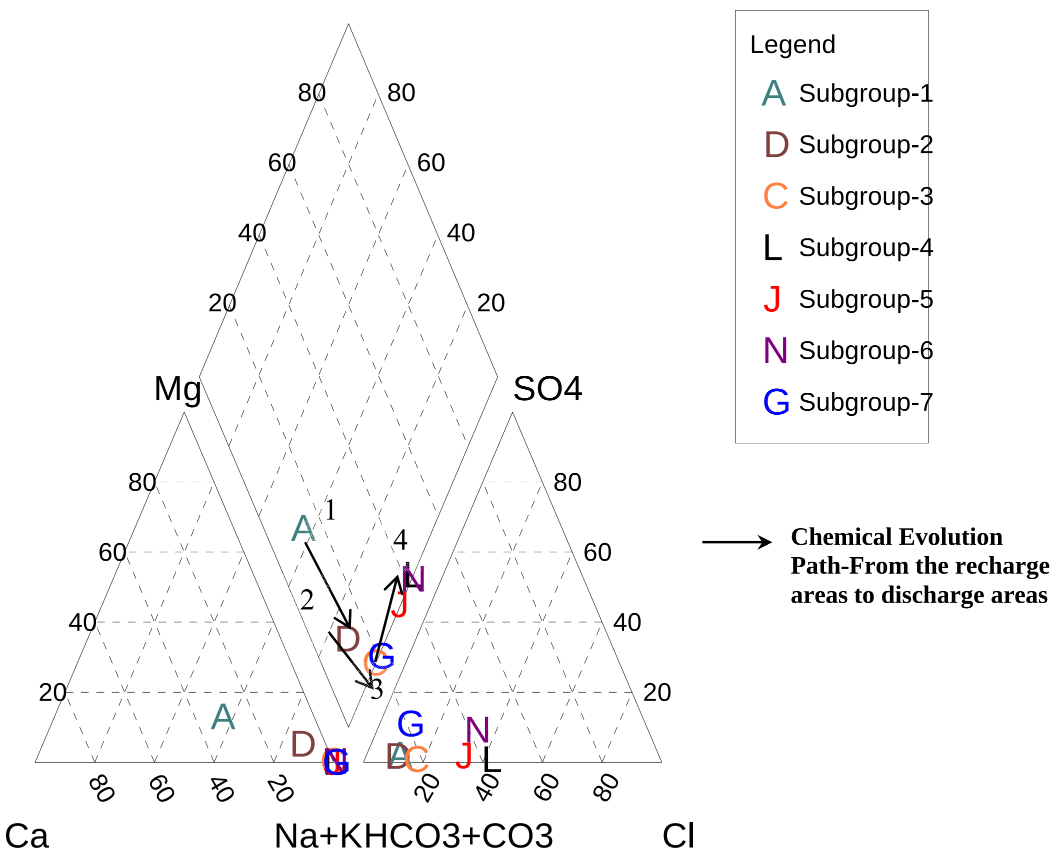


Figure 5.13. Piper plot of the chemical evolution of groundwater in the study area

(Starting from highland and escarpment waters and ending with rift floor waters ; 1→2→3→4). Total dissolved solids (TDS) concentration increases with increasing subgroup number.

Plotting the principal hydrochemical facies on the site map (Fig 5.12) shows that the subgroup-1 (the recharge area) waters are mainly located in the highlands and escarpments. In Appendix3 cold spring samples of subgroup-1 waters (average TDS is ~200 mg/l) reflect the short groundwater flowpaths for the low TDS (dilute) waters. Recharge to these springs probably occurs via fault and/or fracture controlled shallow groundwater flowpaths. Rainwater chemistry is important here to confirm that precipitation form the main source of direct recharge in the highlands. The low TDS (dilute) cold spring waters of subgroup-2 samples in the rift floor indicates the occurrence of local recharge through faults.

On Fig 5.12 the spatial settings of subgroup-1, subgroup-2, subgroup-3 and subgroup-4 represent the continued evolution of water chemistry between recharge and discharge zones.

5.1.5. Hydrochemical variation in relation to groundwater –lake water interaction

The hydraulic connection between the large rift lakes in the study area and their relationships with groundwaters have been studied and testified using the spatial distributions of the major ions compositions of groundwaters and lake waters in section 5.1.2.3. Here further investigation on the chemical relationship between the statistically defined subgroup waters (groundwaters) and the lake waters have been concerned to identify the interaction between the groundwaters to lake waters, the interconnection between lake waters and source of waters.

The geochemical evolution of natural groundwaters tends to change from the carbonate type to the sulphate type and then to chloride type as goroundwater moves from recharge to discharge areas in large drainage basin (Toth, 1963). The other author (Chebotarev, 1955) also stated that groundwater tends to evolve chemically toward the composition of seawater. This evolution is normally accompanied by the following regional changes in dominant anion species.

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

Generally this chemical evolution in the study area is shown by plotting the relative proportion (dominance) of the major anions (HCO_3 and $Cl+SO_4$) with the relative proportion of the dominant cation (Na) in subgroup and lake water samples on the Ludwig Langlier plot (2003) (Fig 5.14).

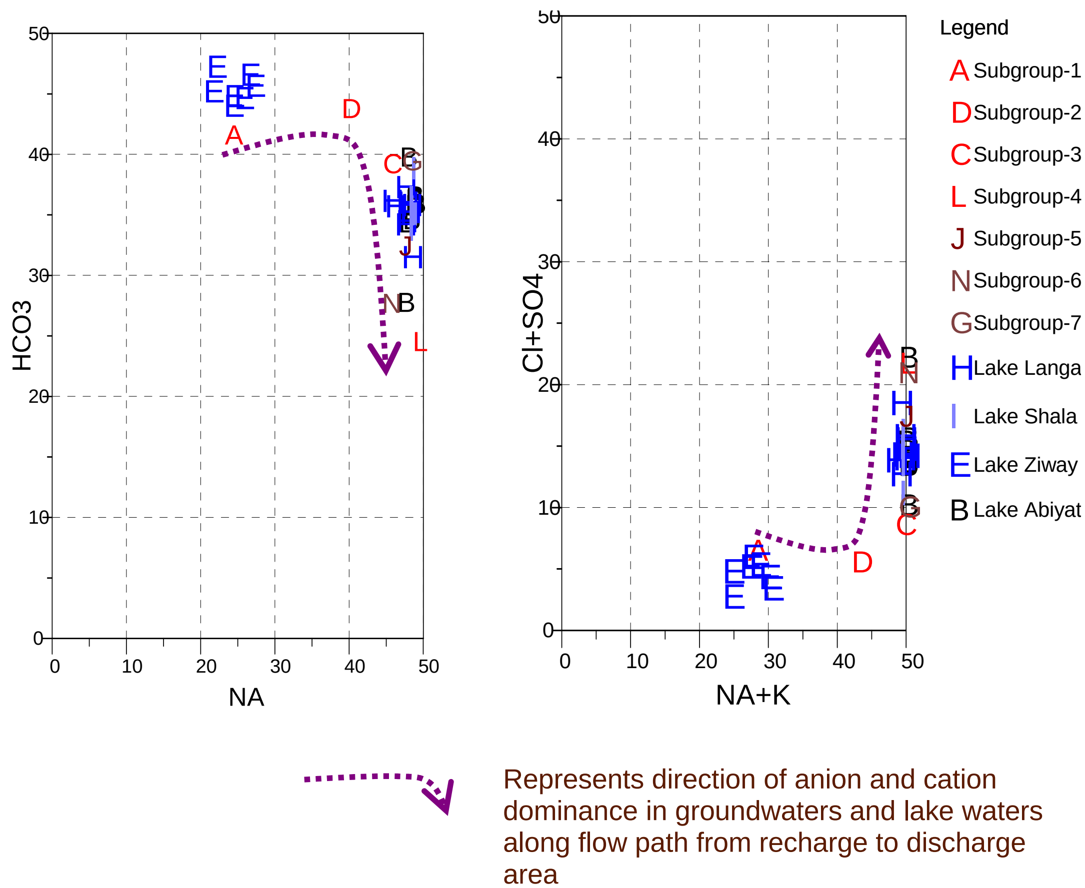


Figure 5.14. Relative proportion of major anions and cation

Fig 5.14a shows that in groundwaters in the area the proportion of bicarbonate than the other major anions generally decreases and the proportions of sodium than the other major cations increases as on goes from the recharge area waters (subgroup-1 waters) to the discharge area waters (subgroup-4 waters). Fig 5.14b shows chloride and sulphate proportion increase than the other anions following groundwater flow paths.

In both Fig 5.14a and 5.14b, lake Ziway waters plotted near the subgroup-1 (recharge area) waters which means they have similar ionic proportion that indicates the subgroup-1 waters are the source waters for lake Ziway waters. This shows that the interaction of the lake Ziway waters with the recharge area groundwaters. The dominance of bicarbonate in lake Ziway waters and subgroup-2 waters (mainly groundwaters in the rift) than the recharge area waters is suggested by UN, 1973 in section 5.1.2.2.

The rest low lying three lakes (Abijta, Langano and Shala) have ionic proportions similar to the subgroup-3 and/or subgroup-4 waters (discharge area waters) and subgroup-5 and/or subgroup-6 waters (geothermal well and hot spring waters). This shows that there are interactions between the lake waters with the groundwaters system and mixing of the lake waters with thermal waters. The interactions of these lake waters (which have similar ionic proportions) with the groundwater system can shows that there is subsurface interconnection between the lakes Abiyata, Shala and Langano.

There is also subsurface interconnection between lake Ziway with the other three lakes. This can shown by the hydrochemical evolution of subgroup-1 waters (have similar ionic proportion with lake Ziway) to the discharge area waters (have similar ionic proportion with lake Abiyata,Langano abd Shala).The presence of subgroup-1 coldsprings north of lake Langano can also show the southward migration of groundwaters.

5.2. ISOTOPE HYDROLOGY

5.2.1. Introduction

The environmental isotopes are the naturally occurring isotopes of the elements found in abundance in our environment and used to trace groundwater sources, recharge processes, geochemical reactions and reaction rates. In this study the environmental stable isotopes oxygen (^{18}O) and deuterium (^{2}H) and the radioactive isotope tritium (^{3}H) were used. The stable isotopes (^{18}O and ^{2}H) provide guide to groundwater recharge identification. The radioactive isotope (^{3}H) is used as a guide to the age of groundwater.

In this study the isotopes techniques together with hydrochemistry are used to asses the hydrogeological system of a chain of rift lakes in the study basin and will be used to support the results obtained from hydrochemical interpretation. All isotope analysis results for this research and the previous data of samples from different water bodies (wells, springs, rivers, lakes and rains) are given on appendix 7 and Fig 5.15 shows the sites where the isotopes are collected.

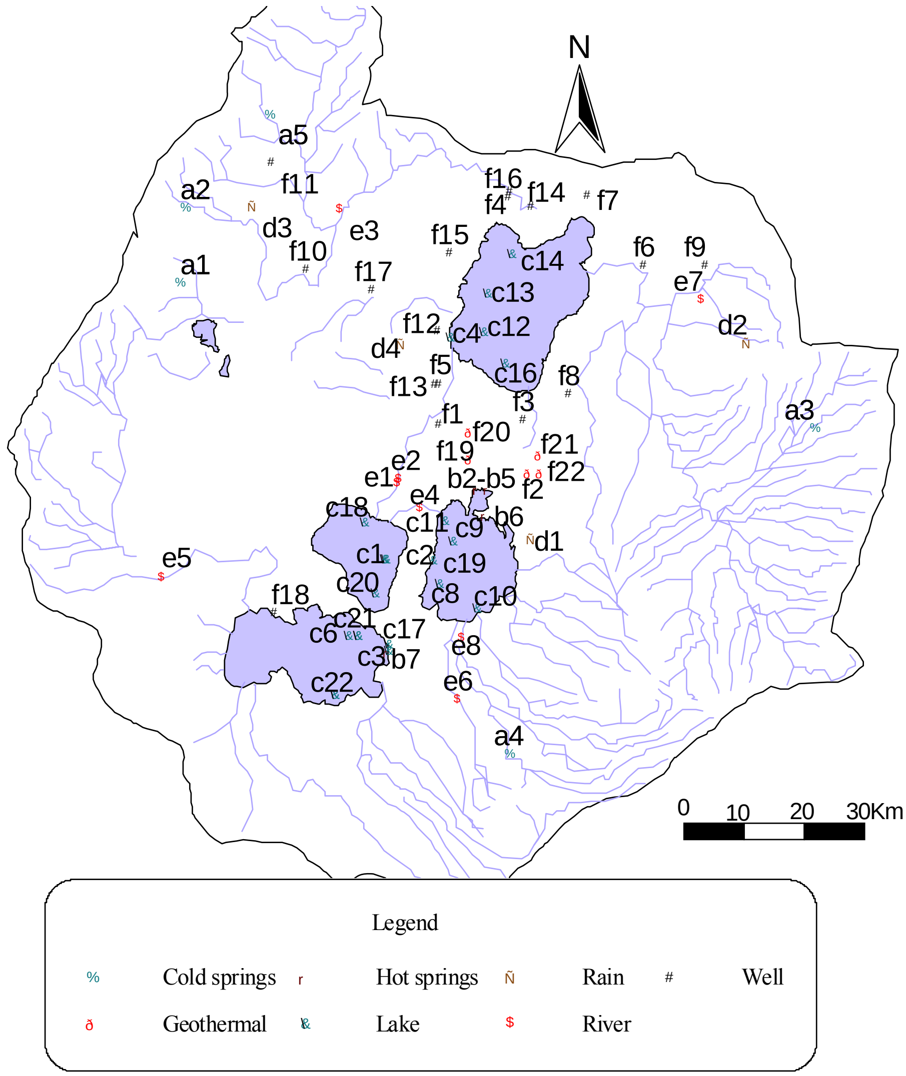


Figure 5.15. Water sampling sites for isotope analysis

5.2.2. Deuterium (^{2}H) and oxygen(^{18}O) isotopes

The Local Meteoric Water Line (LMWL), $\delta^{2}H = 8\delta^{18}O + 12.35$, established by Teclu (1995) for the adjacent Awash basin, has been applied to interpret the stable isotope. Fig 5.16 shows the composition of ^{18}O and ^{2}H of the different water types (rainfall, hot spring, cold springs, cold wells, rivers, lakes and geothermal wells). The isotopic concentrations for these waters are plotted by comparing to the global meteoric water line (GMWL) and the Local Meteoric Water Line (LMWL).

The LMWL is plotted above the GMWL this is due to the isotopic concentrations of precipitation in the study area has more deuterium excess (that is D excess=2.35) than the global averaged precipitations.

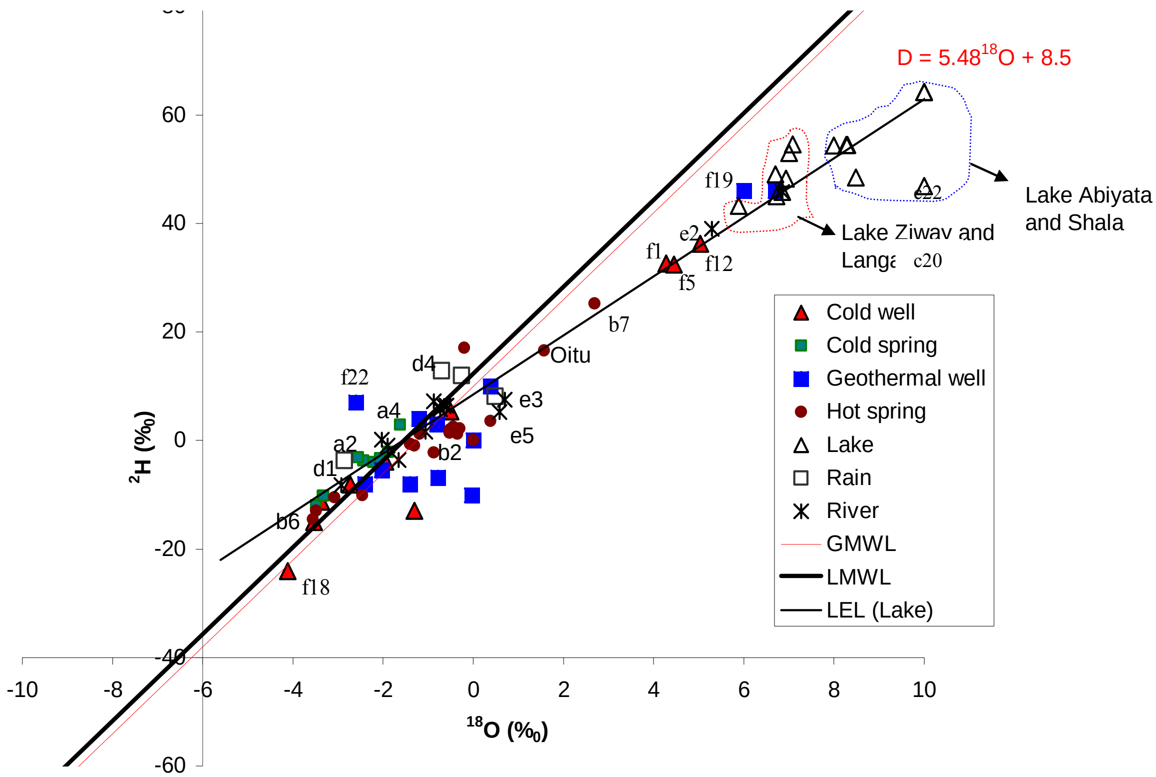


Figure 5.16. Isotope plot of the water samples

This figure has shown that the majority of groundwaters, river waters and rain waters are plotted near the LMWL .This indicate the importance of present day precipitation for groundwater recharge. The lake Waters are plotted far to the right and shifted right down of the LMWL .This shows that the lakes are more enriched with 18O and deuterium. Groundwaters (waters from hot spring, cold springs, cold wells, and geothermal wells) are scattered at different positions on the plot and have differences in ^{18}O and ^{2}H concentrations.

The variations of isotopic concentrations between groundwaters reflect the presence of different groundwater flow systems. The isotopes of the different water bodies in relation to the hydrochemistry are discussed in the following sections to understand the flow systems, interactions between groundwaters and surface water and to identify the origin of waters.

5.2.3. Analysis results from isotopes and hydrochemistry relationships

Scatter plots of hydrochemistry and isotope data for the different water types are prepared for interpretation of the isotope data in relation with hydrochemistry. Fig 5.17 shows the relations between oxygen isotope with electrical conductivity and chloride concentration in samples of different water bodies. The relations between radioactive isotope tritium with electrical conductivity and chloride concentration are shown in Fig 5.18. Isotope and hydrochemical data used for the preparation of the scattered plots are listed in Appendix 7 and the sample sites are shown on Fig 5.15.

I.**Rainfall**

The rainfall samples are not far from the LMWL and show slight variations. Normally rainfall labeled d1 on Fig 5.16 is expected to have a higher isotopic content under a single rainfall event than the rest rainfall samples. The sampling site for rainfall d1 (near lake Langano) might have more chance for evaporative enrichment than the other higher altitude rainfalls. However the difference is resulted probably from the time or season of sampling which have effect on the isotopic fractionations.

II.Lakes

Fig 5.16 shows the lake waters are plotted far to the right and shifted right down of the LMWL .This indicate that the lakes are more enriched with ^{18}O and deuterium resulted from substantial evaporative loss of the lake waters as compared to the present day precipitation. The terminal lakes Abiyata and Shala (labeled c20 and c22 respectively) are highly enriched with isotopes and shows high evaporation loss as compared to the other lakes in the area.

On Fig 5.17 the relationship between ^{18}O and Chloride concentrations shows the lake water labeled c12 (lake Ziway) has similar chloride concentration with the lake water labeled c9 (lake Langano). The ^{18}O enrichment in c9 is higher than c12.This is due to the high evaporation water loss from lake Langano. The geothermal water labeled f19 has similar ^{18}O enrichment but higher chloride concentration than lake Ziway waters (labeled c12).Lake waters labeled c13 has also similar ^{18}O enrichment and Cl concentrations with the geothermal water labeled f20. This shows that there is dilution of the geothermal water by the lake Ziway water. From this it is evidence to conclude that there is southward migration of lake Ziway waters towards lake Langano and mixing with the geothermal waters.

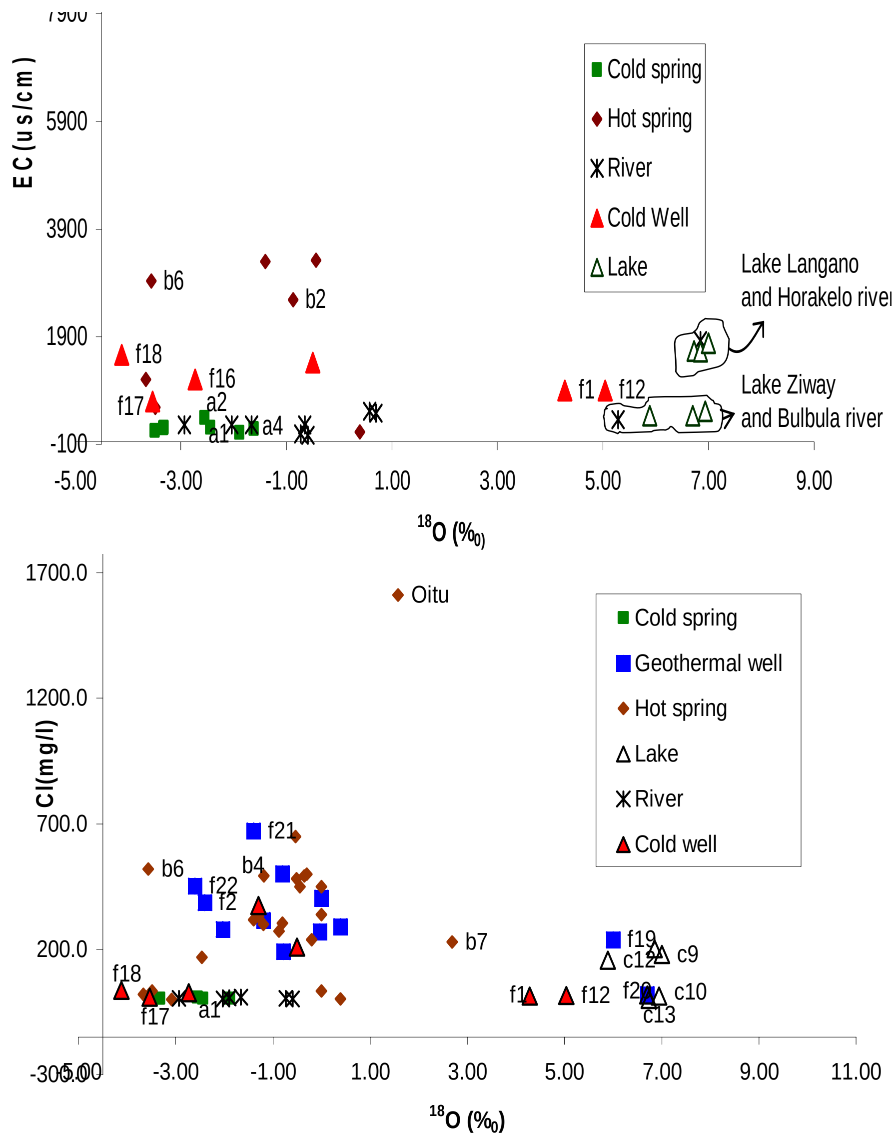
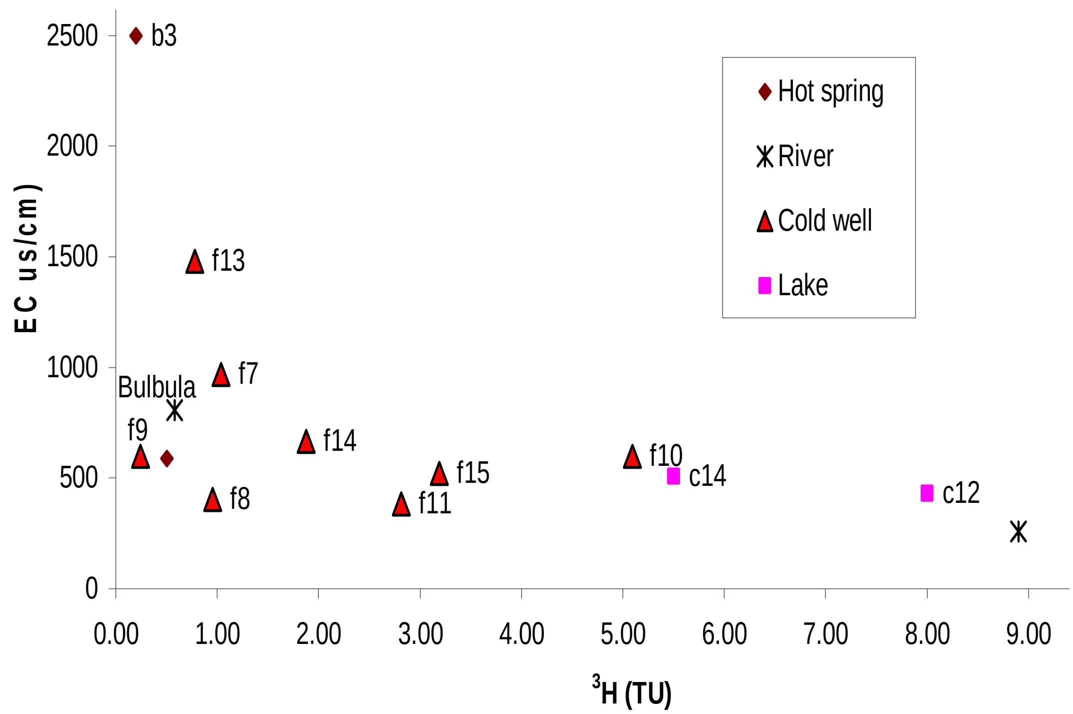


Figure 5.17. The relations of ^{18}O with EC and Cl



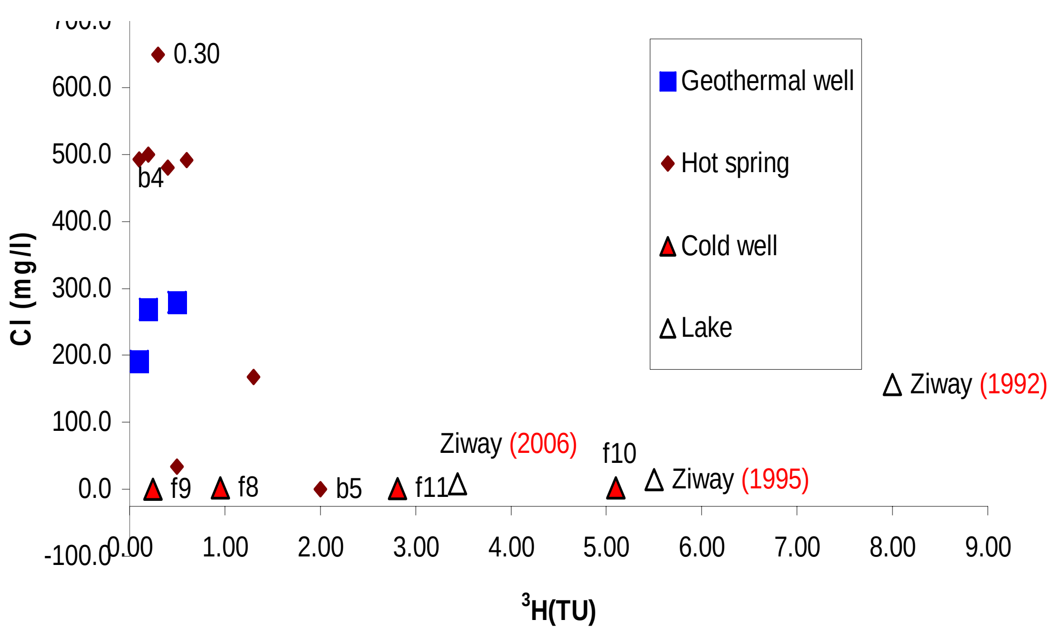


Figure 5.18. The relations of tritium with EC and Cl

III.Rivers

On Fig 5.16 it is shown that the majority of river waters are plotted near the LMWL. This indicates the absence of large evaporation and isotopic fractionation of river waters. The only exceptions are in the rift floor Bulbula river (labeled e2) which represents similar enrichment as the cold well (labeled f12) water and the nearby lake Ziway (5.89‰, 43.2‰) and Horakelo river (6.85‰, 45.8‰) which has similar isotopic composition to the lake Langano (6.73‰, 45‰) and the nearby geothermal well water (6.7‰, 46‰).This is supported by their EC values and chloride concentrations similar to cold well waters and lake waters (Fig 5.17).This shows that there is inflow of isotopically fractionated geothermal waters and shallow groundwaters in to the surface waters. Rivers on the escarpments (labeled e3 and e5) shows slight evaporation enrichment as compared to the enrichment of rivers in the highlands. Therefore it is possible to assume that there is slight evaporative enrichment as they drain long distances from the highlands to the rift.

IV.Cold springs

The plotting position of cold spring waters is similar to that of river, no far from the LMWL, indicating a non-evaporated meteoric origin. Generally, the isotopic signature of cold springs located at low altitude (labeled a4) is heavier than those located on the highlands (labeled a5 and a3). The only exceptions to this are samples collected far from the eastern shore of lake Langano aligned along a large marginal fault systems. These samples are depleted and have low EC as the precipitation (Fig 5.17).The low EC and depletion of these cold springs

V.Hot springs

The isotopic variation in ho springs are higher than any other groundwater body. The plotting position of hot springs shows different sources of water and variable mixing with shallow groundwaters and evaporated lake water. However, the majority of samples plot very close to LMWL indicating that the water comes from the non-evaporated recharge of precipitation.

Hot spring labeled b4 contains high chloride and very low tritium indicating that it is a old deep sourced water. The high EC value and very low tritium concentration in hot spring b3 indicates that it is presence of mixing with fault controlled shallow groundwaters and the lake waters.

VI.Cold wells

The shallow dug wells and boreholes show large isotopic variations. A cold well labeled f1 has slightly similar ^{18}Oenrichment and chloride concentrations with lake c12. The higher isotopic enrichment of c12 than f1 is due to evaporation. This may shows there is migration of water from lake Ziway to lake Abiyata.

VII.Geothermal wells

On fig 5.17, geothermal wells f2. f21 and f22 are depleted in ^{18}O and have high Cl concentrations than the majority of shallow groundwaters and precipitation. This shows that the samples have different source. Geothermal wells f19 and 20 have similar enrichment with the meteoric waters indicating there is mixing with the shallow groundwaters and lake waters.

5.2.3.1. Spatial variation of ^{3}H and ^{18}O isotopes in relation with hydrochemistry

Fig 5.19 shows that the distributions of ^{18}O and tritium contents of water samples which have different EC values. The sizes of the circles and the cross symbols correspond with the isotopic contents of ^{18}O (in ‰) and tritium (in TU) respectively.

I. The Highland and escarpment waters

The low EC values, the depletion with O-18 and the presence of appreciable amount of tritium (0.5 to 10 TU) in highland and transitional escarpment groundwaters indicates that there is fast circulation of groundwaters and low rock- water interaction.

Cold springs on the highlands and escarpment (labeled a1, a2, a3, a4 and a5) are more depleted than the precipitation (d2 & d3) sampled in the highlands. This might be related to seasonal or time biases to recharge of the springs and sampling precipitation which was not reported for the cold springs. Some previous works (Gizaw, 2002) indicate the presence of dissimilarity and imbalance between groundwater and the annual average rainwater ^{18}O and ^{2}H compositions.

River waters sampled in these areas (labeled e3, e5, e6 & e7) have similar ^{18}O concentrations with the precipitation contents (labeled d2 & d3).

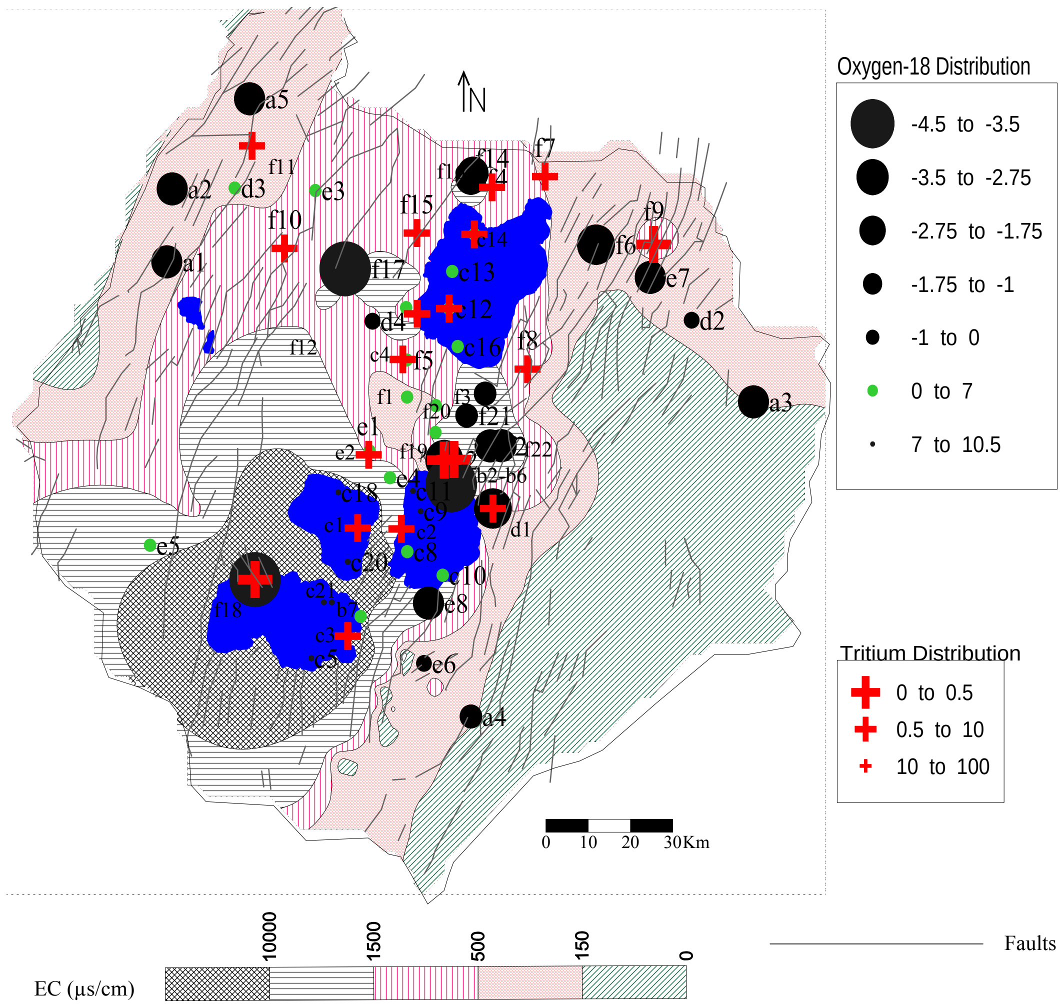
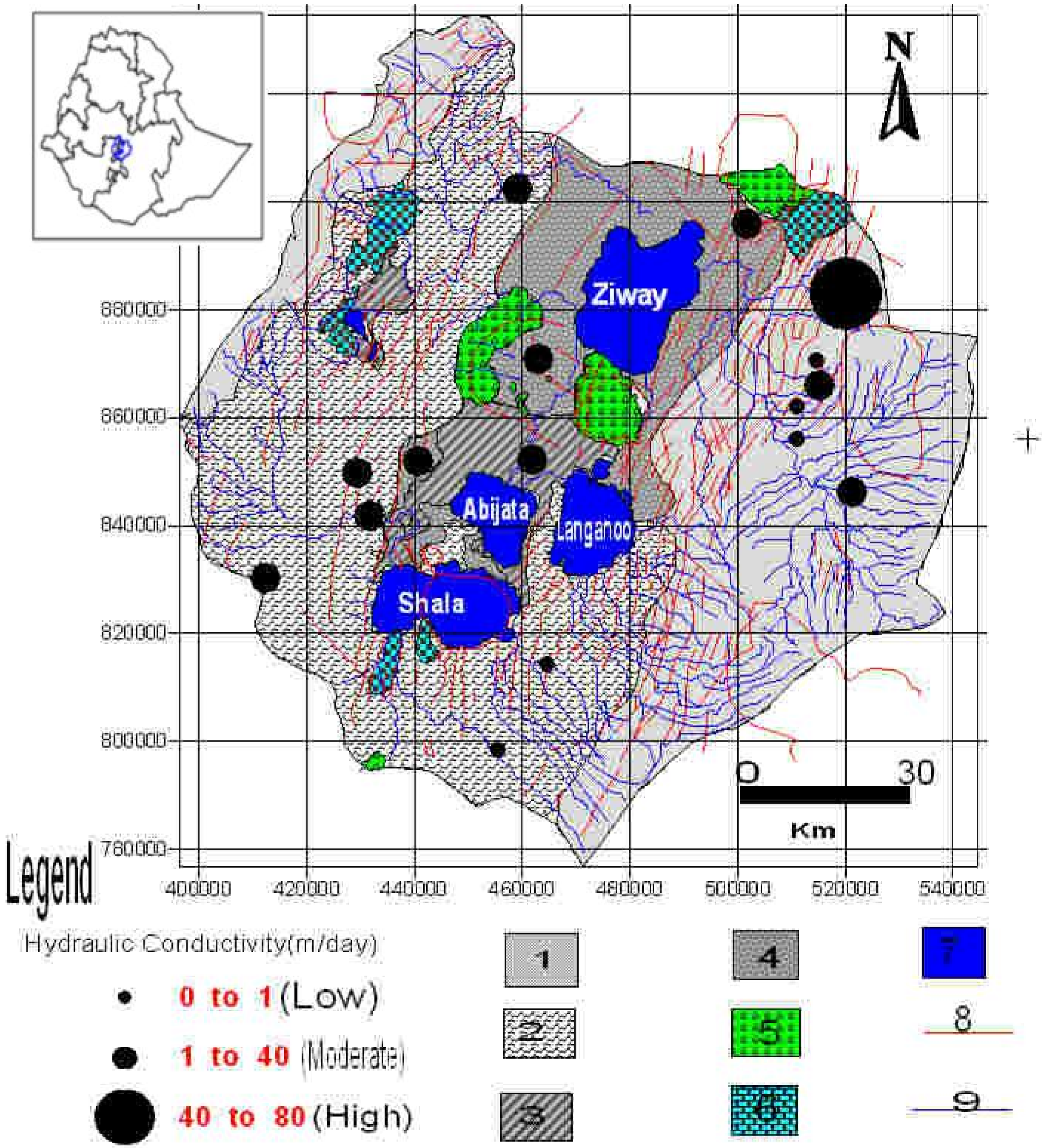


Figure 5.19. The spatial distributions of EC and isotopes (^{18}O and ^{3}H)
(Circle symbol label begins with "a" are cold spring, with "d" are rain and "e" are river samples.)

II. The rift waters in the area

There is high variation in isotopic concentration of the rift waters than the highland and escarpment waters. These variations can be identified using isotopic concentrations of the different waters in the rift and helps to conceptualize the flow system.


N
Ziway
Abijata
Langanoo
Shala
0
30
Km
880000
860000
840000
820000
800000
780000
400000
420000
440000
460000
480000
500000
520000
540000
Legend
Hydraulic Conductivity(m/day)
0 to 1 (Low)
1 to 40 (Moderate)
40 to 80 (High)
1
2
3
4
5
6
7
8
9

The lake waters in the rift have more or less similar tritium contents (0.5 to 10 TU) and they are more enriched in O-18 than the other waters in the basin. This imparts the existence of present day evaporative fractionation of the stable isotopes in the lake waters. The two most alkaline terminal lakes (Abiyata and Shala) which have the highest EC values (> 10000 µs/cm) are more enriched than the other two non-terminal lakes (Ziway and Langano) (Fig 5.7).

The tritium contents of the lake waters are more similar to the majority of the groundwaters and surface waters in the basin these may shows that the lake waters, groundwatres and surface waters have similar recharge source. On the other hand some tritium contents of water from deep wells and hot springs are different from lake waters indicates they have different sources.

The similarity in the water isotopic concentrations of ^{18}O and ^{3}H contents of lake Ziway with the groundwaters and rivers between lake Ziway and lake Abiyata indicates that there is southward migration of groundwaters from lake Ziway finally to lake Abiyata. Groundwaters north of lake Langano have similar O-18 content with the lake Ziway waters may show that there is subsurface hydraulic connection between lake Ziway and lake Langano.

In the rift cold and hot springs and well waters north of lake Langano and well waters east of lake Ziway have similarity in ^{18}O depletion and EC values .This is due to the effect of groundwater recharge through NE-SW trending Wonji Fault Belt (WFB) (Fig 4.1) Groundwaters southeast of lake Ziway are more depleted with ^{18}O indicates that there is no groundwater migration from the lake to the west side of lake past the Aluto caldera. However there is migration of thee depleted groundwater to the more ebriched Langano lake.

Well water in the highly faulted north east of lake Ziway area has locally has EC and low tritium indicates that there is reflects circulation of groundwaters and older ages of the high EC groundwaters.

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

Hydrochemical and isotope techniques were applied to understand the groundwater flow system and the subsurface hydraulic links between the lakes in the Ziway-Shala lakes basin. Interpretations of the statistical cluster analysis coupled with the chemical analysis results of the hydrochemical data and results from analysis of the isotopes data in the area are critically showed the hydrodynamics.From this approach the following conclusions have been drawn.

- The high spatial variations of major cations and anions follows systematic trend along the topographic groundwater flow paths (Fig 5.6). This reflects the different groundwater flow systems and the existence of hydrochemical evolution of waters along the flow path.

- The majority of the waters in the area are Na-HCO_3 type waters.

- The majority of the highlands and escarpments waters are low EC Ca-Mg-HCO_3 type and low EC Na-Ca –HCO_3 type waters. This shows that there is shallow circulation of groundwaters from direct recharge of precipitation and these waters have undergone no marked rock-water interactions.

- The majority of rift floor groundwaters are high EC Na–HCO_3 type waters indicating interactions with the geo-media along the flow path. Shallow groundwaters near the lakes Abiyata, Langano and Shala have very high EC (indicating high residence time and ionic concentrations) and fall in Na-HCO_3 –Cl type waters.

- The majority of waters from the fresh lake Ziway fall in Na-Ca-Mg-HCO_3 type waters which are similar to the highlands and escarpment groundwaters and some of the rift floor waters. Majority of waters from the alkaline lakes Abiyata, Langano and Shala are Na-HCO_3-Cl type waters which have similarity with the discharge area waters between and around them. This shows that there are interactions between the lake water and groundwater.

- In the basin there is a general groundwater hydrochemical evolution along the groundwater flow path from low EC recharge area Ca-Mg-HCO_3 & Na-Ca-HCO_3 type waters into higher EC transition area Na-HCO_3 type waters and to a more concentrated discharge area Na-HCO_3 & Na –HCO_3 –Cl type waters.

- EC map (fig 5.7) shows a distinct zonation of EC & TDS of natural waters following the direction of regional groundwaters flow. The highest EC is localized the lowest elevation including lake Abiyata and Shala and the lowest EC is localized on the highland areas indicating the regional groundwater flow from the highland to the lowest elevation lakes.

- Boreholes (number 46 and 4 on Fig 5.1) have similar chemical composition (have similar water type) as the lake Ziway waters. This shows that there is interconnection between the rift cold groundwaters and the lake waters

- Boreholes (number 9 and 67 on Fig 5.1) and cold spring (75) have a similar hydrochemical signature to the nearby lake Ziway waters. This is evidence for the southward migration of groundwater from lake Ziway towards lake Abiyata and lake Langano parallel to Bulbula river.

- The chemical composition of borehole waters (number 37, 109 and 115) between lake Abiyata and Langano is similar for the nearby lake waters. This shows that there is flow of waters from lake Langano to lake Abiyata alsong the NE-SW trending fault.

- Statistical cluster analysis (the Q-mode HCA technique) of samples defined two major groups and seven subgroup waters by considering the nine hydrochemical variables (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, HCO^{-3}, CO^{-3}, Cl^{-1}, SO^{-4}, and TDS)

- The two major groups are distinct by their TDS. Group-A waters have TDS less than 2000 mg/L. Group-B waters have TDS greater than 2000 mg/L. Group-A waters have 3 subgroups and Group-B waters have 4 subgroups.

- There is relationship between the statistically defined clusters of samples and geographic locations (Fig 5.12)

- Groundwater in the recharge area evolves from a dilute Subgroup-1 waters (Na - Ca– HCO_3 water ,average TDS is ~332 mg/l) to a fresh Subgroup- 2 waters (Na– HCO_3 water , average TDS is ~475 mg/l) to a more concentrated Subgroup-3 waters (Na–HCO_3 water ,average TDS is ~1184 mg/l) and then to Subgroup-4 waters (a brackish Na–HCO_3-Cl water ,average TDS is ~6538 mg/l) along the topographic flowpath (Table 4 and Figs 5.12 and Fig 5.13). Overall, the waters from the area can be classified as recharge area waters (Subgroup-1), transition zone waters (Subgroup-2) and discharge area waters (Subgroup-3 and Subgroup-4).

- The majority of the subgroup-1 waters are located on the highlands and escarpments (some samples are on the highly faulted area of the rift floor indicating the role of faults on the groundwater movement and occurance) and the rest subgroup are situated in the rift floor and partially on the escarpments. The majority samples of subgroup 5, subgroup 6 and subgroup 7 waters are hot springs and geothermal waters.

- The hydrochemical evolution of the subgroup waters shows that there is a general groundwater flow from Subgroup 1 $\rightarrow$ Subgroup 2 $\rightarrow$ Subgroup 3 $\rightarrow$ Subgroup 4. Starting from highland and escarpment waters and ends with rift floor waters. The mean TDS increases with increasing subgroup numbers.

- There is good agreement between results from the chemical analyses and the statistical analyses.

- The majority of groundwaters and rain waters are plotted near the LMWL .This indicates the importance of present day precipitation for groundwater recharge.

- The variation of isotopic concentrations between groundwaters reflects the presence of different groundwater flow systems.

- The low EC highland and escarpment groundwaters are depleted in isotopes and have appreciable amount of tritium (0.5 to 10 TU) indicates that the groundwaters have undergone fast circulation and low rock- water interaction.

- The lake waters are enriched with isotopes. This is due to the existence of evaporative fractionation of the stable isotopes in the lake waters. The two most alkaline terminal lakes (Abiyata and Shala) which have the highest EC values (> 10000 µs/cm) are more enriched than the other two non-terminal lakes (Ziway and Langano) (see the size of circles on the lakes in Fig 5.16)

- Isotopic concentrations of ^{18}O and/or tritium contents of lake Ziway waters (labeled c12 and c16 on Fig 5.19) show similarity with the groundwaters (labeled f1) and rivers (labeled e2 and e4) between lake Ziway and lake Abiyata indicates that there is southward migration of groundwaters from lake Ziway finally to lake Abiyata. Groundwaters (labeled f20) north of lake Langano have similar O-18 content with the lake Ziway waters may show that there is subsurface hydraulic connection between lake Ziway and lake Langano.

- The relationship between 18O and Chloride concentrations (on Fig 5.17) shows that the lake Ziway water (labeled c12) has similar chloride concentration with the lake Langano water (labeled c9). The ^{18}O enrichment in c9 is higher than c12.This is due to the high evaporation water loss from lake Langano. The geothermal water (labeled f19) has similar isotopic enrichment but higher chloride concentration than lake Ziway waters (labeled c12). water. From this it is evidence to conclude that there is southward migration of lake Ziway waters towards lake Langano and mixing with the geothermal waters.

- Lake waters labeled c13 has also similar ^{18}O enrichment and Cl concentrations with the geothermal water labeled f20. This shows that there is dilution of the geothermal water by the lake Ziway

- The low EC & TDS and isotope depleted waters in highly faulted rift waters which have similarity in EC, TDS and depletion with the highland waters indicates the southward migration of highland and escarpment waters through faults and finally to lake Langano. The tectonic structures play a great role on the groundwater flow and chemical evolution.

- There is deeper groundwater circulation of old age on the highly faulted area. This is manifested the rift at north of lake Langano, east of Shala and north east of lake Ziway.

- The lake waters, the majority of the groundwaters and surface waters have similar tritium contents (fig 5.15). This shows that these waters have similar recharge source.

- Tritium contents of water from deep wells and hot springs are different from lake waters indicates they have different sources

- The results obtained from hydrochemistry (chemical and statistical results) match the results from isotope analyses.

In to understand the hydrodynamics in more detail the following recommendations are presented.

⊙ It is useful to conducted Inverse geochemical modeling approach in the area to determine the type and amount in moles of minerals that dissolve or precipitate along a groundwater flow path.

- Application of different techniques of statistical cluster analysis of hydrogeochemical data have to be proposed to constrain water sources, to construct a numerical model of the principal hydrogeological characterstics of the aquifers in the area, and determining their spatial and temporal evolution.

- Tracer techniques

- Continuous water quality monitoring

- Systematic sampling with depth and in relation to geological structures.

REFERENCE

Adams, S., Tredoux, G., Harris, C., Titus, R., Pietersen, K.,(2001) Hydrochemical characteristics of aquifers near Sutherland in the Western Karoo, South Africa. J. Hydrol. 24, 91–103.

Alberto, W.D., Del Pilar, D.M., Valeria, A.M., Fabiana, P.S., Cecilia, H.A., De Los Angeles, B.M., 2001. Pattern recognition techniques for the evaluation of spatial and temporal variations in water quality. A case study: Suquı`a River Basin (Co´rdoba- Argentina). Water Res. 35, 2881–2894.

Alther, G.A., 1979. A simplified statistical sequence applied to routine water quality analysis: a case history. Ground Water 17, 556–561.

Appelo,CAJ. & Postma, 1993.Geochemistry, groundwater and pollution. A.A.Balkema, Rotterdam

Ashley, R.P. and Burley, M.J. (1994). Controls on the occurrence of fluoride in groundwater in the rift valley of Ethiopia. In: Groundwater Quality, pp. 45–54, (Nash, H. and McCall, G.J.H., eds). Chapman and Hall, London.

Barberi, F., Ferrara, G., Santacroce, R. and Varet, J. (1975). Recent volcanic units of afar and their structural significance. In: Afar Depression of Ethiopia, pp. 38–54, (Pilger, A. and Roesler, A., eds). Schweizerbart.

Baxter, R.M., Prosser, M.V., Talling, J.F. and Wood, R.B. (1965). Stratification in tropical African lakes at moderate altitudes. Limnol. Oceano. 10:511–520.

Berhanu Gizaw (1996). The origin of high bicarbonate and fluoride concentrations in waters of the Main Ethiopian Rift Valley, East African Rift system. J. Afr. Earth Sci. 22(4):391–402.

Boccaletti, M., Getaneh, A., Tortorici, L., (1992). The Main Ethiopian Rift: an example of oblique rifting. Ann. Tectonicae 6, 20–25.

Bonini, M., Souriot, T., Boccaletti, M., Brun, J.-P.,(1997). Successive orthogonal and oblique extension episodes in a rift zone: laboratory experiments with application to the Ethiopian Rift. Tectonics 16, 347–362.

Caroline L., Jean-Jacques T, Elisabeth G, Yves T, Kiram L, Jean R, Marc M, Raymonde B, Michel D, Bernard G, Vincent J, Endale T, Mohammed U., Balemwal A.,Tesfaye C., David W, Maurice T,(1999). The Ziway–Shala lake basin system, Main Ethiopian Rift: Influence of volcanism, tectonics, and climatic forcing on basin formation and sedimentation. J. of Palaeogeography, Palaeoclimatology, Palaeoecology.150: 135–177

Chebotarev, I.I. (1955). Metamorphism of natural waters in the crust of weathering. Geochim. Cosmochim. Acta. 8:22–48, 137–170, 198–212.

Craig, H. (1977). Isotope geochemistry and hydrology of geothermal waters in the Ethiopian Rift Valley. Scripps Insi. Oceanography, ept. 77–14, 140 pp.

Craig, H.,Lupton, J.E.and Horowiff, R.M.(1977). Isotope geochemistry and hydrology of geothermal-waters in the Ethiopian Rift Valley. Scripps Inst. of Oceanography. ept. 77–14,160 pp.

Darling, W.G., Berhanu Gizaw, and Arusei, M.K. (1996). Lake-groundwater relationships and fluid-rock interaction in the African rift valley: Isotopic evidence. Journal of African Earth Sciences 22:423–431.

Di Paola, G.M., (1972). The Ethiopian Rift Valley (between 7_000 and 8_400 lat. north). Bulletin Vulcanology 36, 517–560.

Edmunds, W.M., Smedley, P., (2000). Residence time indicators in groundwater: the East Midlands Triassic sandstone aquifer. Appl. Geochem. 15, 737–752.

Edmunds, W.M., Guendouz, A.H., Mamou, A., Moulla, A., Shand, P., Zouari, K., (2003). Groundwater evolution in the Continental Intercalaire aquifer of southern Algeria and Tunisia: trace element and isotopic indicators. Appl. Geochem. 18, 805–822. Farah, E.A., Mustafa, E.M.A., Kumai, H., 2000. Sources of groundwater recharge at the confluence of the Niles, Sudan. Envir. Geol. 39, 667–672.

EIGS (1993). Geothermal Exploration Project data file. Ethiopian Institute of Geological Surveys. Addis Ababa, Ethiopia.

Elizabeth Kebede, Zinabu Gebremariam and Ahlgren, A. (1996). The Ethiopian Rift Valley lakes: Chemical characteristics along a salinity-alkalinity series. Hydrobiologia 288:1–12.

Ellis, A.J. and Mahon, W.A.J. (1977). Chemistry and Geothermal Systems. Academic Press.

EMA (1988). National Atlas of Ethiopia. Ethiopian Mapping Authority, Addis Ababa, Ethiopia.

Farnham, I.M., Stetzenbach, K.J., Singh, A.K., Johannesson, K.H., 2000. Deciphering groundwater flow systems in Oasis Valley, Nevada, Using trace element chemistry, multivariate statistics, and Geographical Information System. Math. Geol. 32, 943–968.

Fournier, R.O. and Truesdell, A.H. (1970). Chemical indicators of subsurface temperature applied to hot spring waters of Yellowstone National Park, Wyoming, USA. Geothermics Special Issue 2:529–535.

Freeze, R.A. and Cherry, J.A. (1979). Groundwater. Prentice-Hall, Englewood Cliffs,N.J., USA, 604 pp.

Fritz, P. & J.C. Fontes (1988). Hand book of environmental isotope geochemistry (volume 1). Elsever, New York. 545 pp.

Gerasimovskiy, V.L. and Savinova, Y.N. (1969). Fluorine contents of volcanic rocks in the rift zone of East Africa. Geochemistry International 6:1124–1128.

Giday Woldegebriel, Aronson, J.L. and Walter, R.C. (1990). Geology, geochronology, and rift basin development in central sector of the Main Ethiopian Rift. Geological Society of America Bulletin 102:439–458. [B34.022].

Gillespie, R., Street-Perrot, F.A., Switsur, R., (1983). Post-glacial arid episodes in Ethiopia have implications for climate prediction. Nature 306, 680–683.

Birhanu Gizaw, B., (1996). The origin of high bicarbonate and fluoride concentrations in waters of the Main Ethiopian Rift Valley, East African Rift system. J. Afr. Earth Sci. 2, 391–402.

Birhanu Gizaw, (2002). Hydrochemical and environmental investigation of the Addis Ababa region, Ethiopia. Ph.D. Diss., Faculty of Earth and Environmental Sciences Ludwig-Maximilians-Univ. Munich.

Grove, A.T., Street, A.F., Goudie, A.S., (1975). Former lake levels and climatic change in the rift valley of southern Ethiopia. Geogr. J. 141, 177–202.

Gu¨ ler, C., Thyne, D.G., McCray, E.J., Turner, A.K., (2002). Evaluation of graphical and multivariate statistical methods for classification of water chemistry data. Hydrogeol. J. 10, 455–474.

Gu¨ ler, C., Thyne (2003).Hydrologic and geologic factors controlling surface and groundwater chemistry in Indian Wells-Owens Valley area, south-eastern California, USA .Jornal Of Hydrology. 0022-1694

Gu¨ ler, C., Thyne, D.G., (2004). Hydrologic and geologic factors controlling surface and groundwater chemistry in Indian Wells-Owens Valley area, southeastern California, USA. J. Hydrol. 285, 177–198.

Haile Gashaw,(1999). Hydrochemistry of waters in lake Ziway area. Integrated development for water supply and sanitation. 25th WEDC Conference. Addis Ababa, Ethiopia

Halcrow (1989). Rift Valley lakes Integrated Natural Resources Development Master Plan. Ethiopian Valleys Development Studies Authorities, Unpub. Report.

Hem, J.D. (1970). Study and interpretation of the chemical characteristics of natural waters, US. Geol. Surv. Water Supply Paper 1473, 363 pp.

Kazmin, V., Seifemichael Berhe, Nicoletti, M. and Petrucciani, C. (1980). Evolution of the northern part of the Ethiopian rift. Atti Convegni Lincei 47:275–292.

Kilham, P. and Hecky, R.E. (1973). Fluoride: geochemical and ecological significance in East African waters and sediments. Limnol. Oceanogr. 18:932–945.

Kingham, T.J., (1975). Rainfall records for the southern Rift Valley of Ethiopia. Land Resources Div., U.K. Min. Overseas Devel., Tolworth, Supplementary Report 18, 50 pp.

Laury, R.L., Albritton, C.C., (1975). Geology of the Middle Stone Age archaeological sites in the Main Ethiopian Rift Valley. Geological Society of America Bulletin 86, 999–1011.

Lofeller, H. (1978). Limnological and paleolimnological data on the Bale Mountain lakes (Ethiopia). Verh. int. Verein. Limnol. 20:1131–1138.

Makin, M.J., Kingham, T.J., Waddams, A.E., Birchall, C.J., Eavis, B.W., (1976). Prospects for irrigation development around lake Ziway, Ethiopia. Land Resources Div., U.K. Min. Overseas Devel., Tolworth, Land Resources Study 26, 407 pp.

M. Benvenuti, S. Carnicelli, G. Belluomini, N. Dainelli, S. Di Grazia,G.A. Ferrari, C. Iasio, M. Sagri, D. Ventra, Balemwald A, Seifu K, (2002). The Ziway–Shala lake basin (main Ethiopian rift, Ethiopia): a revision of basin evolution with special reference to the Late Quaternary. Journal of African Earth Sciences 35:247–269.

Meng, S.X., Maynard, J.B., 2001. Use of statistical analysis to formulate conceptual models of geochemical behavior: water chemical data from the Botucatu aquifer in Sa˜o Paulo state, Brazil. J. Hydrol. 250, 78–97.

Merla, G., Abbate, E., Azzaroli, A., Bruni, P., Canuti, P., Fazzuoli, M., Sagri, M., Tacconi, P., (1979). A Geological map of Ethiopia and Somalia, and comment. CNR, Firenze.

Molla Demellie (2000). Hydrology, hydrogeology and hydrochemistry of the lakes system Haiq-Ardibo, Northern Ethiopia. Unpub. MSc thesis, Addis Ababa University, 135 pp.

Mohr, P. (1970). The Geology of Ethiopia. Addis Ababa University Press, 268 pp.

Mohr, P. (1983). Ethiopian flood basalt province. Nature 303:577–584.

Nicholson, S.E., (1996). A review of climate dynamics and climate variability in eastern Africa. In: Johnson, T.C., Odada, E.O. (Eds.), The Limnology, Climatology and Paleoclimatology of the East African lakes. Gordon and Breach, Amsterdam, pp. 25–56.

Panichi, C. (1995). Isotopic investigation in geothermal hydrology. Mission report code 2010. 5250, 131. C300020389, F2E. Submitted to the isotopic hydrology section of the International Atomic Energy Agency, Vienna.

Peccerillo, A. and Gezahegn Yirgu (1996). Geochemical behaviour of fluorine in the volcanic systems of the Ethiopian Rift Valley: Implications for the problem of high fluorine waters (abstract). In: Program and Abstracts of the third Ethiopian Geosciences and Mineral Engineering Congress, 15–17 November, Addis Ababa.

Piper, A.M., (1944). A graphical procedure in the chemical interpretation of water analyses. American GeophysicalUnion Transactions, vol. 25, pp. 914-923.

Plummer, L., Busby, J., Lee, R.,Hanshaw, B., (1990).Geochemical modelling of the Madison aquifer in parts of Montana,Wyoming, and South Dakota. Water Resour. Res.26,1981–2014

Seifu Kebede (1999). Hydrology and hydrochemistry of Bishoftu crater lakes (Ethiopia): Hydrogeological, hydrochemical and oxygen isotope modeling. Unpub. MSc thesis, Addis Ababa University, 127 pp.

Seifu Kebede (2005). Groundwater recharge, circulation and geochemical evolution in the source region of the Blue Nile River, Ethiopia. Journal of Applied Geochemistry 10.1016.

Solomon Tale (2000). The extent of surface water and groundwater pollution. Unpub. MSc thesis, Addis Ababa University, 135 pp.

Street, F.A. (1979). Late Quaternary lakes in the Ziway-Shala Basin, Southern Ethiopia. (UK). PhD thesis [Quaternaire: STR-80.094].

Stumm, W. & Morgan, J.J., (1970).Aquatic Chemistry, John Wiley & Sons, Newyork: 583pp.

Talling, J.F. and Talling, I.B. (1965). The chemical composition of African lake waters. Int. Rev. Ges. Hydrobiolgia 50:421–463.

Tamiru Alemayehu(2006). Hydrogeochemical and lake level changes in the Ethiopian Rift. Journal of Hydrology . Vol 14902VEERA—150762–. 1–11 pp

Taylor, H.P. (1977). Water/rock interactions and the origin of H_2O in granitic batholiths. J.Geol.Soc (London). 133:509-558.

Teclu, Ayalew. (1995): A preliminary isotopic and geothermal study for the recharge identification of Tendaho geothermal field, Ethiopian Institute of Geological Surveys. Unpublished report. Addis Ababa.

Tenalem Ayenew (1998). The hydrogeological system of the lake district basin, Central Main Ethiopian Rift. PhD thesis, Free University of Amsterdam, 259 pp.

Tenalem Ayenew (2001). Numerical groundwater flow modelling of the central Main Ethiopian Rift lakes basin. SINET: Ethiop. J. Sci. 24(2):167–184.

Tenalem Ayenew (2003).Environmental isotope-based integrated hydrogeological study of some Ethiopian rift lakes. Journal of Radioanalytical and Nuclear Chemistry,Vol. 257, No.1, 11–16 pp

Tenalem Ayenew (2005). Major ions composition of the groundwater and surface water systems and their geological and geochemical controls in the Ethiopian volcanic terrain. Journal of Radioanalytical and Nuclear Chemistry, Vol. 257, No. 1., 11–16 pp. SINET: Ethiop. J. Sci. 28(2): 0379–2897

Tesfaye Chernet (1982). Hydrogeologic map of the lakes region (with memo). Ethiopian Institute of Geological Surveys, Addis Ababa, Ethiopia.

Tesfaye Chernet (1993). Hydro-geology of Ethiopia and Water Resource Development. (Unpublished Report). Geological Survey of Ethiopia, Addis Ababa, 222 pp.

Tesfaye Chernet, Travi, Y. and Valles, V. (2001). Mechanism of degredation of the quality of natural water in the lakes region of the Ethiopian Rift Valley. Wat. Res. 35(12):2819–2832.

Toth, J., (1963). A theoretical analysis of groundwater flow in small drainage basins.Jornal of Geophysical Research, 68 (16):4795-4812.

UNDP (1973). Investigation of geothermal resources for power development: Geology, geochemistry and hydrology of hot springs of the East African Rift System within Ethiopia (with maps), New York.

Von Damm, K.L. and Edmond, J.M. (1984). Reverse weathering in the closed basin lakes of the Ethiopian Rift. Amer. J. Sci. 284:835–862.

WHO (1984): Guidelines for drinking water quality. Report WHO, Geneva, 139 pp.

Wenner, C.G., (1973). A master plan for water resources and supplies in the Chilalo Awraja. CADU Publication no.89, Swedish International Development Agency, Stockholm.

Williams, R.E., 1982. Statistical identification of hydraulic connections between the surface of a mountain and internal mineralized sources. Ground Water 20, 466–478.

Winter, T.C., (1978a).Numerical Simulation of steady state three dimensional groundwater flow near lakes.Water Resources Reasearch, 14: 245-254.

Woldegebriel, G., Aronson, J.L. & Walter, R.C. 1990. Geology, geochronology, and rift basin development in central sector of the Main Ethiopian Rift. Geological Society of America Bulletin, 102 (1990):439-458. [B34.022].

Wood, R.B. and Talling, J.F. (1988). Chemical and algal relationship in a salinity series of Ethiopian inland waters. Hydrobiologia 158:29–67.

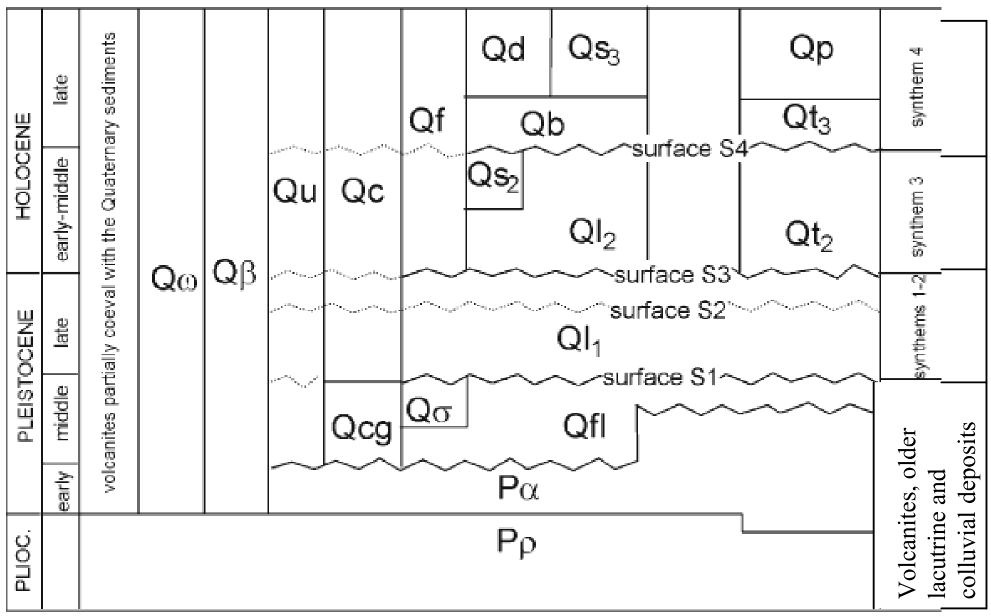
WWDSE (2000). Study of lake Beseka, Final Report Vol. I. Water Works Design and Supervision Enterprise, Addis Ababa, 220 pp.

WWDSE (2001). The study of lake Awassa level rise. Southern Nations Nationalities and Peoples Regional State. Water, Mines and Energy Resources Development Bureau. Unpublished report of the Water Works Design and Supervision Enterprise (main report volume II), Addis Ababa, Ethiopia, 291 pp.

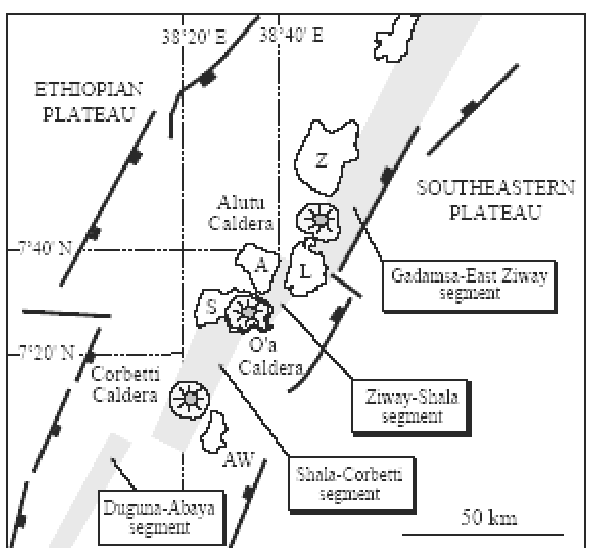
Zanettin, B. (1993). Evolution of the Ethiopian volcanic province. Atti della Accademia Nazionale dei Lincei. Mem. Fis. Acc. Lincei. S. 9, V. 1:153–181, Roma, Italy.

Zenaw Tessema (1996). Hydrochemical and water balance approach in the study of high water level rise of lake Beseka. MSc thesis, The University of Birmingham, 90 pp.

Appendix 1 Chronostratigraphic framework for the plio-quaternary volcanic and sedimentary units (P_ρ =Late Pliocene, P_α =Early Pleistocene, Q=Quaternary and Synthem= major unconformity-bounded units)



Appendix 2. Structural sketch map of the Wonji Fault Belt (WFB) showing the four en e´chelon NNE-trending segments within the Ziway–Shala lake basin system.



Three shield (caldera) volcanoes are present at each WFB offset. From north to south these are the Alutu Caldera, the O'a Caldera, and the Corbetti Caldera (after Mohr, 1960; Mohr et al., 1980). *AW* = Lake Awasa; *S* = Lake Shala; *A* = Lake Abiyata; *L* = Lake Langano; *Z* = Lake Ziway.

Appendix 3 Hydrochemical Data

Note: - BH: *borehole*, CS: *cold spring*, HS: *hot spring*, DW: *hand dug well*, GTW: *geothermal well*, TW: thermal *gradient well*
Unit is meq/l for major ions and mg/l for TDS

Subgroup 1

ID	SampleID	Label	X(m)	Y(m)	Source	Ca	Mg	Na	K	CO_3	HCO_3	Cl	SO_4	TDS
1	BH-11	1	412288	830368	4	1.0	0.3	3.5	0.3	0.2	6.0	0.3	0.0	637
2	BH-26	3	480305	901414	4	1.4	0.3	1.5	0.1	0.0	4.7	0.2	0.1	473
3	BH-33	5	511000	856242	5	1.1	0.5	1.0	0.1	0.0	4.2	0.2	0.0	285
4	BH-34	6	510649	869224	5	1.1	0.9	0.9	0.2	0.7	2.7	0.2	0.3	330
5	BH-37	7	516644	889724	5	1.2	0.4	0.9	0.2	0.0	3.8	0.2	0.0	326
6	BH-50	9	489000	860000	7	2.1	1.0	0.5	0.1	0.0	3.1	0.1	0.2	238
7	BH-6	10	519294	884778	4	1.2	0.4	0.9	0.2	0.0	3.8	0.2	0.0	326
8	BH-79	11	445942	888136	7	1.8	0.5	1.5	0.2	0.5	4.8	0.1	0.0	362
9	CS-11	69	444178	911429	4	0.5	0.3	0.7	0.2	0.0	2.4	0.1	0.0	563
10	CS-13	70	479449	809174	4	0.2	0.1	0.4	0.2	0.0	1.0	0.1	0.1	179
11	CS-22	75	476797	850890	8	0.7	0.1	1.4	0.3	0.7	1.8	0.4	0.0	139
12	CS-23	76	470839	851126	8	0.6	0.1	1.4	0.3	0.7	1.6	0.5	0.0	138
13	CS-33	79	506994	877916	7	0.2	0.2	0.5	0.1	0.0	1.3	0.0	0.0	73
14	CS-34	12	506276	876854	7	1.2	0.2	0.6	0.1	0.0	1.4	0.2	0.0	72
15	CS-38	80	521768	832489	8	0.3	0.1	0.2	0.0	0.0	0.9	0.1	0.0	106
16	CS-39	81	511928	879536	8	0.4	0.2	0.4	0.1	0.0	1.5	0.1	0.1	185
17	CS-5	82	424762	885865	4	0.7	0.4	0.4	0.1	0.0	1.5	0.1	0.1	185
18	CS-6	83	424762	893632	4	0.5	0.2	0.9	0.2	0.0	2.4	0.1	0.0	254
19	CS-8	84	422821	902692	4	1.0	0.5	1.0	0.3	0.0	2.2	0.1	0.1	290
20	CS-9	85	439648	913371	4	0.5	0.5	0.2	0.1	0.0	1.4	0.1	0.0	267
21	DW-12	14	441433	889599	4	1.2	0.4	6.3	0.4	0.0	9.1	0.4	0.1	885
22	DW-23	17	480943	897176	4	1.7	0.1	1.2	0.1	0.0	4.9	0.2	0.0	493
23	DW-7	19	433855	896364	4	1.5	0.6	1.7	0.3	0.0	5.5	0.7	0.1	574
24	DW-8	20	434667	896364	4	1.4	0.7	1.9	0.4	0.0	6.0	0.2	0.2	636

ID	SampleID	Label	X(m)	Y(m)	Source	Ca	Mg	Na	K	CO_3	HCO_3	Cl	SO_4	TDS
25	DW-9	21	433314	895011	4	1.4	1.2	1.0	0.2	0.0	6.0	0.2	0.0	305
26	Hs-27	22	476071	852375	8	1.0	0.8	5.0	0.9	0.7	2.6	3.6	0.4	330
27	Hs-28	23	469455	850822	8	1.2	0.5	6.0	1.2	0.5	4.1	3.4	0.4	315

Subgroup 2

No	SampleID	Label	X	Y	Source	Ca	Mg	Na	K	CO_3	HCO_3	Cl	SO_4	TDS
1	BH-1	25	506221	884425	1	0.19	0.14	2.91	0.33	0.00	3.69	0.03	0.02	256
2	BH-12	26	431494	841849	4	0.42	0.10	4.35	0.77	0.00	5.74	0.10	0.07	612
3	BH-13	27	430345	840524	4	0.05	0.04	11.74	0.41	0.00	10.98	0.24	0.10	1112
4	BH-14	28	429285	849711	4	0.55	0.49	1.91	0.23	0.00	4.13	0.11	0.02	871
5	BH-16	29	440503	858367	4	0.15	0.08	9.13	0.38	0.00	8.67	1.02	0.30	871
6	BH-17	2	437765	867465	4	1.27	0.37	6.96	0.43	0	9.34	0.82	0.27	963
7	BH-18	30	446686	885043	4	0.47	0.21	6.09	0.41	0.00	6.85	0.45	0.06	776
8	BH-19	31	461289	816541	4	0.35	0.16	0.87	0.10	0.00	1.64	0.06	0.24	265
9	BH-2	32	459229	882481	1	0.02	0.02	17.18	0.29	0.00	13.44	1.50	0.94	787
10	BH-20	33	464529	814467	4	0.35	0.16	1.09	0.08	0.00	2.29	0.07	0.08	287
11	BH-21	34	465118	815630	4	0.42	0.12	0.65	0.10	0.00	1.47	0.16	0.11	219
12	BH-22		465147	815578	4	0.27	0.12	0.52	0.10	0.00	1.34	0.00	0.08	203
13	BH-24	35	467797	878153	4	0.35	0.37	8.70	0.38	0.20	7.75	0.51	0.05	934
14	BH-25	36	480403	900580	4	0.35	0.37	8.70	0.38	0.20	9.39	0.51	0.05	934
15	BH-30	37	459810	832677	4	0.07	0.02	13.62	0.64	0.40	7.60	6.01	0.03	1175
16	BH-31	38	521251	846143	5	0.84	0.42	0.96	0.09	0.00	3.32	0.10	0.00	230
17	BH-32	39	512683	851346	5	0.54	0.36	0.65	0.11	0.00	2.20	0.15	0.00	180
18	BH-35	40	514701	870557	5	0.32	0.10	0.78	0.05	0.00	1.50	0.20	0.00	125
19	BH-36	41	514259	873560	5	0.40	0.09	0.47	0.05	0.00	1.30	0.20	0.00	167
20	BH-39	42	501805	895996	5	0.42	0.16	1.53	0.21	0.00	3.50	0.19	0.00	312
21	BH-40	43	498006	892374	5	0.38	0.14	2.71	0.31	0.00	3.70	0.19	0.00	288

No	SampleID	Label	X	Y	Source	Ca	Mg	Na	K	CO_3	HCO_3	Cl	SO_4	TDS
22	BH-41	44	497565	889283	5	0.57	0.45	2.04	0.24	0.00	4.00	0.20	0.00	360
23	BH-42				5	0.37	0.25	1.57	0.16	0.00	2.70	0.19	0.00	264
24	BH-43	45	486788	867554	5	0.70	0.40	3.04	0.13	0.00	4.80	0.39	0.00	398
25	BH-44				8	0.75	0.13	3.24	0.57	0.00	2.30	1.75	0.01	108
26	BH-45	46	469716	890725	8	0.76	0.18	1.49	0.26	0.00	2.16	0.00	0.15	205
27	BH-46	47	462304	867052	8	0.06	0.02	5.17	0.91	0.00	4.92	0.00	0.24	220
28	BH-47	48	461694	809225	8	0.23	0.19	1.77	0.31	0.00	2.10	0.00	0.02	116
29	BH-48	49	466281	808649	8	0.40	0.20	2.97	0.52	0.00	3.54	0.00	0.03	123
30	BH-49	50	500000	883000	7	0.49	0.22	1.00	0.09	0.00	2.02	0.05	0.01	122
31	BH-5	51	478715	828088	4	0.32	0.16	1.09	0.10	0.00	2.28	0.11	0.01	274
32	BH-52	52	469242	806043	7	0.28	0.25	1.61	0.28	0.00	1.80	0.28	0.04	128
33	BH-53	53	461137	815099	8	0.29	0.26	1.50	0.30	0.00	1.68	0.51	0.01	616
34	BH-54	54	472794	814100	8	0.35	0.30	1.70	0.12	0.00	1.80	0.54	0.01	381
35	BH-56				8	0.33	0.27	1.30	0.10	0.00	1.43	0.54	0.04	582
36	BH-57	55	465405	810049	8	0.60	0.51	2.30	0.40	0.00	3.00	0.71	0.01	1137
37	BH-58	56	468826	804967	7	0.32	0.16	1.70	0.30	0.00	1.56	0.56	0.02	150
38	BH-64	57	465424	810049	8	0.80	0.30	2.00	0.50	0.00	4.00	0.17	0.01	810
39	BH-65	58	489060	838182	8	0.45	0.23	1.39	0.25	0.00	2.06	0.00	0.01	121
40	BH-67				8	0.56	0.09	1.84	0.32	0.00	1.52	0.90	0.04	130
41	BH-7	59	454459	796536	4	0.25	0.08	0.61	0.13	0.00	0.88	0.20	0.04	160
42	BH-8	60	455519	798303	4	0.40	0.33	8.48	0.46	0.30	9.00	0.42	0.07	915
43	BH-80	61	467183	869410	7	0.72	0.68	10.00	0.37	0.50	11.50	0.05	0.01	572
44	BH-81	62	465705	820049	7	0.20	0.10	1.20	0.30	0.00	1.80	0.06	0.02	114
45	BH-82	63	495517	871107	7	0.29	0.21	3.47	0.29	0.10	2.80	0.51	0.17	155
46	BH-84	64	497428	892538	7	0.00	0.00	3.36	0.36	0.50	3.70	0.13	0.03	219
47	BH-87	65	504694	889596	7	0.72	0.68	2.77	0.37	0.00	4.40	0.05	0.01	210
48	BH-9	66	426105	811287	4	0.15	0.08	8.70	0.31	0.10	6.70	1.21	0.48	843
49	BH-91	67	491948	870967	7	0.57	0.58	6.79	0.25	0.30	10.50	0.13	0.08	552
50	CS-1	68	430263	842828	1	0.15	0.59	2.35	0.34	0.00	4.59	0.08	0.02	296

No	SampleID	Label	X	Y	Source	Ca	Mg	Na	K	CO_3	HCO_3	Cl	SO_4	TDS
51	CS-14	71	459710	792995	4	0.15	0.12	0.48	0.10	0.00	0.70	0.51	0.02	164
52	CS-19	72	476206	852307	8	0.80	0.40	3.26	0.57	0.97	2.33	1.00	0.14	327
53	CS-2	73	402435	857389	1	0.18	0.09	2.26	0.21	0.00	3.03	0.03	0.02	210
54	CS-21	74	478784	846641	8	0.92	0.40	1.20	0.30	0.73	2.03	0.80	0.00	155
55	CS-27	77	479186	846962	7	0.24	0.14	1.48	0.15	0.30	2.70	0.07	0.02	161
56	CS-3	78	426704	843799	4	0.52	0.70	3.18	0.26	0.00	5.21	0.25	0.22	140
57	DW-1	86	438997	893658	1	0.36	0.88	2.74	0.30	0.00	5.24	0.20	0.15	330
58	DW-10	87	445221	896905	4	0.90	0.62	1.96	0.26	0.00	5.00	0.23	0.14	524
59	DW-13	88	460633	853379	4	0.72	0.25	5.65	0.31	0.00	7.54	0.65	0.07	1000
60	DW-14	89	476342	782975	4	0.25	0.16	0.43	0.30	0.00	1.02	0.51	0.07	164
61	DW-15	90	499074	833040	4	0.25	0.12	0.22	0.03	0.00	0.56	0.45	0.01	100
62	DW-18	91	470118	886893	4	0.52	0.33	19.84	0.51	0.00	16.32	3.64	0.77	1806
63	DW-2	92	463082	855772	1	0.26	0.35	5.44	0.42	0.00	5.90	0.79	0.24	363
64	DW-20	93	483254	898446	4	0.97	0.21	1.61	0.18	0.00	3.65	0.31	0.21	1300
65	DW-22	94	484157	898238	4	0.57	0.21	6.96	0.36	0.00	8.51	0.82	0.01	829
66	DW-24	95	496368	893658	4	0.57	0.16	2.17	0.15	0.00	3.88	0.11	0.03	407
67	DW-25	96	487438	873903	4	0.90	0.58	15.01	0.84	0.00	16.50	1.35	0.34	1800
68	DW-4	97	456317	796236	4	0.27	0.25	1.48	0.56	0.00	2.98	0.11	0.01	366
69	DW-5	98	415724	866326	4	0.25	0.23	0.78	0.38	0.00	1.79	0.17	0.01	320
70	DW-6	99	415724	866326	4	0.77	0.49	0.52	0.15	0.00	3.10	0.23	0.06	330
71	DW-61	100	479108	901415	8	0.57	0.21	6.96	0.36	0.00	8.46	0.82	0.01	829
72	GTW-2	101	473130	861620	6	0.02	0.01	3.87	0.51	0.00	3.38	0.59	0.06	401
73	HS-26	102	478784	846641	7	0.29	0.21	3.47	0.29	0.50	5.10	0.51	0.17	367
74	HS-6	103	412731	865888	4	0.40	0.12	2.39	0.20	0.00	3.74	0.17	0.01	423
75	HS-7	104	432095	878479	4	0.20	0.08	9.79	0.59	0.00	9.83	0.62	0.02	1032
76	TW-5				4	0.40	0.12	2.39	0.20	0.00	3.74	0.17	0.01	423

Subgroup 3

No	SampleID	Label	X	Y	Source	Ca	Mg	Na	K	CO_3	HCO_3	Cl	SO_4	TDS
1	BH-15	105	440615	832269	4	0.10	0.04	15.44	0.64	2.30	9.29	0.96	0.12	1374
2	BH-23	106	456844	884690	4	0.05	0.04	11.53	2.03	0.00	10.24	0.28	0.12	988
3	BH-28	107	467974	863049	4	0.35	0.21	9.57	1.68	0.00	9.83	0.59	0.08	894
4	BH-3				1	0.00	0.00	23.92	1.00	1.75	11.47	9.03	0.23	1675
5	BH-62	108	470161	868877	8	0.22	0.08	10.47	1.84	0.00	10.11	0.00	0.56	600
6	BH-96	109	466726	839869	8	0.01	0.02	19.97	0.74	1.50	10.00	8.01	0.04	1602
7	BH-97	110	467649	866929	8	0.10	0.07	10.87	0.30	1.61	7.60	0.40	0.00	899
8	DW-36	111	469472	871897	8	0.24	0.04	17.74	2.20	0.00	17.68	0.06	0.00	700
9	DW-37	112	468340	885071	8	0.34	0.04	13.26	2.33	0.00	13.12	0.28	0.00	960
10	DW-38	113	463022	875771	8	0.14	0.16	14.70	1.30	0.00	13.96	0.90	0.00	1370
11	GTW-1	114	473069	857081	6	0.02	0.01	24.19	0.97	0.00	16.32	6.52	0.26	1969

Subgroup 4

No	SampleID	Label	X	Y	So	Ca	Mg	Na	K	CO_3	HCO_3	Cl	SO_4	TDS
1	BH-29	115	464400	838560	4	0.07	0.04	87.00	1.05	8.00	44.38	27.05	1.10	6383
2	HS-2	116	460229	825336	1	0.00	0.01	104.40	1.07	7.83	40.48	43.72	0.58	5791
3	HS-9	117	459882	825336	4	0.02	0.04	101.14	0.95	4.40	48.58	45.47	0.42	7443

Subgroup 5

No	SampleID	Label	X	Y	Source	Ca	Mg	Na	K	CO_3	HCO_3	Cl	SO_4	TDS
1	BH-10	118	435998	813937	4	0.09	0.02	45.67	1.94	0.70	30.99	11.23	0.48	4100
2	GTW-4	119	484614	857721	6	0.09	0.02	44.15	3.53	0.00	26.99	18.93	1.36	3991
3	GTW-5	120	484888	854858	6	0.07	0.04	31.54	1.23	0.00	9.90	17.24	1.67	2433
4	GTW-7	121	482908	854827	6	0.06	0.02	37.15	1.20	0.00	28.99	8.52	0.32	3349
5	GTW-8	122	481995	863631	6	0.02	0.01	35.67	3.20	0.00	23.99	11.34	0.91	3192
6	HS-10	123	474644	852428	4	0.07	0.04	38.06	1.18	0.00	25.99	9.65	0.20	3091
7	HS-4	124	475903	848260	1	0.01	0.06	38.28	2.05	0.25	21.47	14.67	0.50	2236

8	HS-8	125	442949	822948	4	0.02	0.04	56.55	2.05	0.00	38.99	13.71	0.67	4424

Subgroup 6

No	**SampleID**	**Label**	**X**	**Y**	**Source**	**Ca**	**Mg**	**Na**	**K**	**CO_3**	**HCO_3**	**Cl**	**SO_4**	**TDS**
1	GTW-3	126	481477	857142	6	0.01	0.01	26.93	3.91	0.00	16.49	7.14	3.19	2977
2	GTW-6	127	482543	859762	6	0.02	0.01	29.93	5.70	0.00	14.00	12.95	3.87	2165
3	HS-3	128	476380	852515	1	0.18	0.44	73.95	3.32	3.25	36.06	19.18	4.06	4606

Subgroup 7

No	SampleID	Label	X	Y	Source	Ca	Mg	Na	K	CO_3	HCO_3	Cl	SO_4	TDS
1	DW-17	129	464706	855772	4	0.05	0.04	33.06	0.51	0.60	23.93	4.51	2.29	2800
2	DW-39	130	466107	876528	8	0.18	0.06	20.00	2.31	0.00	19.59	0.85	2.13	1400
3	HS-5				1	0.00	0.00	25.66	0.61	1.25	6.47	8.60	3.54	1778
4	TW-1				6	0.02	0.02	28.84	0.77	0.00	21.57	0.76	2.44	2396
5	TW-2	131	480927	855133	6	0.05	0.02	24.49	1.28	0.00	36.96	1.44	2.74	3354
6	TW-3				6	0.05	0.01	28.84	1.02	0.00	16.49	0.62	4.62	2297
7	TW-4	132	481672	854871	6	0.05	0.01	36.97	1.28	0.00	25.30	0.56	3.20	3067

Source:-

1: Tenalem Ayenew, 1994
2: Tenalem Ayenew, 1995
3: Tenalem Ayenew, 1996
4: Chernet, 1982
5: Winter, 1973
6: EIGUS Unpublished report
7: Region-4 Water Resource Bureau
8: Shemelis Fikre, 2006

Appendix 4 Fluorine and Electrical Conductivity Data

Note: - BH: *borehole*, CS: *cold spring*, HS: *hot spring*, DW: *hand dug well*, GTW: *geothermal well*, TW: thermal *gradient well*

Fluorine and Electrical Conductivity

ID	SampleID	Label	X	Y	Ref	F	EC
			m	m		mg/l	us/cm
9	BH-50	9	489000	860000	7	0.47	390
11	BH-79	11	445942	888136	7	1.46	599
12	CS-34	12	506276	876854	7	2.93	121
21	DW-9	21	433314	895011	4	0.70	500
22	Hs-27	22	476071	852375	8	0.1	660
23	Hs-28	23	469455	850822	8	0.11	630
24	Hs-29	24	476776	849776	8	1.2	3298
25	BH-1	25	506221	884425	1	3.40	420
32	BH-2	32	459229	882481	1	14.70	1430
46	BH-45	46	469716	890725	8	2.33	410
47	BH-46	47	462304	867052	8	1.82	440
48	BH-47	48	461694	809225	8	1.25	232
50	BH-49	50	500000	883000	7	1.10	190
53	BH-53	53	461137	815099	8	0.39	1100
54	BH-54	54	472794	814100	8	0.00	680
55	BH-57	55	465405	810049	8	0.58	2030
61	BH-80	61	467183	869410	7	1.52	953
62	BH-81	62	465705	820049	7	1.56	183
63	BH-82	63	495517	871107	7	1.76	255
64	BH-84	64	497428	892538	7	0.11	362
65	BH-87	65	504694	889596	7	1.52	347
67	BH-91	67	491948	870967	7	2.83	924
68	CS-1	68	430263	842828	1	3.10	485
72	CS-19	72	476206	852307	8	2.22	654
73	CS-2	73	402435	857389	1	2.50	345

ID	SampleID	Label	X	Y	Ref	F	EC
74	CS-21	74	478784	846641	8	1.81	310
75	CS-22	75	476797	850890	8	0.09	272
76	CS-23	76	470839	851126	8	1.72	276
77	CS-27	77	479186	846962	7	1.46	269
79	CS-33	79	506994	877916	7	0.32	119
86	DW-1	86	438997	893658	1	1.30	600
92	DW-2	92	463082	855772	1	3.20	660
101	GTW-2	101	473130	861620	6	2.00	350
102	HS-26	102	478784	846641	7	1.76	587
104	HS-7	104	432095	878479	4	5.20	3000
114	BH-62	108	470161	868877	8	1.84	1200
117	DW-36	111	469472	871897	8	0.28	1100
118	DW-37	112	468340	885071	8	0.24	1500
119	DW-38	113	463022	875771	8	0.14	1600
120	GTW-1	114	473069	857081	6	25.00	1860
123	HS-2	116	460229	825336	1	82.00	7330
126	GTW-4	119	484614	857721	6	27.80	3350
127	GTW-5	120	484888	854858	6	23.00	2990
128	GTW-7	121	482908	854827	6	27.00	2880
129	GTW-8	122	481995	863631	6	48.00	2750
131	HS-4	124	475903	848260	1	31.00	2830
133	GTW-3	126	481477	857142	6	40.80	2110
134	GTW-6	127	482543	859762	6	36.60	2740
135	HS-3	128	476380	852515	1	19.40	5830
137	DW-39	130	466107	876528	8	0.66	1600
138	TW-2	131	480927	855133	6	26.00	2300
139	TW-4	132	481672	854871	6	67.00	2640

ID	SampleID	Label	X	Y	Ref	F	EC
143	BH-98	133	465849	875172	8	22.20	2044
144	BH-99	134	469780	886339	8	3.00	1129
145	BH-100	135	461636	876692	8	10.90	1108
146	BH-101	136	467850	876939	8	2.00	843
147	BH-102	137	454205	927485	7	0.53	336
149	BH-104	139	440104	897285	7	0.72	387
150	BH-105	140	497428	892538	7	2.00	362
151	BH-106	141	512305	888797	7	0.07	598
153	BH-108	143	496897	878167	7	0.32	382
155	BH-110	145	489629	867767	7	0.56	404
156	BH-111	146	494513	874565	7	0.89	327
157	BH-112	147	492768	900237	7	0.98	409
170	BH-125	155	463641	815493	7	1.85	200
171	BH-126	156	463869	818142	7	1.43	200
172	BH-127	157	468074	818339	7	1.59	300
173	BH-128	158	466285	808653	7	1.89	300
174	BH-129	159	468515	812780	8	1.1	200
175	BH-130	160	461832	818752	8	0.54	200
176	BH-131	161	461694	809225	8	1.25	200
177	BH-132	162	457346	800261	8	1.26	100
178	BH-133	163	454757	802859	8	79.5	100
179	BH-134	164	447039	791276	8	11.6	800
180	BH-135	165	443435	793226	8	0.76	1400
181	BH-136	166	413624	805137	8	1.83	552
182	BH-137	167	418707	805069	8	5.05	700
183	BH-138	168	469242	806043	8	0.76	200
184	BH-139	169	470180	807113	8	0.7	100
185	BH-140	170	468826	804967	8	1.43	300
191	BH-146	173	480034	902598	8	0.22	744
192	BH-147	174	453540	880517	8	66.00	1658
193	BH-148	175	468549	879876	8	11.85	1026
195	BH-150	176	469214	876445	8	2.31	841

ID	SampleID	Label	X	Y	Ref	F	EC
196	BH-151	177	463022	881265	8	20.20	2444
197	BH-152	178	468340	885071	8	6.80	1535
198	BH-153	179	462287	874686	8	12.50	1287
204	CS-45	184	476071	852375	8	1.90	660
205	CS-46	185	469455	850822	8	2.10	630
206	CS-47	186	476776	849776	8	22.70	3298
207	CS-48	187	458982	928434	7	1.05	214
208	CS-49	188	520028	846699	7	1.39	92
209	CS-50	189	517502	856932	7	1.42	116
210	CS-51	190	506630	881603	7	1.47	130
211	CS-52	191	519559	866324	7	1.52	87
212	CS-53	192	524458	845085	7	1.71	73
213	CS-54	193	501708	882598	7	3.33	157
220	DW-64	198	461400	853200	8	1.56	560
221	DW-65	199	466171	853151	8	2.00	636
226	DW-70	203	469472	871897	8	5.40	110
227	DW-71	204	468340	885071	8	4.50	150
228	DW-72	205	463022	875771	8	2.60	16
229	DW-73	206	466107	876528	8	12.50	160
230	DW-74	207	464619	883154	8	16.20	2444
231	DW-75	208	468966	875469	8	4.10	2044
232	DW-76	209	468339	882533	8	12.20	2516
233	DW-77	210	467160	882850	8	11.70	1935
234	DW-78	211	465611	870255	8	5.70	899
235	DW-79	212	464487	870520	8	3.65	900
236	DW-80	213	469596	884833	8	4.60	1416
237	DW-81	214	479438	899958	7	3.43	2110
238	DW-82	215	484556	900062	7	3.49	1979
239	DW-83	216	479284	897491	7	4.07	1872
240	DW-84	217	478626	896813	7	5.78	748
241	DW-85	218	478624	898012	7	8.69	1014
242	DW-86	219	469574	886013	7	10.84	1368

ID	SampleID	Label	X	Y	Ref	F	EC
243	DW-87	220	469720	885980	7	15.20	990
244	DW-88	221	469116	880786	7	38.83	206
245	DW-89	222	504303	888600	7	104.23	678
259	L-1	234	459848	834000	1	190.00	26000
260	L-2	235	456561	854364	7	2.15	3100
261	L-3	236	470997	875048	8	1.05	426
263	L-5	237	472772	875967	8	0.95	420
264	L-6	238	470297	875979	8	1.01	416
265	L-7	239	465212	832755	8	1.91	1610
266	L-8	240	465994	838411	8	1.91	1630
267	L-9	241	453038	835315	8	183.00	27356
268	L-10	242	458218	821044	8	196.00	27488
271	L-13	244	469774	877102	7	1.22	428
274	L-16	247	500454	884887	1	0.30	200
275	RV-1	E1	461066	853323	5	3	190
276	RV-2	E2	461232	853940	5	2.1	400
277	RV-3	E3	451466	897888	5		309

Source:

1: Tenalem Ayenew, 1994
2: Tenalem Ayenew, 1995
3: Tenalem Ayenew, 1996
4: Chernet, 1982
5: Winter, 1973
6: EIGUS Unpublished report
7: Region-4 Water Resource Bureau, unpublished report,2002
8: Shemelis Fikre, 2006

Appendix 5 Basic statistics for Subgroups' (derived from HCA) Parameters

Subgroup	Basic Statistics	Ca (meq/l)	Mg (meq/l)	Na (meq/l)	K (meq/l)	CO_3 (meq/l)	HCO_3 (meq/l)	Cl (meq/l)	SO_4 (meq/l)	TDS (mg/l)
1	Maximum	2.05	1.18	6.31	1.20	0.73	9.06	3.62	0.44	885
	Minimum	0.21	0.08	0.17	0.02	0.00	0.90	0.02	0.00	72
	SD	0.50	0.29	1.67	0.26	0.28	2.02	0.90	0.12	196
2	Maximum	1.27	0.88	19.84	0.91	0.97	16.50	6.01	0.94	1806
	Minimum	0.00	0.00	0.22	0.03	0.00	0.56	0.00	0.00	100
	SD	0.26	0.19	4.07	0.18	0.18	3.52	0.83	0.16	389
3	Maximum	0.35	0.21	24.19	2.33	2.30	17.68	9.03	0.56	1969.00
	Minimum	0.00	0.00	9.57	0.30	0.00	7.60	0.00	0.00	600.00
	SD	0.13	0.06	5.24	0.69	0.92	3.13	3.52	0.17	439.52
4	Maximum	0.07	0.04	104.40	1.07	8.00	48.58	45.47	1.10	7443.00
	Minimum	0.00	0.01	87.00	0.95	4.40	40.48	27.05	0.42	5790.70
	SD	0.04	0.02	9.25	0.06	2.03	4.05	10.17	0.36	837.11
5	Maximum	0.09	0.06	56.55	3.53	0.70	38.99	18.93	1.67	4424.00
	Minimum	0.01	0.01	31.54	1.18	0.00	9.90	8.52	0.20	2235.70

	SD	0.03	0.02	7.77	0.90	0.25	8.34	3.65	0.52	783.89
6	Maximum	0.18	0.44	73.95	5.70	3.25	36.06	19.18	4.06	4605.70
	Minimum	0.01	0.01	26.93	3.32	0.00	14.00	7.14	3.19	2164.60
	SD	0.10	0.25	26.32	1.24	1.88	12.08	6.02	0.46	1243.09
7	Maximum	0.18	0.06	36.97	2.31	1.25	36.96	8.60	4.62	3354.00
	Minimum	0.00	0.00	20.00	0.51	0.00	6.47	0.56	2.13	1400.00
	SD	0.06	0.02	5.61	0.61	0.49	9.25	3.04	0.88	695.34

Appendix 6 Borehole hydraulic conductivity

Name	*X(UTM)*	*Y(UTM)*	*Total Depth(m)*	*Hyd Conduct(m\day)*	*Aquifer*
BH-1	521251	846143	80	38.58	Ignimbrite
BH-2	511000	856242	151	0.03	Ignimbrite
BH-3	510944	862096	125	0.02	Ignimbrite
BH-4	515055	866097	168	18.14	Ignimbrite
BH-5	514701	870557	115	0.02	Ignimbrite
BH-6	520076	882997	105	41.6	Ignimbrite
BH-7	519294	884778	120	0.08	Ignimbrite
BH-8	455519	798303	145	0.24	Ignimbrite
BH-9	412288	830368	145	8.67	Ignimbrite
BH-10	431494	841849	186	6.14	Lacustrine Sediment

BH-11	429285	849711		13.87	Ignimbrite
BH-12	440615	852123	85	6.69	Lacustrine Sediment
BH-13	464529	814467	109	0.73	Vocanic Sand
BH-14	459185	902574	122	2.94	Lacustrine Sediment
BH-15	501805	895996	102	4.12	Basalt
BH-16	462853	870941	71	8.4	Lacustrine Sediment
BH-17	461786	852249	71	3.12	Lacustrine Sediment

Appendix 7 Isotope Data

Cold Springs

No	***Sample_ID***	***Label***	***Location(UTM)***		^{18}***O*** (‰)	^{2}***H*** (‰)	^{3}***H*** ***(TU)***	***Cl*** (mg/l)	***F*** (mg/l)	***EC*** (µs/cm)	***DATE***	***T(⁰C)***	***pH***
			X(m)	Y(m)									
1	CS-1	a1	424762	885865	-2.44	-3.70		4.0		208	77		
2	CS-2	a2	425733	898162	-2.55	-3.10		9.0		390	77		
3	CS-3	a3	530253	862243	-1.89	-2.10	nd	4.0	1.0	120	77	17.9	6.4
4	CS-4	a4	479449	809174	-1.62	2.90				185	77		
5	CS-5	a5	439648	913371	-2.21	-4.05					96		
6	CS-6		ET38		-3.49	-12.00	nd	5.0	2.6	156	77	nd	7.1
7	CS-7		ET39		-3.33	-10.20		4.0		198	77		7.6
8	CS-8		ET40		-3.32	-10.20	nd	5.0	1.3	218	77	nd	7.3
9	CS-9		ET50		-2.06	-3.30					77		

Hot Springs

No	*Sample_ID*	*Label*	*Location(UTM)* X(m)	Y(m)	^{18}O (‰)	^{2}H (‰)	^{3}H (TU)	*Cl* (mg/l)	*F* (mg/l)	*EC* (µs/cm)	*DATE*	$T(^0C)$	*pH*
1	HS-10		ET26		-0.44	2.50	0.00	449.0	14.0	3320	77	96.0	8.7
2	HS-11		ET27		-3.48	-13.00	0.50	34.0	1 7	590	77	38.0	7.9
3	HS-12		ET30(Shala HS)		2.50					10000	77		
4	HS-13		ETH39		-2.46	-10.10	1.30	168.0	nd		92	65.0	8.3
5	HS-14		Springs		-0.80		nd	305.0	nd		88	93.2	8.5
6	HS-15		Spring6		-1.20		nd	300.0	nd		88	94.3	7.5
7	HS-16		Spring84		-1.30	-1.00	0.00	331.0	nd		88	60.7	7.6
8	HS-17		Spring94		-0.20	17.00	0.00	238.0	nd		88	0.0	8.8
9	HS-18		UN73.12		0.00	0.00	0.00	449.0	14.0		73	93.0	8.9
10	HS-19		UN73.16		0.00	0.00	0.00	34.0	2.0		73	38.0	8.0
No	*Sample_ID*	*Label*	*Location(UTM)* X(m)	Y(m)	^{18}O (‰)	^{2}H (‰)	^{3}H (TU)	*Cl* (mg/l)	*F* (mg/l)	*EC* (µs/cm)	*DATE*	$T(^0C)$	*pH*
11	HS-2	b2	474644	852428	-0.87	-2.20	nd	272.0	1 2	2580	73	91.7	8.8
12	HS-20		UN73.84		0.00	0.00	0.00	339.0	38.0		73	61.0	8.3
13	HS-21		SP10		-0.53	1.40	0.30	649.0	nd		73	0.0	9.1
14	HS-22		SP12		-0.30	2.20	0.20	500.0	nd		92	0.0	9.2
15	HS-23		SP119		-0.35	1.20	0.60	492.0	nd		92	0.0	9.2
16	HS-24		SP119		-0.51	2.00	0.40	480.0	nd		92	0.0	9.2
17	HS-25		Oitu		-1.40	-0.68		318.0	38.0	3298	96		6.6
18	HS-26		Oitu		1.57	16.60		1612.0	20.0		96		
19	HS-3	b3	476380	852515			0.20			2500	77		
20	HS-4	b4	474644	852428	-1.19	1.20	0.10	493.0	nd		92	61.0	8.3
21	HS-5	b5	474644	852428	-3.08	-10.50	2.00	1 16	nd		92	46.0	8.0
22	HS-6	b6	475903	848260	-3.56	-14.58		520.0	31.0	2930	96		

23	HS-7	b7	459615	826048	2.69	25.20		228.0	10.0		96		
24	HS-8		ET11 (Imba Koto)		-3.66			21.0		1100	77		
25	HS-9		ET25		0.39	3.60	0.00	2.0	nd	125	77	96.0	6.8

Lakes

No	***Sample_ID***	***Label***	***Location(UTM)***		^{18}***O*** (‰)	^{2}***H*** (‰)	^{3}***H (TU)***	***CI*** (mg/l)	***F*** (mg/l)	***EC*** (µs/cm)	***DATE***	***T(^{0}C)***	***pH***
			X(m)	Y(m)									
1	LK-1	c1	459090	840967			1.07		190.0	11000	Apr-06		
2	LK-10	c5	447612	821037	8.28	54.40					77		
3	LK-11	c6	448182	825023	8.30	54.40				23500	77		9.6
4	LK-12	c7	447612	829009	8.49	48.40					96		
5	LK-13	c8	469819	836981	6.85	45.80	nd	202.0	15.3		77	nd	8.8
6	LK-14	c9	470389	843814	7.00	53.00	nd	180.0	nd	1780	88	25.0	9.1
No	***Sample_ID***	***Label***	***Location(UTM)***		^{18}***O*** (‰)	^{2}***H*** (‰)	^{3}***H (TU)***	***CI*** (mg/l)	***F*** (mg/l)	***EC*** (µs/cm)	***DATE***	***T(^{0}C)***	***pH***
			X(m)	Y(m)									
7	LK-15	c10	474375	834134	6.73	45.00	nd	1 80	1 3		77	nd	9,2.
8	LK-16	c11	471528	847230	7.10						92		
9	LK-17	c12	475513	877979	5.89	43.20	8.00	156.0	nd		92	nd	9.2
10	LK-18	c13	476083	884242	6.70	49.00	nd	18.0	nd		88	22.0	7.3
11	LK-19	c14	480069	890506	6.94	48.20	5.50	14.0	nd		92	nd	8.4
12	LK-2	c2	466947	840824			2.14			1850	Apr-06	26.0	9.0
13	LK-20	c16	478930	872854	3.65					435000	96		
14	LK-21	c17	459650	827035			6.70						
15	Lk-22	c15	Chitu		10.48						77		
16	LK-3	c3	459515	826048			3.59		196.0	21900	Apr-06	26.0	10.0
17	LK-4	c4	469774	877102			3.44	8.0	1.2	465	Apr-06	23.0	9.0
18	LK-5	c18	455584	845522	10.00	64.20				16200	77		9.6

19	LK-6	c19	459000	840967	10.00	64.20	nd	1896.0	1 20		77	24.2	9.6
20	LK-7	c20	457292	835273	10.00	46.85					96		
21	LK-8	c21	454445	828440	7.09	54.50				23500	77		9.6
22	LK-9	c22	453876	822176	8.00	54.30					77		

Rain

No	***Sample_ID***	***Label***	***Location(UTM)***		^{18}***O*** (‰)	^{2}***H*** (‰)	^{3}***H*** (TU)	***Cl*** (mg/l)	***F*** (mg/l)	***EC*** (µs/cm)	***DATE***	***$T(^0C)$***	***pH***
			X(m)	Y(m)									
1	RN-1	d1	477246	847603	-2.85	-3.70	4.90	nd	nd		92	nd	nd
2	RN-2	d2	514542	880766	-0.26	11.90					93		
3	RN-3	d3	431210	898294	0.49	8.05					96		
4	RN-4	d4	468725	877076	-0.70	12.85					96		

River

No	***Sample_ID***	***Label***	***Location(UTM)***		^{18}***O*** (‰)	^{2}***H*** (‰)	^{3}***H*** ***(TU)***	***Cl*** (mg/l)	***F*** (mg/l)	***EC*** (µs/cm)	***DATE***	***$T(^0C)$***	***pH***
			X(m)	Y(m)									
1	RV-1	e1	461066	853323			0.58			807	Apr-06	23.0	8.0
2	RV-10		ET37		-2.93	-8.20	nd	4.0	1 .1	258	77	nd	7.8
3	RV-11		ET47		-0.65	6.30				262			7.6
4	RV-12		ETH40		-1.66	-3.60	8.90	8.0	nd	258	77	20.0	7,7
5	RV-13		RV1		-0.87	7.25							
6	RV-14		RV2		-1.06	1.60							
7	RV-2	e2	461232	853940	5.29	39.00				360			7.6
8	RV-3	e3	451466	897888	0.70	7.50				480			8.0
9	RV-4	e4	464895	849454	6.85	45.80				1820			6.8
10	RV-5	e5	421760	838070	0.58	5.20				510			7.7
11	RV-6	e6	470999	818130	-0.59	6.40	nd	2.0	1.0	72	77	nd	7.8

12	RV-7	e7	511691	883239	-2.03	0.10	nd	2.0		262	93	nd	8.3
13	RV-8	e8	471812	828302	-1.90	-1.00	nd	7.0	nd		88	20.0	6.8
14	RV-9		ET34		-0.73	5.70	nd	4.0	0.7	88	77	nd	7.8

Well

No	***Sample_ID***	***Label***	***Location(UTM)***		^{18}***O*** (‰)	^{2}***H*** (‰)	^{3}***H (TU)***	***Cl*** (mg/l)	***F*** (mg/l)	***EC*** (μs/cm)	***DATE***	***T(^{0}C)***	***pH***
			X(m)	Y(m)									
1	WL-1	f1	467974	863049	4.28	32.60		14.0		900	77	30.0	8.1
2	WL-10	f2	482908	854827	-2.40	-8.00	nd	385.0	nd		88	124.0	9.0
3	WL-11	f3	481995	863631	-1.30	-13.00	nd	374.0	nd		88	340.0	6 09
4	WL-12	f4	479438	899958	-1.95	-3.93					96		
5	WL-13	f5	467892	869314	4.45	32.38					96		
6	WL-14	f6	501935	888761	-3.37	-11.30					96		
No	***Sample_ID***	***Label***	***Location(UTM)***		^{18}***O*** (‰)	^{2}***H*** (‰)	^{3}***H (TU)***	***Cl*** (mg/l)	***F*** (mg/l)	***EC*** (μs/cm)	***DATE***	***T(^{0}C)***	***pH***
			X(m)	Y(m)									
7	WL-15	f7	492768	900237			1.04			969	Apr-06		
8	WL-16	f8	489629	867767			0.95	1.7	0.6	404	Apr-06	26.0	8.0
9	WL-17	f9	512305	888797			0.24	0.4	0.1	598	Apr-06	26.0	6.0
10	WL-18	f10	445942	888136			5.10	2.4	1.5	599	Apr-06	25.0	7.0
11	WL-19	f11	440099	905430			2.81	1.3	0.7	385	Apr-06	27.0	7.0
12	WL-2	f12	467797	878153	5.04	36.20		16.0		900	77	24.0	7.4
13	WL-20	f13	467183	869410			0.78		1.5	1480	Apr-06	29.8	8.4
14	WL-21	f14	483254	898446			1.88			665	Apr-06		
15	WL-22	f15	469716	890725			3.19			520	Apr-06		
16	WL-23		Wild Life of langanoo		-0.50	5.30	0.00	209.0	nd	1420	77	45.6	8.2
17	WL-24*		Langanoo hot well		0.39	10.00	0.00	291.0	nd		77	43.0	9.1
18	WL-25*		Langanoo hot well		0.00	1 1	0.00	405.0	nd		88	53.0	9.4

19	WL-26*		Langanoo hot well		-1.20	4.00	0.00	315.0	nd		88	61.0	8.8
20	WL-27*		Langanoo hot well		-0.80	3.00	0.00	501.0	nd		88	74.0	7.2
21	WL-28*		Aluto LA-3		-0.78	-6.90	0.10	191.0	nd		92	314.0	8.7
22	WL-29*		Aluto LA-6		-0.03	-10.10	0.20	269.0	nd		92	335.0	8.3
23	WL-3	f16	479815	900819	-2.73	-8.10		27.0		1100	77	45.0	7.8
24	WL-30*		Aluto LA-9		-2.03	-5.50	0.50	279.0	nd		92	282.0	8 28
25	WL-4	f17	456844	884690	-3.53	-15.00		9.0		690	77	35.0	7.6
26	WL-5	f18	440615	832269	-4.12	-24.10	0.00	36.0	32.5	1560	77	34.0	9.0
27	WL-6*	f19	473069	857081	6.00	46.00	nd	238.0	nd		88	73.0	9,6
28	WL-7*	f20	473130	861620	6.70	46.00	nd	20.0	nd		88	96.0	9.1
29	WL-8*	f21	484614	857721	-1.40	-8.00	nd	671.0	nd		88	235.0	6.7
30	WL-9*	f22	484888	854858	-2.60	7.00	nd	451.0	nd		88	282.0	8.3

Source: - ***Apr-06***=Shemelis Fikre (2006), 96=Tenalem Ayenew (1996), ***92*** and ***93***= Geothermal exploration project (EIGS, 1992-1993), ***88***=Gizaw et.al.(1988), ***77***=Craig et.al(1977), ***73***= UN(1973).

Note: * represents Geothermal wells.