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# ADDIS ABABA UNIVERSITY

## School of Earth Sciences


# Lake-Groundwater Interaction and Isotope Mass Balance of lake Ziway An Integrated approach

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


**CHAKA CHANDE LOLLO**


**SEPTEMBER, 2020**

**ADDIS ABABA, ETHIOPIA**

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**By**

**Chaka Chande Lollo**

| **Approved by Board of Examiners:** | **Signature** |
| --- | --- |
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| **Dr. Tilahun Azagegn** (Advisor) | ______________________________ |

## Abstract

An integrated approaches based on the application of stable isotope of water ($^{2}H$ and $^{18}O$), radiogenic-isotope of Radon ($^{222}Rn$) and piezometric evidences are employed in this research to determine the interaction between the lake water and the adjacent groundwater and to evaluate the water balance of the lake Ziway particularly for estimating the groundwater inflows and outflows of the lake.

The result based on $\delta^{18}O$-isotope mass balance of the lake shows groundwater inflow accounts for about 4% of total inflow and groundwater outflow accounts for about 8% of total outflow.

With respect to the lake and groundwater interaction, the analysis of isotopic compositions of groundwaters shows groundwaters located in the south and southwest of Lake Ziway have similar isotopic composition to that of the lake. This demonstrates the lake and groundwater interaction in that sector of the lake. In contrast groundwater located in the highlands and escarpments displays isotopic composition similar to the precipitation, portraying no hydrologic link between the lake and the subsurface waters in these sectors.

Radon-222 concentrations in the lake varied spatially from less than 35.2 – 96.6 Bq/m$^3$. Results from $^{222}Rn$ measurements shows high concentration values of 96.6 Bq/m$^3$ and 78.5 Bq/m$^3$ at the northeast and southeast shores of the lake respectively demonstrating lacustrine groundwater discharges into the lake in that regions from local flow systems.

The piezometric evidence is also in support of this observation. In the region between northeast and southeast groundwater level lies above the lake surface level and this indicates the groundwater flow to the lake. In the western and southern sectors of the lake the groundwater level lies below lake level and thus demonstrates groundwater flow direction to the south and southwest.

Evidences from various methods clearly proved the presence of lake and groundwater hydraulic link in the south and southwest sectors indicating the lake recharges the groundwater. This work in particular demonstrates the importance of stable isotope of water in defining separately the groundwater flux components of the hydrologic budget of the lake and in determining the lake-groundwater interaction.


Key Words: - Lake Ziway; Lake-Groundwater Interaction; Lake Water Balance; $^{222}Rn$ Activity; Stable Isotopes ; Piezometric evidence; Water Resource Management; Ecosystem,

## *Acknowledgment*

Foremost, I would like to express my sincere gratitude to my former advisor Dr. Seifu Kebede and my present advisor Dr. Tilahun Azagegn for their persistent support, remarkable patience, and immense knowledge sharing. Their guidance has helped me in all the time of my research work and writing of this thesis.

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# Acronyms

| | |
|---|---|
| AAU | Addis Ababa University |
| $Bq/m^3$ | Becquerel per Meter cube |
| DEM | Digital Elevation Model |
| EARS | East African Rift System |
| EC | Electrical Conductivity |
| FAO | Food Agricultural Organization |
| GMWL | Global Meteoric Water Line |
| GSE | Geological Survey of Ethiopia |
| GPS | Global positioning system |
| IAEA | International Atomic Energy Agency |
| ITCZ | Inter Tropical Convergence Zone |
| LMWL | Local Meteoric Water Line |
| LZB | Lake Ziway basin |
| MER | Main Ethiopian Rift |
| MOWIE | Ministry of Water Irrigation and Energy |
| MWR | Ministry of Water Resource |
| NMSA | National Metrological Service Agency |
| OWWDSE | Oromia Water Works Design and Supervision Enterprise |
| SDZFZ | Silti-Debrezeit fault zone |
| TDS | Total dissolve solids |
| UNDP | United Nation Development Program |
| UNESCO | United Nations Educational, Scientific and Cultural Organization |

| | |
|---|---|
| USGS | United States Geological Survey |
| VSMOW | Vienna Standard Mean Ocean Water |
| WFB | Wonji Fault Belt |
| WWDSE | Water Works Design and Supervision Enterprise |
| ZSB | Ziway-Shala Basin |

# 1. Introduction

## 1.1 Background Information

Lake Ziway is the only freshwater lake in the central MER (that constitutes a group of four lakes) which provides a number of multiple uses including water supply and ecological services. The interaction of the lake with the contiguous groundwater and the groundwater fluxes, the often overlooked components, of the hydrologic budget is not studied.

Determining the interactions between lake and the adjacent groundwater systems is critical to understanding hydrogeological systems, protecting lake's ecosystems, and managing water resources. In particular, it is vital to define the groundwater inflows and outflows of the lake and whether the lakes recharge local groundwater or are fed by groundwater and to evaluate the magnitude of the flux between groundwater and the lake.

In past, surface water and groundwater systems have been treated as separate entities in the research, development and management of water resources. However, it has become apparent that they are a linked components of a hydrologic systems which continuously interact in many different ways. In the recent years, some scholars such as Winter et al (1998) and Sophocles (2002) have attempted to describe the interaction of groundwater with surface waters (streams, lakes and wetland). And further noted the chemical interaction between them, the interaction in different geologic settings, the impacts of anthropogenic activities on the interactions, and in conclusion emphasized the need to consider them as a single source.

Groundwater and surface waters interacts in various ways. In addition to precipitation (direct recharge) water in lakes, wetlands, and streams can recharge groundwater systems, and vice versa: groundwater systems discharge into lakes, wetlands, and streams. Because of such interchange of water between these two components of the hydrologic system, development or contamination of one commonly affects the other (Winter et al. 1998). Uncontrolled exploitation of water from either groundwater or surface waters can result in a far-reaching decline in groundwater watertable, lake levels drop or drying of streams.

In Ziway lake basin where population growth, expansion of large and small industries and irrigation sites, and climate changes are leading to constantly increasing demand for water an understanding of their interactions is critical in water protection and conservation efforts. It is also evident that protection of both groundwater and surface water, is of major importance for sustaining their multiple uses such as water supply, fish and wildlife habitats, swimming, and fishing (Kebede et.al 2009; Ayenew, 1998).Such expansion and development has brought stress on demand of water. This further exacerbates the already existing shortage of water in the area owing to water quality problems that usually related to hydrogeochemical processes.

Therefore, carrying out lake water and groundwater interactions researches, particularly in such regions where there is a competing demand for water resources, has its own significance to improve the evaluation of the water resources and to make rational use of them. Investigation of groundwater surface water interaction provides vital information for water resource management sectors to evaluate water resource allocation, needs and impacts on lake-groundwater ecosystem (Sophocles, 2002).

The interactions of lake-groundwater, the discharge of groundwater to lake and the opposite flow direction the recharge of lake to groundwater aquifer, can be estimated indirectly by balancing method of environmental tracers. Environmental tracers such as stable and radiogenic isotopes measured in lake waters and groundwater provides important information for a systematic understanding of the hydrologic fluxes between lake water and groundwater. For this research an integrated approaches is used to delineate areas of lake-groundwater interaction and quantification of groundwater components of the hydrologic budget. The investigation utilizes measurement of Radon ($^{222}$Rn) and analysis of stable isotopes results of Hydrogen and Oxygen ($\delta^{2}$H and $\delta^{18}$O) coupled with piezometric evidences. These environmental tracers are the well-recognized tools to examine the bidirectional flow of water and to quantitatively estimate the hydrologic fluxes of a lake.

Therefore, conducting such a groundwater and surface water interaction studies provide useful information for the sustainable utilization of both groundwater and surface water resources. Sustainable utilization of these water resources, in turn assists to protect the fragile ecosystem from various adverse factors, that can be caused by natural process or anthropogenic factors.

## 1.2 Research Objectives

The primary objective of the research is to investigate surface water-groundwater interaction and to determine the isotope mass balance of Lake Ziway.

The specific objectives of this research are

- To investigate the surface water-groundwater interaction around the lake using radiogenic isotope ($^{222}$Rn) and also to delineate the recharge and discharge zone.
- To determine direction of groundwater flow using stable isotopes ($\delta^{18}$O-δD ) and piezometric evidences
- To quantitatively estimate the water balance of the Lake employing the stable isotope ($\delta^{18}$O-δD) mass balance method

## 1.3 The Structure of the Thesis

The thesis is organized in five chapters. After the introduction to the general problem and research objectives (Chapter 1), Chapter 2 presents a general description of methodologies employed to the determination of Lake-Groundwater interaction, the estimation of the evaporation of the lake and identification of the groundwater recharge and discharge zones using integrated techniques including isotope hydrology and piezometric data, Characterization of the study site is discussed in Chapter 3. Chapter 4 is devoted to the presentation and discussion of the study findings. The final chapter 5 gives the conclusion and recommendation of this work. It summarizes the research by converging outcomes from different approaches used in the study and by forwarding imperative recommendation.

## 1.4 Literature Reviews

In Ethiopia varies studies have been carried out on the lakes of Ethiopian rift valley from different view points of interest by national and international scholars. A number of studies that have been carried out in the Ziway-Shala Basin (ZSB) include investigations for geology and volcano-tectonics purposes (Di Pola, 1972; Dainelli et al., 2001), surface and groundwater potential (Wenner, 1972; HALCROW,1989), a regional geology and hydrogeology of lake districts (Chernet, 1982), geothermal energy sources (UNDP,1973) , the paleo-environment reconstruction (E.Gilbert, et.al 2008), lake level changes and hydrogeochemistry of lakes and groundwaters (Alemayehu et al., 2005 ; Fikre, 2006 ), the evaluation of groundwater and surface water interaction (Ayenew, 1998; Ayenew et al., 2008; Deribissa, 2006); estimates of evaporation rate from Ziway lake ( Vallet-Coulomb, et al., 2001); Analysis of hydrological response of Ziway–Shala basin to changes in climate and human activities (Legesse, 2002); the $\partial^{18}O$ and $\partial^{2}H$ enrichment of Ethiopian lakes ( Kebede et al., 2008 ); Lake-groundwater relationships, oxygen isotope balance and climatic sensitivity of the Bishoftu crater lakes. (Kebede, et al., 2002); etc.

When one examines the details of some of the studies conducted to date with respect to the hydrology, hydrogeology, hydrogeochemistry of the ZSB, there is no researches that were carried out with specific consideration to evaluate the interaction of the lake and the contiguous groundwater in the area and further to specifically estimate groundwater inflow and outflow components separately, which is either neglected or calculated as net-flux or a difference parameter. The current study considers the isotopic signatures of the lake water and groundwater coupled with piezometric evidences to critically understand the hydraulic exchange of the lakes and groundwater and determine the groundwater flux separately which is the often overlooked parameter in the lake water balance and the gap observed in the research. Determination and delineation of the interaction perimeters of the lakes and groundwater; and quantification of the groundwater components separately of lake water budgets are new works that supplement the existing ones, thus bridging the research gap, providing useful information for policy makers and general public to manage these resources on sustainable basis. And further paves ways for similar new researches in the Ethiopian Lakes hydrologic balance studies using the environmental isotopes as ideal tracers.

### 1.5 Statement of the Problem and Research questions

Many researches and studies have been carried out on Ziway-Shala Basin concerning various groundwater and surface water issues. In these previous studies a systematic investigation of the lake water and groundwater interactions and the determination of the groundwater components in water balance of the lake Ziway are not taken into consideration. Consequently, this research is aimed to answer 1.) Whether there exist any interaction between Groundwater and Lake Ziway? 2.) What is groundwater flow direction in Lake Ziway environs? 3.) What are the magnitude of groundwater flux components in the lake water budget?

## 1.6 Relevance of Research

An effective utilization and sustainable management of water resources in the study basin calls for the understanding of groundwater and surface water interaction and treating both resources as being a single interconnected system. Particularly, in order to responsibly develop and manage lakes it is important to understand fluxes into and out of lakes. Groundwater and surface water inflow play an important role in controlling lake water balance, water chemistry, aquatic habitat and biodiversity. Surface water inflows to lakes are relatively easy to characterize, but groundwater inflows remains less obvious or unrecognized. Several cases have been observed where contaminant and/or nutrient-rich groundwater entering lakes has led to lake pollution and/or eutrophication (Hagerthey and Kerfoot, 1998; Zhang et al., 2010; Zhu and Schwartz, 2011).

Lake Ziway, the only fresh water lake among the four series of the lake in Ziway-Shala basin, is currently under intense pressure attributed to natural and anthropogenic factors. The lake has experienced a decline in water level and water quality as well (Jansen, 2007; OWWDSE, 2016). Characterizing the groundwater–lake interactions may provide some insight into processes controlling the hydrologic, hydrogeologic and further nutrients dynamics within Ziway Lake.

Flow of Groundwater to lakes or vice-versa can be especially difficult to determine using traditional techniques because of the large degree of heterogeneity in geologic material—especially in fractured and faulted terrain of Lake Ziway.

Many of studies conducted in the area provide a general overview of the hydrology of Lake Ziway. Conversely, none of these studies addressed an important groundwater issues such as groundwater recharge and discharge, and magnitude of groundwater fluxes of budget of the lake.

Considering the fact that still exists a knowledge gap regarding understanding the interactions of the lake and groundwater , this study is conducted with the primary objective of understanding the role of lake in the hydrologic system of the groundwater and particularly to quantitatively know the groundwater components in the water budget of Lake Ziway. This study applies an integrated approach of environmental stable and radiogenic isotope methods in conjunction with piezometric evidences. It can bridge the existing gap in the lack of information on lake-groundwater interactions in the area and help illustrates the significance of groundwater for the hydrology of Lake Ziway. The results could also support the development of efficient and all-inclusive lake management plans to monitor Lake Ziway and the contingent ecosystem in environmentally acceptable and financially plausible ways.

# 2. Methodology of the Research

## 2.1. Material Used and Sampling

Different materials used for this research are

- Geological map, hydrogeological map and DEM (digital elevation model)
- Software's: Arc-GIS 10.3, Global Mapper 13, Surfer 10, Grapher 8, Starter 4, Microsoft Offices, (MS-word, MS-excel),
- GARMIN GPS-Vista (hand GPS)
- Bottles for collection of borehole and spring water samples
- RAD-7 with its accessories including the big bottle, the desiccant (the drying unit for extracting the humidity from the gas loop before entering to the RAD-7 instrument)

Lake water samples are collected for the isotopic composition analysis ($^{18}O$and $^{2}H$) and radon concentration measurement. The sampling also included groundwaters, springs and river waters in the vicinity of the lake.

The radon concentration measurement is carried out using RAD7, the highly versatile portable radon detector. The RAD7 is operated through five modes available: Sniff, Auto, Wat-40, Wat-250, and Normal. SNIFF mode is used to follow rapid changes of radon concentration. This mode sets the RAD7 to detect only the radon and is used in this study to measure the radon concentration of the lake. The readings was taken along longitudinal transects and perimeters of the lakes. These lines were selected based on hydrologic set up of the lake and the anticipated influences of the geological and structural settings of the area.

Sampling of water for oxygen-18 and deuterium analysis was undertaken in the areas adjacent to lake from groundwaters, rivers and springs. During sampling no filtration or preservation is required in order to stabilize the sample and minimize the interaction with the atmosphere. The sample bottles having 30ml in volume with a double capped polyethylene are used for collecting the sample from field. The bottles are completely filled and instantly tightly capped in order to avoid exchange of gas with the atmosphere. Then the bottles are properly and carefully labeled. The samples oxygen and hydrogen analysis were performed at isotope laboratory of Department of Earth Sciences, Addis Ababa University. The instrument used for the water sample analysis atomic absorption spectrophotometer. The results are reported in per mil (%o) relative to

VSMOW (Vienna Standard Mean Ocean Water) with a standard deviation of ±0.2‰ for 18O and ±1‰ for $^2$H.

### 2.2. Research Methodologies

This research utilizes the stable environmental isotope **( δ $^{18}$O- δ D**) of the water, the radiogenic isotope (**$^{222}$Rn**) methods and the piezometric evidences to study the lake-groundwater interactions and estimate the water balance of the lake. The principles behind for the application of isotope methods are:

- Lake-Groundwater interaction tracing around lakes uses the advantage that, owing to evaporative water loss, lakes are enriched with respect to the present day rainfall and with respect to groundwaters adjacent to them. Up-gradient groundwaters and down-gradient groundwaters that are partially or completely fed by lake water can then be identified based on the degree of their isotopic enrichments. Direction of groundwater flow around lakes can be inferred from a simple **δ $^{18}$O - δ D** plot or from a spatial plot of these isotopes around lakes (Seifu K. 2004).
- Tracing groundwater fluxes in the vicinity of lake using radon is based on the concentration gradient between the surface water and groundwater. The activity concentrations in groundwater depending on the lithology are much higher than in surface water. This contrast has been used to study groundwater flow in the vicinity of lakes (Hoehn and von Gunten, 1989; Schubert et al., 2006; Kluge et.al, 2007). Furthermore, due to its high activities in groundwater and comparatively low activities in the lakes, it can also be used as a sensitive natural tracer to quantify groundwater inflow into lakes (T. Kluge, et.al 2007).
- Piezometric evidence for determining hydraulic connectivity between surface water-groundwater is based on the fact that differences in groundwater head variation and distribution within the subsurface can assist to identify areas with high and low hydraulic head which in turn help to define the groundwater movement and flow direction. This hydraulic gradient of the water table or potentiometric surface is a very important technique in clearly tracing surface water and groundwater interaction. Where potentiometric surface slopes suggests groundwater flow in the direction.

- The isotope mass balance approach for estimating the water balance parameters has been demonstrated in varies studies of open water bodies ( Dincer, 1968; Gat, 1970,1981; Zuber,1983; Krabbenhoft 1990; Kebede, 2004). The underlying principle for the use of isotopes of water in quantifying water flux around lakes is based on the fact that using hydrologic budget and isotopic budget of a lake the two water budget components that cannot be directly measured, the groundwater flow components, can be determined separately without revisiting the knowledge of catchment hydrographic properties or gauged hydrometric records (Kebede, 2004).

The main importance of carrying out this research by supporting with piezometric evidences is to cover the data and knowledge gap attributed to lack of information as a result of various reasons.

# 3. Characteristics of Ziway Basin

## 3.1. Location

Lake Ziway is situated in the northern part of Central Ethiopian Rift Valley catchment at about 150km south of the Capital Addis Ababa. It is the largest lake in Ziway-Shala basin (ZSB) and occupies a shallow depression on the flat rift terrain bounded by two flanking highlands, Guraghe Mountain in the west and Arussi massifs from eastern side.

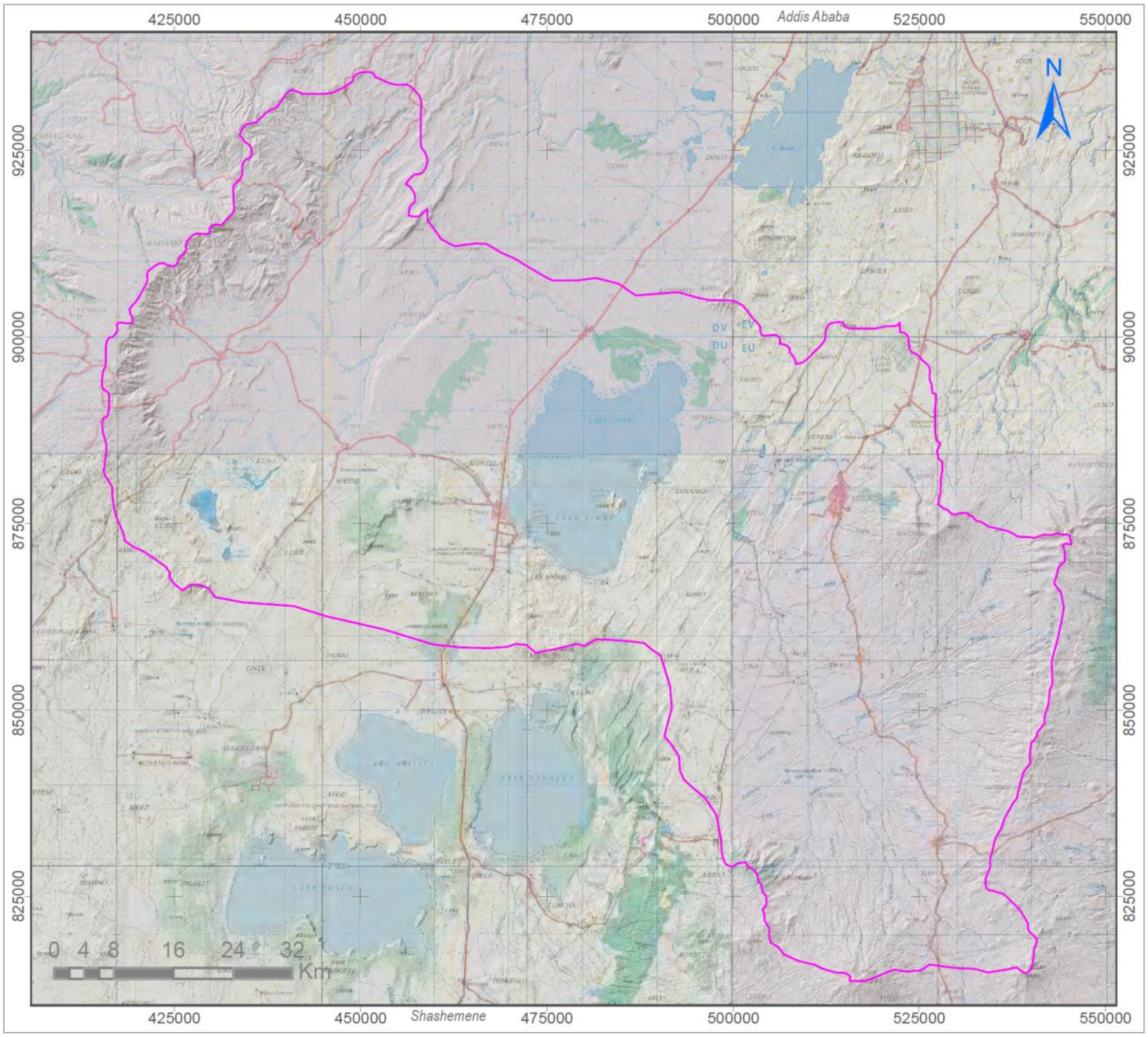


Figure 1. Location Map of the lake Ziway with its catchment boundary

### 3.2. Physiography

Physiographic setup of a given area is one of the factor that determines the recharging and discharging condition of an area which can assist either infiltration to the ground or promotes runoff. The physiographic features of the study area can be broadly classified as the low lying rift valley, the transitional escarpments and the elevated plateaux on either side of the rift.
The Rift valley is the down-faulted tectonic structures that divided both highlands and with a gentle flat topography dotted by volcanic centers.

The transitional escarpments (an intermediate plateau between 2000 and 3000 m) are characterized by a series of steep NNE – SSW running parallel faults.

The highlands bounding the study area from both sides have topographic relief as high as 4000masl and are marked by volcanic ridges which represent the surface water divide of the area.

### 3.3. Climate

The climatic condition of the area is highly influenced by altitude, geomorphology, vegetation cover and other factors. The lake Ziway basin is characterized by a semi-arid to sub-humid climate. The mean annual precipitation and mean annual temperature vary from 700 mm and 20°C on the rift floor, to 1200 mm and 15°C on the humid plateau and escarpment, respectively.

The region is characterized by three main seasons. The rainfall distribution is mainly controlled by the northward and southward seasonal migration of the Inter Tropical Convergence Zone (ITCZ). The long rainy season, the summer monsoon rainfall, occurs from June to September when ITCZ lies at the north of Ethiopia. The big rain represents nearly about 70% of the mean annual total (Degefu, 1987).The dry period extends between October and February when the ITCZ lies south of Ethiopia. The 'small rain' season representing 20 – 30% of the annual amount occurs during March to May when the ITCZ moves from south to north over the country. The pattern of increasing rainfall associated with increasing altitude is modified in the high altitude already due to the influence of the high mountains which may cause either rain shadows or areas of heavy orographic rainfall (Makin et al., 1975). Highlands flanking the Rift Valley intercept most of the monsoonal rainfall in the region, resulting in a strong moisture deficit in the rift floor in general and near the lakes in particular.

The mean annual humidity at Ziway (the closest station to the lake) is 0.67 and it varies between 0.6 and 0.77. Recent years has shown a progress in a good estimates of evaporation of lake Ziway (Vallet-coulomb et al., 2000; Ayenew, 2003). The Penman method gives an annual evaporation rate of 1870 mm. In this study, this value is adapted since the method computes the evaporation from open-water surface using standard climatological records of daily sunshine hours, temperature, humidity and wind speed. Seasonal stratification is absent in lake Ziway owing to its shallow depths (Baxter et al., 1965).

### 3.4. Land Use and land Cover

The low lying region around lake Ziway is typically of semi-arid land characterized by dry land acacia. Much of the higher escarpments below 3000 m are either cultivated or under grass. The main crop near the lakes region is maize. With increasing altitude, the basin is mainly characterized by traditionally cultivated/pasture land with wheat and barley being the major crops, together with Ssome oil crops and false banana.

There are only some remnants of the afromontane forest that still existed some decades ago between 2000 and 3000m on the eastern Ethiopian plateaux bordering the rift and dominated by *Podocarpus gracilior* and *Juniperus procera* (Friis, 1986). The Ericaceous belt extends up to 3600m where it grades into Afroalpine type of vegetation (Chaffey, 1978).

On the plateau, above 2000 m, the basalt, tuff and ignimbrite with additional volcanic ash give rise to soils with high silt and clay contents (Makin et al., 1975). These vary from relatively deep dark brown silty clay to red clays on the well-drained undulating terrain around Assela and poorly drained greyish brown to black silty clays on more gentle slopes around Sagure (Markin et al., 1975).

On the low land area around Lake Ziway, the soils are developed on lacustrine sediments and are predominantly of sandy texture. These are generally thin with less than 1 m thickness (Chernet, 1982).

According to Hayal et al. (2015) agriculture is the most dominant land-use system, representing 74% the total land use type within the watershed, contributing to the livelihoods of the majority of the watershed population. The Lake Ziway water demands have massively increased along with increased population and intensification of agriculture since the end of the last decade. The current water use rate is approximately 223 million $m^3$per year (Jansen et al., 2007) of which irrigation water use varies 150-200mcm. Irrigation water is mainly sourced from surface water, either by river diversion (44%) or from lake Ziway (31%), and only 25% of the land is irrigated using groundwater through existing wells (Rodriguez de Francisco, 2008).

## 3.5. Geology of the Ziway Lake Basin

The geology of a given area play a significant role in the hydrogeological and hydrological issues of the basin. The geology of Lake Ziway area is made up of three major Units which can be subdivide into different units by lithostratigraphic association. The major units are: the basement and mesozoic sedimentary cover; pre-quaternary volcanic and volcaniclastic rocks; and quaternary sedimentary deposits.

### 3.5.1. Basement and Mesozoic Sedimentary Rocks (Bm)

It has a limited exposure at kela horst in the northwestern extreme of the basin at the foot of the major western plateau-rift escarpment. The horst consists of a strongly weathered basement rocks overlain by layers of Mesozoic sedimentary successions (OWWDSE, 2016).

### 3.5.2. Volcanites, Volcaniclastics and Older Lacustrine Deposits

This group of rocks consist of six units ranging in age from Oligocene to Middle Pleistocene covering largest portion of the basin area. These include the older plateau volcanics on either side of the rift basin and the rift floor ignimbrites, which constitute almost entirely the rift floor except where it is overlain by recent (Quaternary) sedimentary deposits.

***Volcanites of the Plateau (Tt):*** are constituted by basalts and rhyolitic ignimbrites and tuffs. The volcanics occurs dominantly in the western part of the catchment and form thick beds of flood basalts. The rhyolitic ignimbrites and tuffs exposed at the eastern (the Arsi plateau) and the western plateau and escarpment zones of the Ziway –Shala Lakes basin.

***Arusi Shield Volcanoes (Mt):*** These shield volcanoes are mainly constituted by basalts, mugearites and subordinate trachytes and phonolites. In the basin these volcanoes constitute the highest altitudes at the eastern plateau where the major River Ketar starts. Most of the Chilalo Mt. and the ridge to the south, Mounts Kubsa, Chike and Kecha as well as Duro belong to this unit.

***Rift Floor Ignimbrites (Pp):*** These volcanics are composed of peralkaline rhyolitic ignimbrites and poorly welded ignimbrites and pumice fall. They are the most dominant rocks in the rift floor occupying the wide flat terrain of the lakes basin and the strongly faulted and active zones of the rift to the east and west: the WFB and the SDZFZ, respectively. They are dominantly exposed at the WFB forming NNE-SSW oriented horsts and grabens east of Lake Ziway determining the direction of river flow and the accumulation of surface water in seasonal swamps.

***Gademota –Balci Alkaline and Peralkaline rhyolitic lavas (Pa):*** These are made up of alkaline and peralkaline rhyolitic lava flows and domes with pumice, tuffs and ashes as well as obsidian flows. They are exposed at Gademota immediately west of Lake Ziway and near the southwestern rift margin forming prominent domal topography above the rift floor ignimbrite.Gademota rhyolitic ridge crops out as a remnant of a large caldera, rising in an arc structure, 25–30 km in diameter, up to 400 m above the plain west of Lake Ziway.

***Alutu –Bericcio Rhyolitic Lava Flows (Qw)****:* These young axial volcanic centers are made up of rhyolitic lava flows and domes with pumice, tuffs and volcanic ashes and are represented in the basin by the Bora volcanoes, the Alutu volcano and the small southwestern islands of Lake Ziway. The Alutu volcanic complex located immediately south of Lake Ziway at the axis of the WFB has a great significance in the evaluation of the outflow of water from Lake Ziway. The rocks are generally impermeable and act as barriers of groundwater flow. However, the volcano lies above the strongly faulted rocks of the WFB, and these deep-seated faults could facilitate focused groundwater leakage from the Lake Ziway towards Lake Langano.

***Wonji –Butajira Basaltic Lava Flows (Qb) and Scoria Cones (Qb1):*** These are exposed in two distinct areas following major tectonic lines, at the WFB and the SDZFZ, east and west of Lake Ziway, respectively. The basaltic lava flows in most cases effectively seal the vertical faults east of Lake Ziway in the WFB, acting as barriers to groundwater and surface water flow. These basaltic barriers are hardly fractured and effectively impermeable, facilitate the accumulation of water in some seasonal swamps in the adjoining grabens in one hand, and flow of surface and groundwater to the south towards the Lake Langano region, i.e., effectively channeling water away from Lake Ziway on the other.

### 3.5.3. Quaternary Sedimentary Units

The sedimentary deposits ranging in age from Late Pleistocene to Late Holocene represent a complex succession of lacustrine and fluvial deposits. They are mostly lacustrine deposits and include recent colluvial and fluvial deposits. The lacustrine deposits are formed during the various stages of evolution of the lake basin and currently exposed at the lake margins. This group of rocks have limited exposure and where they occur they can influence groundwater flow regimes and strongly determine the hydrochemistry (OWWDSE, 2016). At least two major periods of lake expansion followed by very distinct lake low stand during the Late Holocene lead to the separated Lakes Phase observed today (Benvenuti et al., 2002). These periods of Megalake Phase and Macrolake Phase are recorded by lacustrine deposits of late Pleistocene ($Ql_1$) and ($Qt_2$, $Ql_2$, and $Qs_2$) sediments, respectively. Two main phases of lake shrinking are documented by colluvial, fluvial, lacustrine and volcaniclastic deposits referred to the terminal Pleistocene Reduced Lakes (Qcg, Qu/$Qu_1$, Qc), and to the late Holocene Separated Lakes ($Qt_3$, Qbs, $Qs_3$, Qp and Qf, Qdm, Qd) phases. These fluctuations were mainly forced by climatic change and modulated by volcano–tectonic events (Le Turdu et al., 1999; Benvenuti et al., 2002).Complete desiccation of lake Ziway is evidenced by buried paleovalley (Benvenuti et al., 2003).

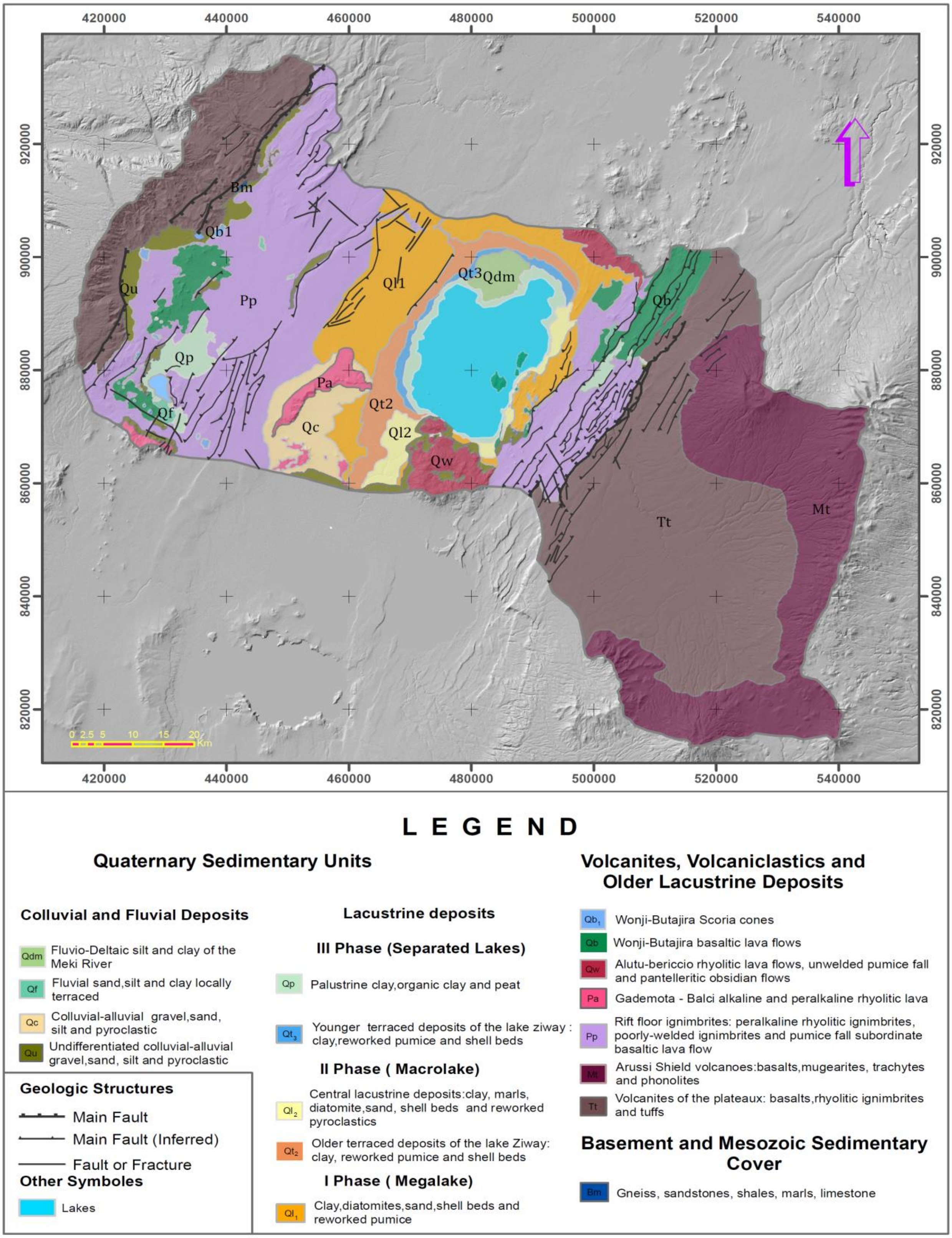


Figure 2. Geological map of lake Ziway Basin (from Dainelli et al., 2001)

### 3.6. Geomorphologic and Basin Architecture

The geomorphology and basin architecture of the area are of significant importance for surface water and groundwater flow regimes. It is mostly the result of volcanotectonic events, with some overprinting of lakeshore processes, alluvial and colluvial activities and fluvial processes. The study area is characterized by varied topographic setup ranging from highly elevated mountains and rugged terrains to plain low lands. The arcuate Guraghe escarpment and Gash Megal topographic high in the west and the Arusi shield volcanoes (Chilalo, 4005m; Kecha, 4245m; Badda, 4170m) in the east represent the highly elevated topography in the basin. The rift center which encompass the study lake is characterized by flat plain topography dotted by volcanic scoria cones and calderas, such as Bora-Berricio, Aluto and Gademotta which form the prominent topographic high over the flat terrain (Figure 3.4 and 3.5).

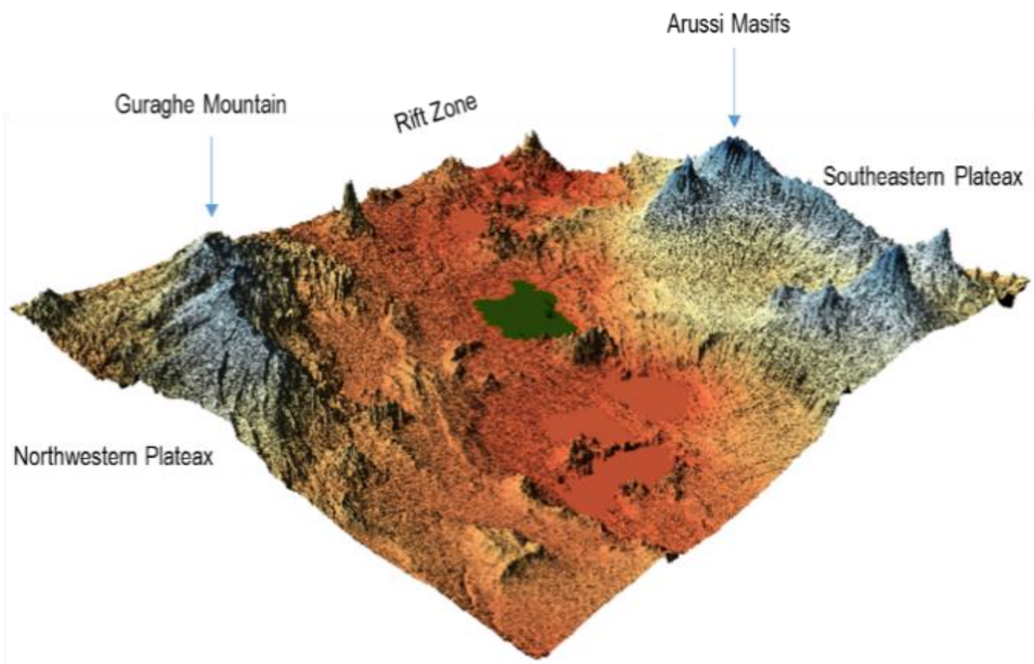


Figure 3. Geomorphology of LZB (3D View) the dark green at Center represent lake Ziway

The WFB and the SDZFZ are the two major tectonic-geomorphic features in the basin with prominent influence on the basin architecture and the subsequent hydrological and hydrogeological processes (OWWDSE, 2016, Ayenew 1998). These WFB and the SDZFZ are the conspicuous volcano-tectonic features that have strongly affected the rift floor ignimbrites forming prominent horst and graben topographies at the eastern margin of the lake Ziway, as well as the western margin of the basin respectively (Figure 4). A generally flat and subdued topography of the central part of the rift is underlain by successive layers of lacustrine sediments and colluvial, alluvial, fluvial and fluvio-lacustrine deposits.

The flow of the major rivers from plateaux and the groundwater flow systems are strongly controlled by these NNE-SSW faults acting as either a barrier or channel to the surface water and groundwater flow (OWWDSE, 2016, Ayenew 1998). For instance, WFB diverts groundwater parallel to the rift axis transferring substantial groundwater from Ziway catchment to Langano at the expense of lake Ziway (Ayenew, 2006).

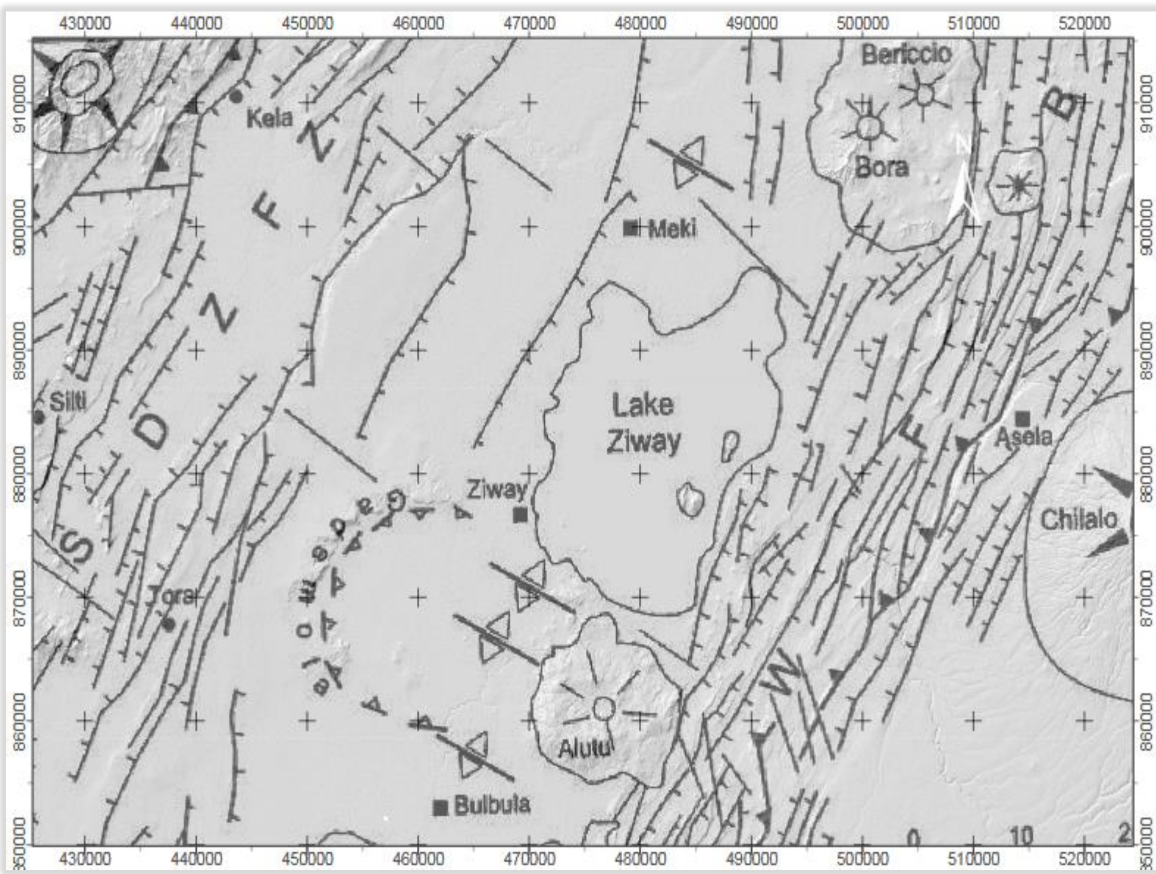


Figure 4. Volcano–tectonic features of LZB (modified from Benvenuti et al, 2002) WFB: Wonji Fault Belt; SDZFZ: Siltie-Debre Zeit Fault Zone

## 3.7. Hydrology

### 3.7.1. Lake Ziway

Ziway Lake is a large open and shallow lake in Ziway-Shala basin (ZSB) with a surface area of 445km$^2$, a shoreline length of 137 km, a catchment of about 7,380 km$^2$, and a mean and maximum depths of 2.5m and 9m respectively as shown in Table 1. Depending on the water inflow, the surface of the lake swings between 435 and 485 km$^2$. It lies in a shallow down-warped depression. Some studies confirm that in the past the four lakes (Ziway, Abiyata, Shala and Langano) were joined in one large fresh-water lake that overflowed to the Awash basin to the north. As a result of climate changes, the large lake started to shrink ultimately forming the current four lakes (Benvenuti et al., 2002).

The lake is of freshwater quality and used for both domestic water supply and irrigation purpose with a potential of irrigating 1,700 ha but is presently irrigating about 1,000 ha (HALCROW, 1992). In addition to this the lake is used for commercial fishing and has a potential yield of 2,500-6,500 tons/yr (Atkins & Partners, 1965). Tilapia nilotica, African *Cat fish and Crusian carp* are the three major species of fishes that currently dominates the composition of the stock (70%, 20%, and 10% respectively) (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 amounts to 1102 mcm. Despite the exceeding outflow, the level of the lake remained constant reflecting the role of the groundwater inflow to the lake (Ayenew, 1998) in maintaining the hydrologic balance of lake Ziway.

### 3.7.2. Rivers & tributaries

A river is a naturally flowing water source that flows towards a lake/a river or in some cases sinks into the ground becoming the main source of recharge for the aquifer. The flow of rivers is principally governed by certain natural factors (geology, physiography and climate) and can be affected by various human activities such as agricultural practices. Such factors play a great role in influencing the flow and physicochemical characteristics of a river as well as the interaction of surface water with the groundwater.

Meki and Ketar rivers constitutes the two major surface inflows to lake Ziway while Bulbula river is the surface outflow of the lake which finally feeds the downgradient lake Abijata ( Figure 5). The Meki and Ketar drainages features a well-developed surface hydrographic network of ZSB system. Meki River originates from highland of northwestern plateau that comprise Muri and Asta Dega Mounts at an altitude about 3,600m asl. Its tributaries drain the eastern flank of the plateau and is influent at its lower reach over the lacustrine deposit at the rift. It is the largest rivers that carries considerable loads of sediments and forms a well-developed deltas at its mouth in the north border of the lake. (Figure 2).In recent years and during the field survey, it is observed that it tends to dry out during long dry seasons.

Katar River is another feeding river for the Lake Ziway that starts from the Arusi highlands in the East. In contrast to Meki river, it is effluent at its lower reach and perennial throughout the year. It’s relatively the most irrigated river together with its tributaries in the highlands as well as in the lowland.

Bulbula River is a surface overflows from lake Ziway to Abijata lake. It play a major sustaining role in the Lake Abiyata ecosystem. The decreasing volume of Lake Abiyata has been attributed to the declining discharges of Bulbula river.

Precipitation on the lake surface (753 mm/yr) is inferred from the records of three meteorological stations close to the lake: Abura, Meki and Ziway (Vallet-Coulomb, 2000). River discharge data are available for the two main tributaries (Table 1). The Meki River is gauged near Lake Ziway and the Ketar River is gauged at two stations; at Abura and Sagure. The lake overflow, the Bulbula River, was also gauged at the outlet.

The important long-term morphometric and hydrologic characteristics of the lake and rivers used for computation of water balance of the study lake are presented in table 1.

*Table 1 Main characteristics of lake Ziway (Measured Average values of monthly data between December 1968 and December 1995)*

| | Lake level (m asl) | Lake volume ($km^3$) | Lake surface ($km^2$) | Precipitation on lake surface ($km^3yr^{-1}$) | Ketar River inflows ($km^3yr^{-1}$) | Meki River inflows ($km^3yr^{-1}$) | Bulbula River outflows ($km^3yr^{-1}$) |
|---|---|---|---|---|---|---|---|
| *Mean* | 1636.1 | 1.76 | 445 | 0.335 (753 mm/yr) | 0.418 | 0.273 | 0.157 |
| *max* | 1637.3 | 2.36 | 536 | 0.458 (996 mm/yr) | 0.687 | 0.463 | 0.403 |
| *Min* | 1635.2 | 1.34 | 432 | 0.214 (479 mm/yr) | 0.254 | 0.118 | 0.022 |

*(Source: Vallet-Coulomb et al., 2001)*

### 3.7.3. Small lakes and wetlands

In the LZB small lakes and wetlands are common at the foot of escarpments and fault zones. The most notable in the wide plains and volcanic cones close to the Guraghe mountain range is lake Abaya and the small circular crater lakes of Har Shetan. Lake Harakelo with associated long swamps and lake Harobata occupy the rift-within-rift structures of the WFB in the eastern side of the Ziway Lake. These lakes and swamps are flushed by both surface and groundwater from the highlands and fracture systems and play a very important role in providing water supply for the rural community and for animal drinking.

Particularly the north, western and south peripheries of lake Ziway are fringed with marshy or swampy wetlands. The lake Ziway and the rivers form an important ecosystem providing prolific environmental functions and services like shelter for a rich diversity of plants, aquatic birds, fish and hippos; and maintenance of riverside and wetlands biodiversity. The marshes around the lake also support several waders, and roosts of several thousands of cormorants, ducks and geese lodges around the lake. The long shoreline of lake Ziway is covered with submerged vegetation which offers breeding and nursery places for fish when inundated (Spliethoff et al., 2009).

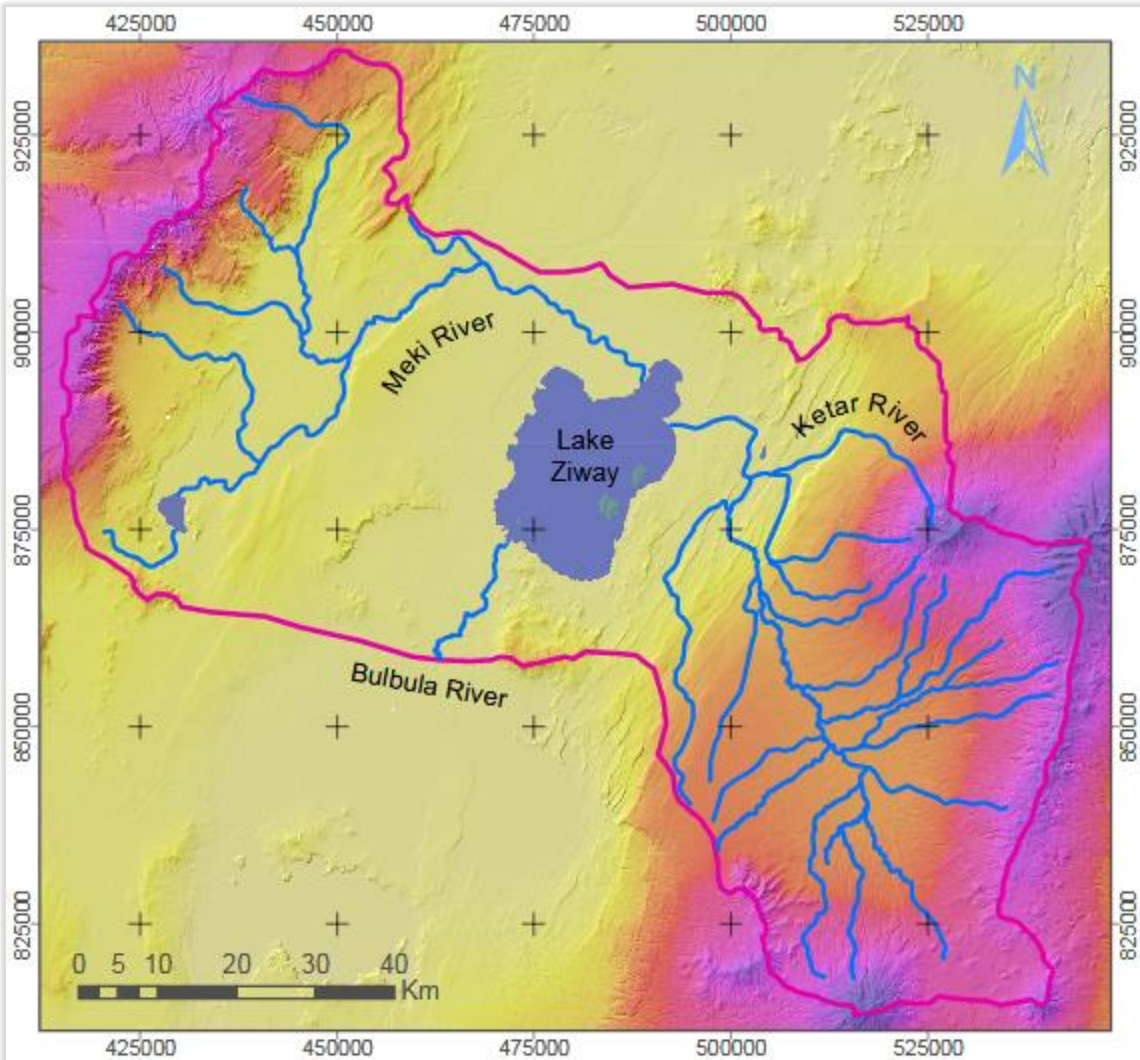


Figure 5. Drainage systems of Lake Ziway

## 3.8. Hydrogeology

### 3.8.1. Major Hydrogeologic Units and Aquifer Characteristics

The volcanic aquifer of Ethiopia is considered as the least understood hydrogeologic system (Ayenew, 1998; UNESCO, 2006; Kebede, 2013). According to Ayenew et al, 2008, comprehensive hydrogeological investigations in the Ethiopian volcanic terrain and associated quaternary sediments, the volcanic aquifers show extreme variations in aquifer hydraulic characteristics and recharge rates. The flow of groundwater is strongly controlled by the structure and geomorphological setup of the volcanic rocks and associated sediments. The recharge varies in a wide range between a few mm to 400 mm/yr with transmissivity varying between 27 and 135 $m^2$/d. The thick volcanics interbedded with river gravels and sands form deep confined and semi-confined aquifers with artesian conditions at places. Intermountain grabens and rift floor sediments associated with fractured volcanics form the largest aquifers under watertable and semi-confined conditions. The highland aquifers have groundwaters with relatively lower ionic concentration (TDS ranging from 50 to 1200 mg/l) while the rift waters have high salinity and fluoride, which is the major national water quality problems that account for 80% of groundwater well failures and abandonment after construction in the central Ethiopian rift according to the survey of Kassa (2007).

The aquifer characteristics of Lake Ziway Basin is discussed based on their lithostratigraphy and hydrogeologic characteristics. According to EIGS (1993) two major aquifer classes were identified based on the mode of origin and rock types. These are extensive aquifers with intergranular permeability, and extensive aquifers with fracture permeability. These in turn are divided each into high, moderate and low productive aquifers with mean values of 14.5, 2.1, and 0.25 m/day respectively.

The volcanites of the plateaus, Arusi shield volcanoes, the rift floor ignimbrites and wonji- butajira basaltic lava flows which cover the largest area of LZB constitute an extensive aquifers with fracture permeability (Figure 2).They have generally low to moderate permeability and productivity. But they have high permeability where cut by the dense Wonji Fault. Some springs which discharge from the contacts of jointed and massive flows of these units become the starting points for perennial streams which flows down to the lake.

The lacustrine deposits and colluvial-fluvial deposits of the basin which cover areas immediate to lakes form the extensive aquifers with intergranular permeability. The lacustrine sediments show a lot of differences in their permeability; those showing the highest permeability are the ones consisting of volcanic sands or water-lain volcanic sands. As a whole, the lacustrine sediments maybe taken to have a moderate or high permeability and productivity (EIGS, 1993).

### 3.8.2. Recharge and Discharge Conditions

Recharge is one of the elements of a hydrologic process that determines deep drainage or deep percolation to an aquifer. The recharge / discharge and flow systems of a groundwater at a certain area depends on certain variables such as the amount of precipitation, physiography, geological structures, geological formations and the type of land use and land cover of the region. There are various mechanisms in which aquifers can get recharge such as diffuse (direct) or preferential (localized/indirect) recharge (Andarge Yitbarek, 2010). Diffuse recharge occurs when water is added to the groundwater due to excessive soil moisture. Whereas the preferential occurs when there is a concentrated percolation of water to the water table (Lerner et.al, 1990). At some places of the rift valley the presence of fractured rock exposure in wide areas favor a direct and localized recharge from an inflow of rainfall that fall on plateau area.

Precipitation is the main source of recharge for both surface water bodies and groundwater. In Ziway lake basin the highlands receives high mean annual rainfall compared to the rift parts of the basin (500 - 1000mm). According to EIGS (1993) the annual recharge values vary between 150-250mm in the highland and 50-150mm in the rift floor. The direct recharge from rainfall in the area is about 10 to 20% of the mean annual rainfall.

The principal geological formations in the highland is the volcanites of the plateaux overtopped by volcanic shield, and rift floor ignimbrites which mainly comprises fractured volcanic rocks. Direct recharge from precipitation takes places through fractures in volcanic rocks and discharge in the form of springs.

The flat topography of the rift dominated by lacustrine deposits plays a vital role in promoting recharge to the groundwater than creating runoff. The dense fault systems and joints in the rift valley play a significant role for fast vertical recharge of the aquifer that flows from the plateau.

The groundwater continuity and inflow to the rift floor is facilitated by the nature of the bounding fault (Seifu Kebede et.al, 2008) and hydraulic gradients. The presence of depressional valleys in the escarpments and rift floor makes the surface water to enter to the ground, through volcanic cracks and joints. Since these depressional valleys are often occupied by seasonal ponds and occasional surface runoff are observed. In the rift valley there are also additional recharging possibilities other than surface runoff percolation and rain fall infiltration. The percolation through rivers bed and seepage from irrigation returns are the other sources of recharge to the valley aquifer. This usually occurs whenever the groundwater level is lower than the river beds. In such phenomena the aquifers can receive significant amount of water from rivers.

The lower plain of Lake Basin lies between 1600m and 1700m physiographically such low lying areas are generally consider as a discharging zone. This plain has a mean annual rainfall that is less than 600mm.In such arid regions the groundwater recharge in a basaltic terrain is reported to be about 10% of the annual rainfall. It can be inferred from the fact that owing to low precipitation, the groundwater in the area can not only be recharged from rainfall but also the subsurface flow from the fracture openings of the volcanic rocks and unconsolidated sediments of the catchment can be the major recharge sources of groundwater in the rift.

# 4. Results and Discussion

## 4.1. Lake Groundwater interaction and Groundwater flow direction

### 4.1.1. Radon Isotope in Lake Ziway

Radon-222 is an environmental tracer that has been used for tracing groundwater inflows locations to streams and lakes and the ocean since 1960. It is an endogenous radioactive noble gas, with a half-life of 3.8 days, produced in the subsurface by α-decay of radium ($^{226}Ra$), which is part of the uranium ($^{238}U$) decay chain (Figure 6). It is soluble in water, and its behavior and concentration in groundwater are strongly influenced by the geological nature of the substratum and by the occurrence of Rn parent elements. The most important processes for Rn transport in groundwater are diffusion and convection (Barbieri, 2019). After groundwater containing radon discharges to surface water bodies, radon activities decrease due to gaseous exchange with the atmosphere and radioactive decay. The radon activity within a lake will therefore reflect the water balance over a period of a few days prior to measurement. Importantly, since radon activities in rainfall are very low, the contribution of precipitation and surface runoff to the lake radon budget will usually be negligible, and so the radon activity will be largely determined by the groundwater inflow rate. Such natural variations of Rn ($^{222}Rn$) concentrations are the fundamental prerequisite of using this radioactive gas as a tracer to detect interactions between the surface water and the groundwater.

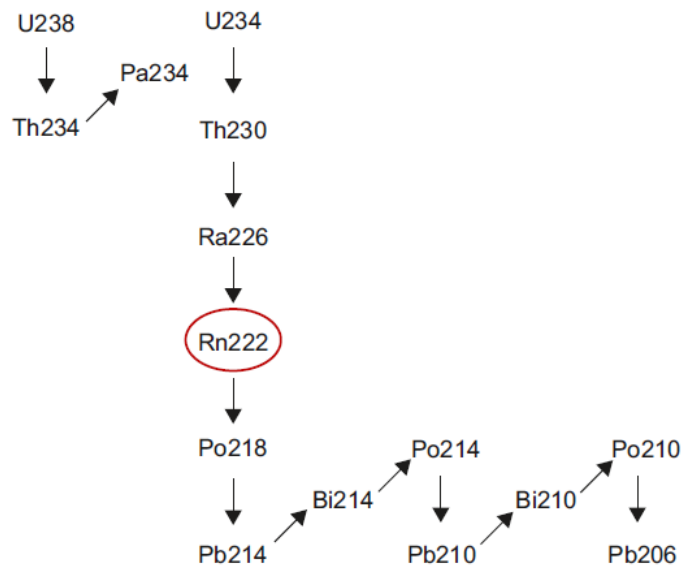


Figure 6. Decay chains of $^{238}U$, vertical steps represent alpha decay; steps to the side represents beta decay (after Kendall and McDonnell 1998)

A total of 31 water samples were collected to analyze for their radon concentration along two preferred transects and margins of the lakes. In addition, water samples have been measured from hot springs, Bulbula River and boreholes for comparison. These transects are selected in two directions corresponding to the major lake axis in NE-SW and NW-SE directions. The spatial variations in radon concentration within the lake has been constructed. From these variation pattern, the groundwater discharge zones were identified on the basis that the radon activity within a lake reflects the groundwater discharges to surface water bodies since the contribution of precipitation and surface runoff to the lake is usually negligible.

Figure 7 depicts the measured spatial radon concentration of lake Ziway and the radon concentration error bar representation is shown at Appendix II. Along the eastern part of the lake seven radon concentration measurements were taken. The radon concentration in the eastern part varies between 35 Bq/m$^3$ and 96.6 Bq/m$^3$. At five sites along the western part of the lake Radon concentration measurements are done which shows concentration values in the range between 4 Bq/m$^3$ and 17.6 Bq/m$^3$.

Radon concentration measurements are done along two transects set in NE-SW and NW-SE direction across the center of the lake. Along a line in NE-SW at seven measurement points the sampling was done and the radon concentration varies between 8.8 Bq/m$^3$ and 61.5 Bq/m$^3$ while along the NW-SE at six measured sites it ranges from 8.8 Bq/m$^3$ and 44.8 Bq/m$^3$. At southeast sector of the lake roundabout to Tulu-Gudo Island the measured values at seven sites varies between 17.6 and 96.6 Bq/m$^3$.

Radon concentration measurements are also done along the Bulbula River at four different sites starting from near its exit from lake Ziway to its entry to lake Abijata and the values range are in between 8.8 Bq/m$^3$ and 70.4 Bq/m$^3$.

Groundwater sample measurements was also done at four different boreholes and the groundwater shows concentrations in the range of 2,653.3 Bq/m$^3$ and 12,010.5 Bq/m$^3$.

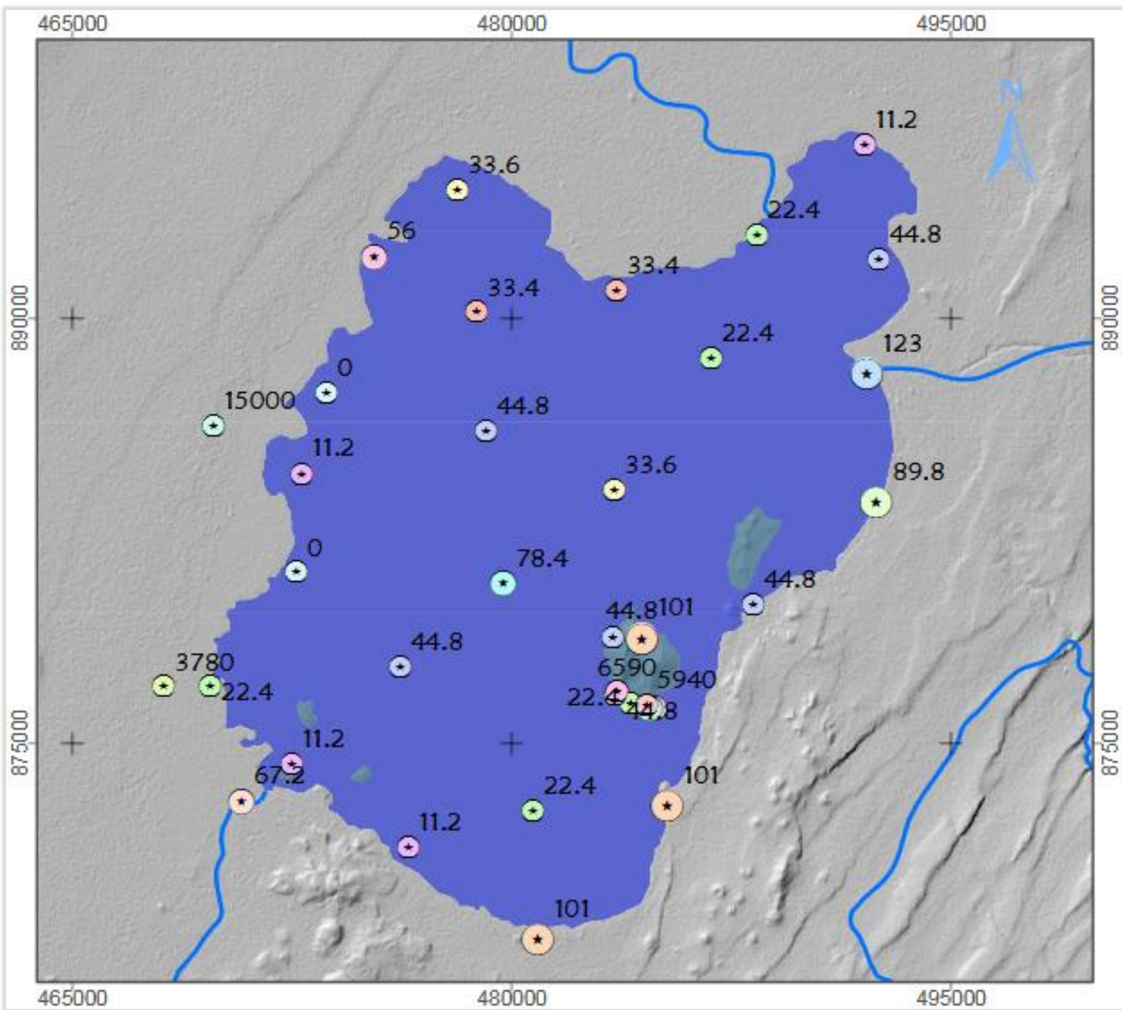


Figure 7. Spatial variation of Radon Concentration in the lake Ziway (The presented values are Radon-in-air as measured by RAD7, converted by 0.785 into radon in water)

Figure 7 depicts the measured spatial radon activity of lake Ziway. The $^{222}Rn$ values along the eastern part ranges in between 35 Bq/m$^3$ and 96.6 Bq/m$^3$ while that of the western part is between 4 Bq/m$^3$ and 17.6 Bq/m$^3$. The radon concentration values suggest that the two regions depicts contrasting figures, the eastern side showing higher values as compared to the western margins.

Particular pronounced figures 79.2 and 96.6 Bq/m$^3$ are observed along the eastern margin in areas nearby Ketar river entrance to the lake and at the southeast shore of the lake.

These elevated radon concentration shows the discharge of groundwater into the lake at eastern sector of the lake and particularly at the NE and the SE shore of the lake. In contrast the western shore shows low concentrations thus indicating groundwater outflow zone in the western region.

$^{222}Rn$ values along the transects near the central sector of the lake shows elevated values, intermediate values compared to the two regions, this suggests possible groundwater discharges to lake through buried paleovalley of the lake Ziway.

The measured Rn-222 values of lake water around Tulu-Gudo Island varies in between 17.5 and 96.6 Bq/m3. The maximum value shows the islands groundwater interaction with the lake in its northern than the south sector where famous hot springs are available. The Rn-222 values of the hot springs ranges in between 3,532 and 5,173 Bq/m$^{3.}$ This elevated concentration suggests the springs are feed by deep groundwater sources unaffected by the dilution from the lake.

The $^{222}Rn$ value of the borehole at western side of the lake which is very close to the lake (< 2km) showing the most highly pronounced value (12,010.5 Bq/m$^3$ ) and the parallel $^{222}Rn$ values of the lake in that regions showing the least figures (4 Bq/m$^3$) strongly indicates the absence of groundwater discharges to lake from the western sectors.

The measured Rn-222 values along the Bulbula River show elevated values at its upper reach (≅ 10km from lake Ziway) than lower reach. This indicates groundwater inflows occurs to the river at the upper reach from the lake water dominated aquifer.

#### 4.1.2. Isotope Compositions of different water types

In this research the isotope data obtained from primary analysis of water samples collected during the field and secondary data from water samples reported in published sources were utilized. Stable isotope of $^{18}O$ and $^{2}H$ of 52 water samples were analyzed to qualitatively define the lake-aquifer interaction and detect the direction of groundwater flow in the surroundings of the lake.

The isotope analysis results from different water types: groundwaters (30), lakes (7), rivers (7), springs (5), and geothermal wells (2) are given in Appendix II. Water sampling points are shown on Figure 8. Figure 9 shows $\delta^{18}O$ - $\delta^{2}H$ plots these water bodies with respect to Local Meteoric Water Line (LMWL) and Local Evaporation Line (LEL). The collected samples of the groundwaters of LZB show a wide range of isotopic composition from -3.53 to 5.51‰ for $\delta^{18}O$ and -15 to 39.50‰ for $\delta^{2}H$. Within this range also included that from hand dug well $\delta^{18}O$ (1.15 - 4.86‰) and $\delta^{2}H$ (15.2-34.9‰). The isotopes composition from springs has $\delta^{18}O$ (-2.44 to -3.40) and $\delta^{2}H$ (-3.70 to -12.70).

Stable isotopes of water molecule namely $\delta^{18}O$ and $\delta^{2}H$ were used to detect direction of groundwater flow. Stable isotopes of water ($\delta^{18}O$, $\delta^{2}H$) are proven tools in detecting surface water-groundwater interaction. During evaporation water bodies undergo isotope fractionation leaving heavy isotopes of water ($\delta^{18}O$, $\delta^{2}H$) behind at predictable amount. This will generally leave open water bodies and rivers which underwent evaporation enriched in the heavy isotopes. Water bodies which have not undergone evaporation contain more light isotopes and thus are depleted in the heavy isotopic species. The distinction between the evaporated waters and unevaporated waters in terms of their isotopic content allows the detection of water flow paths if one is interacting with the other. Since Lake Ziway is an open water it undergoes evaporation which enriches its isotopic composition. This process makes the Lake Ziway to attain a distinct isotope signature compared to groundwater and surface water flowing into the Lake. Groundwater which receives water from the Lake thus should show the isotopic signature of the Lake thereby allowing the detection of groundwater outflow zones from the Lake.

Groundwater flow direction has been reconstructed from the pattern. The pattern shows most depleted (negative) $\delta^{18}O$ value occupying the groundwaters and springs in the higher altitude areas and in deep wells in the rift floor (Figure 8). The most enriched values are clustered around the fringes of the Lake in the South and in the southwestern sector. This zone where the $\delta^{18}O$ in groundwater shows enrichment is indicator of the groundwater outflow zone from lake Ziway towards that sector. The $\delta^{18}O$-$\delta^{2}H$ plot (Figure 9) also shows that the lake water and the Borehole waters South and South West of the Lake plot below the Global Meteoric Water Line (GMWL) indicating evaporation affecting the waters. This means since the Lake water is exposed to open water evaporation, the evaporation signal of the boreholes waters in the S and SW is due to the groundwaters connection to the Lake. The Tuff spring and the groundwaters from the Eastern highland show depleted signal (the lower corner of the Figure 8) testifying direct recharge from rainfall in this region. The fact that the Hand dug wells plot below the GMWL is also indicative of the effect of evaporation, probably indicating direct evaporation from the hand dug wells taking place in the region. This evaporation from shallow aquifer is possible considering the shallow water table and the course grained nature of the volcanic clastic aquifer.

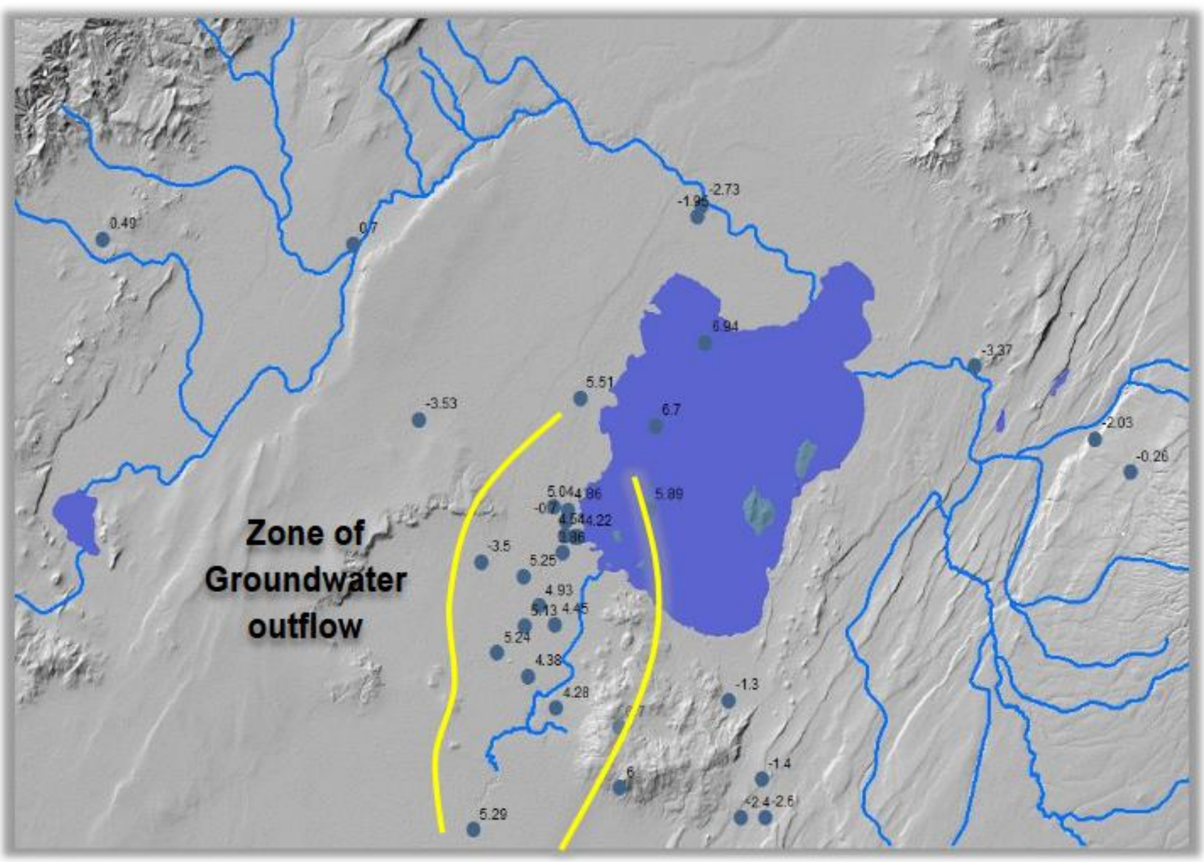


Figure 8. The spatial distribution of the $\delta^{18}O$ of groundwaters of the lake catchment

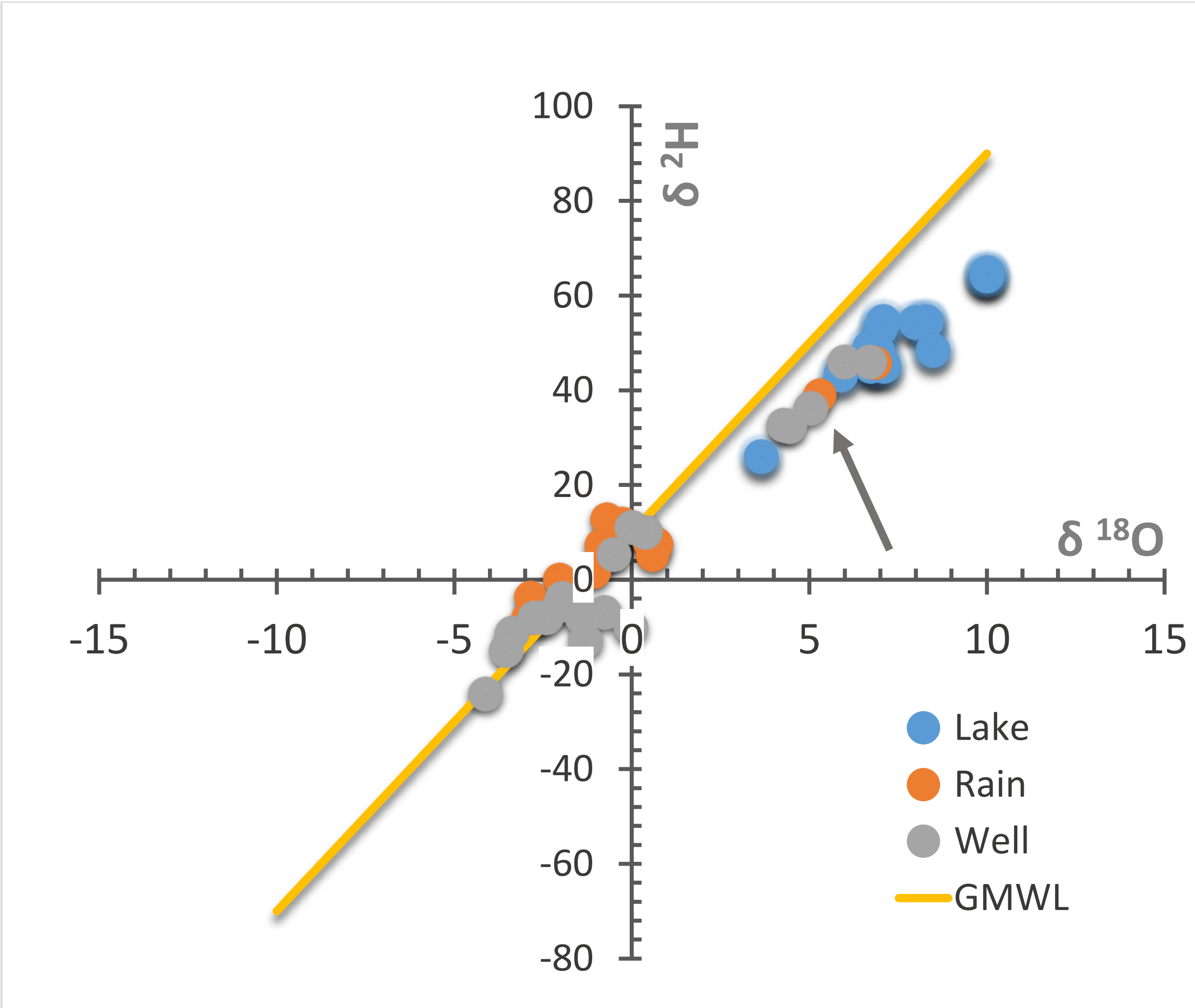


Figure 9. The isotopic compositions of lake, springs and boreholes. The arrow points to Groundwater in S and SW sector of the lake

### 4.1.3. Piezometric Evidence

Based on the spatial and temporal distribution of hydraulic head surrounding a lake, groundwater-lake systems can be described as one of the following types: (1) recharge systems where the lake surface is higher than the surrounding water table and where water flows to the groundwater system; (2) flow-through systems, where the lake gains water from the groundwater system in some parts of the lake and loses water to the groundwater system in other parts of the lake; and (3) discharge systems, where the lake level is lower than the surrounding water table and where water flows to the lake (Walker,1998). Further classification of lakes relates to their position within the regional groundwater-flow system. Terminal-lake systems defined as lakes that function as the discharge point of the regional groundwater-flow. For terminal lakes, water is removed by evaporation.

Depending on piezometric data collected from different organization (WWDSE, OWWSDE, etc…) a numbers of boreholes exists in the areas surrounding the lake. The groundwater level of the boreholes in the vicinity of the lake are used to determine the variation and distribution of groundwater head. This helps in identifying areas with high and low hydraulic head. By using the head distribution and topographic variation a water table contour map is generated. From such graphical representation of hydraulic gradient of the water table or potentiometric surface groundwater flow and movement direction have been determined. In this way the existence of the hydraulic interconnection of the surface water and aquifer system were easily determined.

In areas with shallow gradient of water table, the groundwater contours is spaced in a pronounced way just as in the rift center. Conversely, where the hydraulic gradient is steep the groundwater contours is very closer to each other. This suggests that groundwater is flowing in the direction that the water table or potentiometric surface is sloping.

Figure 10 shows the piezometric surface of the groundwater. The contour map exhibits the water table sloping toward the lake in eastern side and away from the lake in the western margin and southwest direction. This suggests that groundwater enters into the lake along the east side, in particular the southeast sector and leaves the lake in the west and southwest margin of the lake.

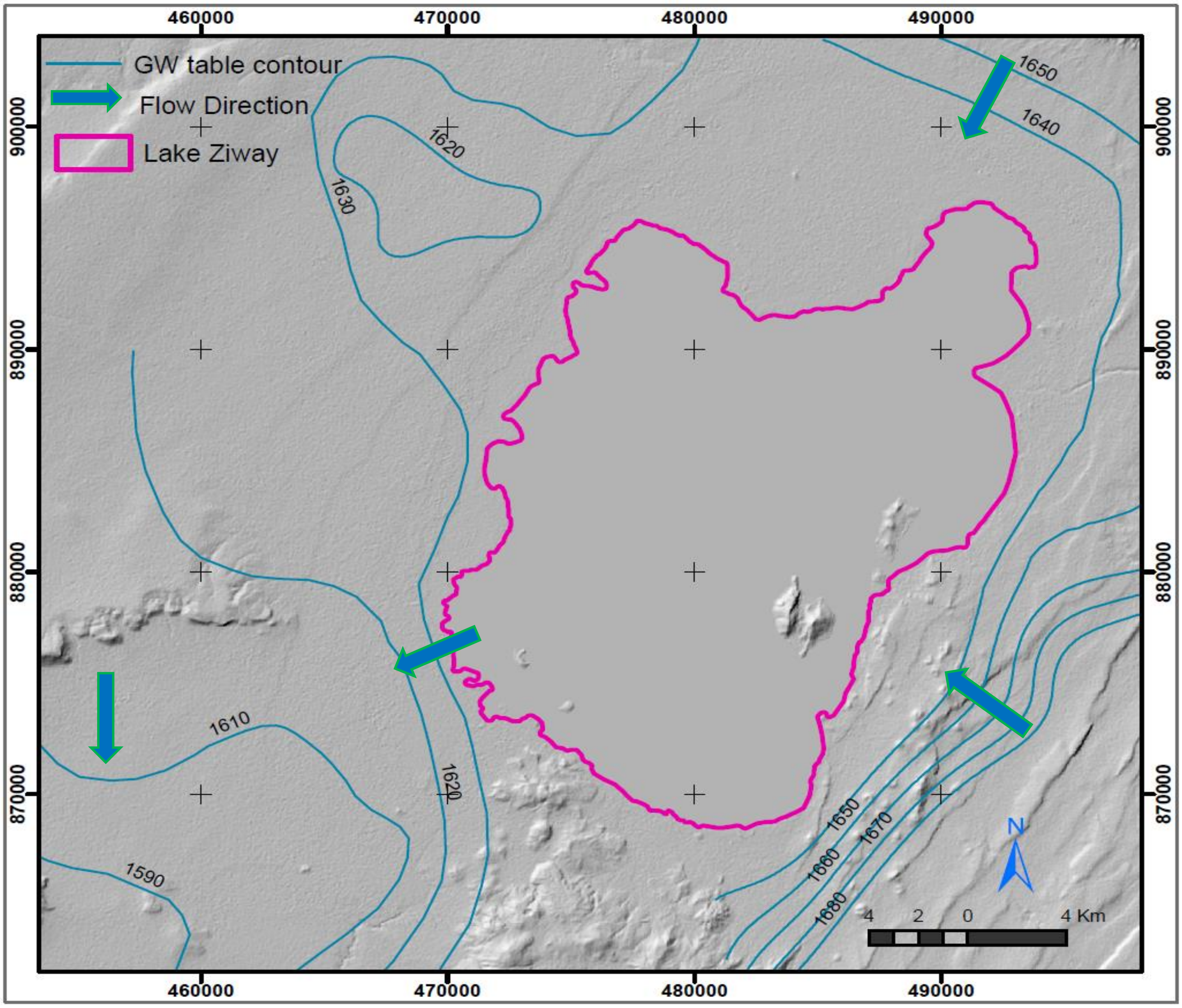


*Figure 10. Groundwater table contour*

## 4.2. Water $\delta^{18}O$-isotope mass balance of Lake Ziway

### 4.2.1. Introduction

Lakes are complex dynamic systems, interacting with the local environment and connected to the water cycle through both surface and underground inflows and outflows, as well as via precipitation and evaporation fluxes (Figure 11). For a proper lake management, it is often important to establish the water budget, quantifying all incoming and outgoing water fluxes.

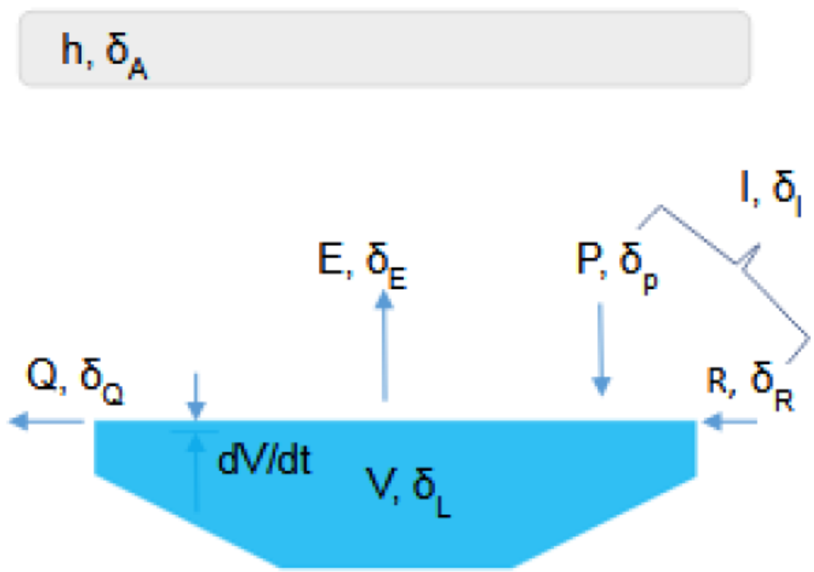


Figure 11. Schematic diagram showing components of hydrologic fluxes and their isotopic compositions for a lake system.

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Where I is total in inflow, where I = P + R; P is precipitation, R is runoff: surface inflow and groundwater inflow combined; E is evaporation; Q is the liquid outflows (surface outflow and groundwater outflow), V is lake volume, dV/dt is change in lake storage, and h is ambient atmospheric humidity. Where $\delta$ values refer to the isotopic compositions of the respective components. $\delta_A$ and $\delta_L$ denote the isotopic compositions of ambient atmospheric moisture and lake water, respectively. Where $\delta_I$ is the isotopic composition of the total inflow, $\delta_Q$ is the isotopic composition of the liquid outflow and $\delta_E$ isotopic composition of evaporative flux

### 4.2.2. Theoretical Considerations

The stable isotopes of water, $^{2}H$ and $^{18}O$, have been shown to be the most useful tracers in establishing a lake water balance, in particular concerning the subsurface components. The stable isotope method of determining the water balance of lakes is based on the fact that the evaporation process leads to a measurable enrichment of $^{2}\delta$ and $^{18}\delta$ of the lake water. The degree of evaporative enrichment is controlled by meteorological variables such as the atmospheric relative humidity over the lake and the surface water temperature, and is correlated with the lake water balance. The isotopic composition of an evaporating lake will evolve along a line (LEL) which has a slope significantly smaller than eight (MWL).The water budget of lakes is based on the mass conservation law and has the form of a balance equation.

The water-mass balance of a lake at hydrologic steady-state (i.e. undergoing evaporation while maintaining constant volume) is described by

$$I = Q + E \qquad (1)$$

where I is total inflow to the lake comprised of precipitation over the lake, surface and groundwater inflow; $Q$ is total outflow incorporating surface and groundwater outflow; $E$ is the evaporation flux from the lake;

The analogous isotope-mass balance equation using $^{18}O$ or H as a tracer for a well-mixed lake is

$$I\delta_I = Q\delta_Q + E\delta_E \qquad (2)$$

Where $\delta_I$ is the isotopic composition of the total inflow, $\delta_Q$ the isotopic composition of the liquid outflow and $\delta_E$ isotopic composition of evaporative flux.

Substitution of Eq. (1) and rearrangement of Eq. (2) in terms of the ratio of vapour outflow to liquid inflow then yield

$$\frac{E}{I} = \frac{\delta_I - \delta_L}{\delta_E - \delta_L} \qquad (3)$$

For well-mixed lakes it is apparent that $\delta_Q = \delta_L$ where $\delta_L$ is the isotopic composition of lake-water. While seasonal variation is characteristic in some lakes, the steady-state isotope mass balance remains a useful description of the mean conditions of the lake water balance for each year.

Although $\delta_I$ and $\delta_L$ can be obtained through either sampling or analysis, determination of $\delta_E$ is complicated by the difficulty of selectively sampling evaporating moisture in the presence of ambient moisture (Zuber, 1983). Nevertheless, $\delta_E$ may be estimated from evaporation pan experiments (Welhan and Fritz 1977; Allison et al., 1979), through calibration against an index lake of known water balance (Dincer, 1968), or from theoretical relations alone.

Based on the simplified form of the boundary-layer flux model of Craig and Gordon (1965) the isotopic composition of the evaporation flux can be estimated whose simplified formula for $\delta_E$ reads as:

$$\delta_E = \frac{\delta_L - h\delta_A - \varepsilon}{1 - h} \qquad (4)$$

where h is the atmospheric relative humidity expressed as a decimal fraction ranging from 0 to 1 and normalized to the temperature of the air-water interface; $\delta_A$ is the isotopic composition of atmospheric moisture unaffected by vapor from the lake, and $\varepsilon$ is the total isotopic separation factor that comprises both equilibrium $\varepsilon^*$ (a function of temperature) and kinetic $\Delta\varepsilon$ components and is given by:

$$\varepsilon = \varepsilon^* + \Delta\varepsilon \qquad (5)$$

$$\varepsilon^* = 1000\,(1 - \alpha^*) \qquad where \qquad \alpha^* = 1/\alpha \qquad (6)$$

where $\alpha$ is the equilibrium isotopic fractionation factor which is 1.0098 for $^{18}O$ at 25 ℃.

Equilibrium separation factors $\varepsilon^*$ for oxygen and hydrogen are adequately known as a function of temperature from laboratory experiments by Majoube (1971) and Gonfiantini (1986). Hence using ( $\alpha^* = \frac{1}{\alpha} = 0.9903$) the equilibrium separation factors ( $\varepsilon^*$) equals 9.7‰.

For water balance applications, $\Delta\varepsilon$ can be approximated by

$$\Delta\varepsilon \;=\; C_k\,(1-h) \qquad (7)$$

Where $\left(C_k = \frac{D}{D_i}\right)^n - 1$ and D is the molecular diffusion coefficient of $^1H_2{}^{16}O$, $D_i$ is the molecular diffusion coefficient of $^1H_2{}^{18}O$ or $^1H^2H^{16}O$, and n is a turbulence parameter such that $n = \frac{1}{2}$ for mean turbulent flow, $n = \frac{2}{3}$ for laminar flow and $n = 1$ for static transport (Gonfiantini, 1986; Merlivat, 1978). Use of $n = \frac{1}{2}$ which corresponds to $C_K$ values of approximately 14.3 and 12.5‰ for oxygen and hydrogen, respectively, is a suitable approximation for natural evaporation from lakes (Gonfiantini, 1986). Inserting the

Equation (4) introduces a new unknown namely the isotopic composition of local atmospheric moistures. Several methods are applied to calculate $\delta_A$. The method most often applied is to calculate $\delta_A$ from monthly $\delta_P$ values assuming isotope equilibrium at ground level temperature. This method of estimating $\delta_A$ does not work satisfactorily in arid or semi-arid regions or during extensive dry periods in the tropics.

Another method of estimating $\delta_A$ uses constant-volume class A evaporation pans operated on the lake shore or, preferably submersed pans operated on a floating platform. The disadvantage of this approach is that such observation station requires daily maintenance.

An alternative method of evaluating $\delta_E$ can be from another lake located in the vicinity of the studied lake, which has no outflow (surface or underground). Such lake is called a terminal lake. The weighted mean annual $\delta_A$ values obtained in such way can be further inserted in eq. 3 to calculate annual mean values of $\delta_E$ for the studied lake. The latter approach has been used in varies studies (Dincer, 1968; Gat and Levy, 1978; IEAE, 1981).

For this study Hora lake ($\delta^{18}O$ = 7.2‰ and $\delta D$ = 37.6‰) has been used as an index terminal lakes (Kebede et al, 2001) to determine the weighted average annual $\delta_A$.

The isotopic composition of a terminal lake in a balanced state of total inflow and outflow ($E = I$) will approach a steady state value (IAEA, 1981) so that

$$\delta_E = \delta_I \qquad (8)$$

where $\delta_I$ is the weighted isotopic composition of total inflow. The $\delta_I$ value can be obtained from the intersection of local evaporation line with the local meteoric water line (figure 12) for $^{18}O$ or Deuterium. The lakes in the ZSB plots on evaporation line defined by $5.5\delta^{18}O + 8.5$ (Ayenew 1998). The intersection of LMWL with this evaporation line gives a $\delta_I$ value of -2.6‰ for $^{18}O$ and 5.8‰ for $^2H$.

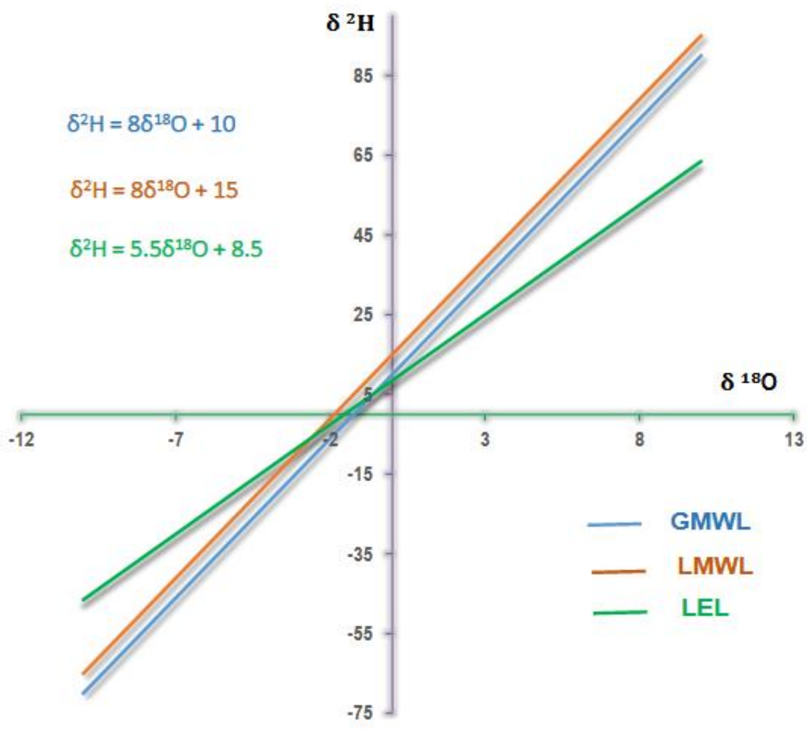


Figure 12. Local Meteoric Water Line and Local Evaporation Line (Source: Ayenew, 1998)

By using Hora lake as Index Lake and inserting ( $\delta_E = \delta_I$ = -2.5‰ and $\delta_L$=7.2‰) into equation (4) the unknown regional parameter $\delta_A$ is estimated to be -12‰.

Using equation (5) the total fractionation factor ($\varepsilon$) which is the sum of equilibrium separation factor ($\varepsilon^*$) and kinetic fractionation factor ($\Delta\varepsilon$) is estimated to be 15.4‰. While using equations (6) and (7) equilibrium separation factor ($\varepsilon^*$) and kinetic fractionation factor ($\Delta\varepsilon$) are estimated to be 9.7‰ and 5.7‰ respectively.

The average relative humidity record found from the meteorological station close to the lake is 0.6 (Vallet-coulomb et al, 2001; Kebede, 2002).

Substituting for $\delta_E$ in Eq. (3) as suggested by Gat and Levy (1978) yields

$$X = \frac{E}{I} = \frac{\delta_L - \delta_I}{m\,(\delta^* - \delta_L)} \quad or \qquad (9)$$

where x is a throughflow index, i.e. the fraction of total water inputs lost by evaporation. Given the estimate of evaporation from a lake the only unknown in equation (9) is the total inflow. Since precipitation and surface inflow can be determined from meteorological record, groundwater inflow can be estimated as a difference between the total inflow and them. Evaporation of lake Ziway is 1870mm/yr (Vallet-coulomb et al, 2001) multiplying by lake surface area gives a value of 832mcm per year.

Where $\delta^*$ is the limiting isotopic enrichment for a water body evaporating to dryness under local climate conditions (Gat and Levy, 1978; Gat, 1981) and given by

$$\delta^* = \frac{h\delta_A + \varepsilon}{h - 10^{-3}\Delta\varepsilon} \approx \delta_A + {}^{\varepsilon}/_{h} \qquad (10)$$

where $m$ is the enrichment slope as defined by (Welhan and Fritz, 1977; Allison and Leaney, 1982)

$$m = \frac{h - 10^{-3}\varepsilon}{1 - h + 10^{-3}\Delta\varepsilon} \approx \frac{h}{1-h} \qquad (11)$$

Therefore, the limiting isotopic enrichment is determined to be 13.7‰ and the enrichment slope is calculated to be 1.5.

The average $\delta^{18}O$ composition of lake Ziway, $\delta_L$, is 6.2‰. By inserting these values into equation (9) gives a throughflow index value (E/I ratio) of 0.78 which is a fraction of total inflows lost by evaporation.

Because of recent progress in estimating evaporation rate from lake Ziway (Vallet-Coulomb et al., 2000; Ayenew, 2003) in this study, equation (9) has been used to estimate the groundwater inflow to Lake. This allows also the estimation of groundwater outflow rate.

Precipitation on lake and total surface water inflow can be known from meteorological record of lake Ziway (Table1), and therefore the only unknown in equation (9) will be groundwater inflow. Evaporation of lake Ziway is 1870mm/yr (Vallet-Coulomb et al., 2000), multiplying it by lake surface area (Table 1) gives a value of 832mcm per year. Using the values of the throughflow index and the evaporative flux, the total water flows to lake (equation 9) is estimated to be 1066mcm per year. Precipitation on lake and Surface inflow (ketar and meki rivers) are 335 and 691mcm per year respectively (Table 1). Therefore, groundwater inflow estimated to be 40mcm per year.

Considering Ziway lake as assumed to be in hydrologic steady state, total inflows are balanced by total outflows. Groundwater outflow from the lake is therefore calculated to be 77mcm per year.

### 4.2.3. Discussion

In this research the water $\delta^{18}O$ isotope of Lake Ziway is used to estimate its water budget. The main purpose of the water balance computation is to estimate the groundwater inflow and outflow rates to the Lake. The method employed the isotope balance approach. In this approach, the combination of the hydrologic and isotope mass balance equations (equation 1 and 2) is utilized. The $\delta^{18}O$-based water balance of the lake is computed on the basis of the regional parameters estimated from the index lake and on the various hydrological parameters of the lake presented in Table 1. And by inserting these parameters into above equations the lake water budget is determined.

The water balance of the lake estimated from the $\delta^{18}O$-isotope balance computations is given in Table 3. The isotope balance approach shows evaporation accounts for the dominant loses of water from the lake, which is estimated to be 78% of the total inflow loses.

The total groundwater outflow accounts for 8% of total outflow (evaporation and surface water outflow combined) from the Lake and groundwater inflow to the lake accounts for 4% of the total inflow from precipitation on lake and surface water inflow.

*Table 2: Inputs to the $\delta^{18}$O-Isotope mass balance equations*

| Parameter | Value | Method of estimation |
|---|---|---|
| $\alpha$ | 1.01 | Temperature dependent constant |
| $h=e_a/e_s$ | 0.60 | Estimated from adjacent meteorology station |
| $\Delta\varepsilon= (1-h)C_k$ | 5.72 | Estimated as in the equation |
| $\varepsilon^*=(1-\alpha^*)*1000$ | 9.70 | Estimated as in the equation |
| $\varepsilon=\Delta\varepsilon + \varepsilon^*$ | 15.42 | Estimated as in the equation |
| $C_k$ | 14.30 | Empirical constant |
| $\delta_I$ | -2.60 | Estimated from Index lake method |
| $\delta_A$ | -12.07 | Estimated from Index lake method |
| $\delta^*$ | 13.70 | Estimated from all the other parameters |
| $\delta_L$ | 6.20 | Measured from lake waters |

Where, h is humidity normalized to lake surface temperature, $C_k$ is evaporation resistance factor, $\varepsilon$ total separation factor, $\varepsilon^*$ is equilibrium separation factor, $\Delta\varepsilon$ is kinetic separation factor, $\delta_E$ isotopic composition of evaporating water, $\delta_I$ is net isotopic composition of inflowing water, $\delta_A$ is isotopic composition of ambient air, $\delta_E$ the isotopic composition of evaporation, $\delta^*$ is the limiting isotopic composition for oxygen in the region (the maximum enrichment that could be attained).

Table 3: Water balance of Lake Ziway determined from $\delta^{18}$O-Isotope balance equation

| Water balance component | Annual flow in MCM (Million $m^3$) | Remark |
|---|---|---|
| Rainfall on the Lake | 335 | |
| Direct open water evaporation from the Lake | 832 | |
| Total surface water inflow from the catchment | 691 | |
| Total groundwater inflow from the basin | 40 | 4% of total inflow |
| Total surface water outflow from the Lake | 157 | |
| Total groundwater outflow from the Lake | 77 | 8% of total outflow |

The throughflow index (E/I ratio) obtained from the isotopic mass balance approach is in good agreement with the estimates determined from physical water balance method which give E/I ratios varying between 0.75 and 1 for the majority of the rift valley lakes (Ayenew, 1998; Vallet-Coulomb et al., 2000; Legesse, 2002; Makin et al. 1975).

## 5. Major Scientific Conclusions and Recommendations

The combined results from $^{222}Rn$ concentration measurements, analysis of the isotopic compositions ($\delta^{18}O$ and $\delta^{2}H$) and the supportive piezometric evidences provide a complementary evidence to identify and delineate zones of lake and groundwater interaction.

The convergent evidence clearly suggest that the eastern margin is groundwater influx zones into lake Ziway and the south  and southwest sectors are the groundwater outflow regions. This signifies the groundwater discharge to lake from local flow systems (possibly from immediate lacustrine deposits) in the eastern region and the lake recharges the local aquifer in the south and southwest sectors. The recharge in this area could be facilitated by fractures and faults that affected the lake.

The water balance results of the $\delta^{18}O$ method showed groundwater flux around the lake accounts for around 12 % of the total flow. The contribution of groundwater inflows to lake hydrologic budgets seems insignificant however its importance/impacts on the ecological functions of the lake by transporting solutes and nutrients to the lake cannot be ruled out.

The groundwater outflow exceeds the groundwater inflow contribution. This is because of the fact that the regional water table is below the Lake level in several sector of the region particularly south and southwest of the Lake  and may be due to influence of geological structures. Regardless of its relatively lower contribution to the water flows, the role of the groundwater outflow in regulating the salinity of the lake cannot be ruled out.

The water balance results of the $\delta^{18}O$ method give reliable results consists with estimates determined by physical hydrologic methods (Ayenew, 1998; Vallet-Coulomb et al., 2000; Legesse, 2002; Makin et al. 1975) and thus increasing confidence on the values obtained.

The water balance study revealed the existence of interactions between the lake and the groundwater and thus indicating it is a throughflow systems. This shows the role of groundwater in the hydrology of the lake and the role of lake on adjacent groundwater in contrast to the classical common assumptions that neglect groundwater in most of the lakes budgets in the rift valley. The research clearly demonstrate that   any   future development and management of water resources in this area should be seen in integrated manner by accounting lake and groundwater as a   single resource.

The study also demonstrates that the lake is evaporation-dominated. This combined with the rising demand for consumptive water use particularly for irrigation directly from lake or the inflowing rives in excess of 234mcm per year (the surface and groundwater outflows of lake Ziway) will change the lake from freshwater to saline lake type and will turn the lake into a terminal lake. This will have a negative impacts on the sensitive aquatic ecosystem and socioeconomic activities. Therefore adaptive integrated and foresighted management of both water systems as a single resource is of imperative importance.

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# Appendix

## I. Radon concentration Values

| Radon-222 readings at selected points on Lake Ziway | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| No. | Date | Location (GPS) | | | Radon Readings ( Cycles) | | | | Remark |
| | | X | Y | Z | 1 | 2 | 3 | 4 | |
| 1 | 30/11/2017 | 469698 | 877039 | 1633 | 0.00 ± 44.8 | 11.2 ± 54.00 | 22.4 ± 61.2 | 11.2 ± 54.1 | |
| 2 | 1/12/2017 | 492053 | 896123 | 1934 | 0.00 ± 44.8 | 0.00 ± 44.8 | 11.2 ± 54.1 | 11.2 ± 54.1 | |
| 3 | 2/12/2017 | 486795 | 888589 | 1638 | 11.2 ± 54.1 | 22.4 ± 61.2 | 0.00 ± 44.8 | 44.8 ± 72.5 | |
| 4 | | 488364 | 892942 | 1639 | 22.4 ± 61.2 | 22.4 ± 61.2 | 22.4 ± 67.2 | 44.8 ± 72.5 | |
| 5 | | 492518 | 892087 | 1629 | 0.00 ± 44.8 | 33.6 ± 67.2 | 44.8 ± 72.5 | 33.6 ± 67.1 | |
| 6 | | 486181 | 883888 | 1637 | 11.2 ± 54.1 | 33.6 ± 67.2 | 33.6 ± 67.2 | 11.2 ± 54.1 | |
| 7 | 3/12/2017 | 492103 | 888084 | 1640 | 0.00 ± 44.8 | 11.2 ± 54.1 | 123 ± 100 | 89.7 ± 89.7 | |
| 8 | | 492440 | 883532 | 1635 | 78.4 ± 85.8 | 89.8 ± 89.8 | 67.2 ± 81.7 | 44.8 ± 72.5 | |
| 9 | | 488233 | 879908 | 1636 | 33.6 ± 67.1 | 44.8 ± 77.3 | 11.2 ± 54.1 | 56.0 ± 77.3 | |
| 10 | | 484857 | 876251 | 1639 | 11.2 ± 54.1 | 22.4 ± 61.2 | 33.6 ± 67.2 | 78.6 ± 86.0 | |
| 11 | 4/12/2017 | 483617 | 876797 | 1642 | 11.2 ± 54.1 | 11.2 ± 54.1 | 33.6 ± 67.1 | 11.2 ± 54.0 | |
| 12 | | 484057 | 876434 | 1643 | 33.6 ± 67.2 | 11.2 ± 54.0 | 22.4 ± 61.9 | 0.00 ± 44.8 | |
| 13 | | 485301 | 872810 | 1639 | 33.6 ± 67.2 | 55.7 ± 76.9 | 101 ± 93.1 | 78.4 ± 85.8 | |
| 14 | | 480875 | 868096 | 1640 | 56.0 ± 77.3 | 101 ± 93.5 | 44.7 ± 72.5 | 22.4 ± 61.5 | |
| 15 | 14/04/2018 | 483546 | 891033 | 1636 | 22.4±61.2 | 0.00 ± 44.6 | 33.4 ± 66.9 | 33.6 ± 67.2 | |
| 16 | | 478122 | 894538 | 1639 | 0.00 ± 44.8 | 33.6 ± 67.2 | 33.6 ± 67.1 | 33.6 ± 67.1 | |
| 17 | | 475278 | 892157 | 1637 | 0.00 ± 44.8 | 56.0 ± 77.3 | 0.00 ± 44.8 | 22.3 ± 61.0 | |
| 18 | | 478784 | 890239 | 1636 | 22.4 ± 61.2 | 33.4 ± 66.9 | 22.4 ± 61.2 | 33.6 ± 67.2 | |
| 19 | 16/04/2018 | 472627 | 881054 | 1637 | 0.00 ± 44.8 | 0.00 ± 44.7 | 0.00 ±44.8 | 11.2 ± 54.1 | |
| 20 | | 472815 | 884537 | 1640 | 11.2 ± 54.1 | 11.2 ± 54.1 | 22.4 ± 61.2 | 0.00 ± 44.8 | |
| 21 | | 473659 | 887411 | 1638 | 22.4 ± 61.2 | 0.00 ± 44.8 | 0.00 ± 44.8 | 22.4 ± 61.2 | |
| 22 | 17/04/18 | 472476 | 874293 | 1641 | 0.00 ± 44.7 | 0.00 ± 44.8 | 11.2 ± 53.8 | 11.2 ± 54.1 | |
| 23 | | 476468 | 871321 | 1639 | 11.2 ± 54.1 | 33.6 ± 67.1 | 11.2 ± 54.1 | 0.00 ± 44.7 | |
| 24 | | 480702 | 872644 | 1639 | 22.4 ± 61.2 | 33.6 ± 67.1 | 22.4 ± 61.2 | 11.2 ± 54.1 | |
| 25 | 18/04/2018 | 477959 | 876765 | 1642 | 0.00 ± 44.8 | 44.8 ± 72.5 | 11.2 ± 54.1 | 44.8 ± 72.5 | |
| 26 | | 484436 | 878715 | 1640 | 67.2 ± 85.8 | 101 ± 93.3 | 78.4 ± 85.5 | 67.1 ± 85.7 | |
| 27 | | 479114 | 886072 | 1641 | 56.1 ±77.4 | 44.8 ± 72.5 | 44.7 ± 72.3 | 22.4 ± 61.2 | |
| 28 | | 479121 | 880589 | 1635 | 89.8 ± 89.9 | 78.4 ± 85.8 | 78.4 ± 85.8 | 44.8 ± 72.5 | |
| 29 | 19/04/2018 | 483438 | 878779 | 1634 | 78.4 ± 85.8 | 11.3 ± 54.3 | 44.8 ± 72.4 | 44.7 ± 72.3 | |
| 30 | | 484693 | 876228 | 1637 | 11.2 ± 54.0 | 11.2 ± 54.1 | 44.8 ± 72.5 | 55.7 ± 76.9 | |
| 31 | | 483520 | 876702 | 1638 | 11.2 ± 54.1 | 33.6 ± 67.2 | 33.6 ± 67.2 | 44.8 ± 72.5 | |
| 32 | 7/12/2017 | 458081 | 848419 | 1578 | 0.00 ± 44.8 | 22.3 ± 60.8 | 22.4 ± 61.4 | 22.4 ± 61.2 | Bulbula River |
| 33 | | 461070 | 853321 | 1581 | 56.0 ± 77.3 | 11.2 ± 54.1 | 11.2 ± 53.8 | 67.2 ± 81.7 | |
| 34 | | 467281 | 863961 | 1595 | 11.2 ± 54.1 | 89.7 ± 89.7 | 78.3 ± 85.7 | 22.4 ± 61.1 | |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 35 | 8/12/2017 | 470739 | 872941 | 1638 | 0.00 ± 44.8 | 67.2 ± 81.7 | 55.9 ± 77.2 | 22.4 ± 61.1 | |
| 36 | 9/12/2017 | 468102 | 877004 | 1664 | 866 ± 221 | 3080± 399 | 3780 ± 438 | 4150 ± 462 | Donbosco Borehole |
| 37 | 15/12/2017 | 463088 | 867134 | 1672 | 841 ± 218 | 3250± 405 | 4040 ± 450 | 3930 ± 445 | Anano Borehole |
| 38 | | | | | 1050 ± 249 | 3730± 435 | 4360 ± 468 | 3761 ± 485 | |
| 39 | | 501319 | 889352 | 1677 | 954 ± 231 | 2510 ± 360 | 3130 ± 399 | 3380 ± 414 | Habura/Ogolcho Borehole |
| 40 | 17/04/2018 | 483568 | 876829 | 1636 | 2010 ± 324 | 5680 ± 530 | 6590 ± 570 | 6600 ± 571 | Tulu Gudo Springs |
| 41 | | 484585 | 876369 | 1639 | 2440 ± 356 | 5940 ± 542 | - | - | |
| 42 | 18/04/2018 | 469796 | 886236 | 1659 | 4790± 488 | 13k3 ± 802 | 15k3 ± 863 | 14k5 ± 841 | Abosa Borehole |
| 43 | 20/12/2017 | 439976 | 1006431 | 2538 | 661 ± 196 | 2450 ± 356 | 3350 ± 412 | 3180 ± 403 | Holeta : Town Waterr Supply Borhole : 338m |
| 44 | | 445785 | 1001591 | 2476 | 2100 ± 331 | 3560 ± 408 | - | - | Holeta : Agri. Research Institute Borehole, 75m |

## II. Isotope composition of Lakes, groundwaters and springs

| Site Name | Type | X | Y | Depth | $\delta^{18}O$_‰ | $\delta^{2}H$_‰ | Source |
|---|---|---|---|---|---|---|---|
| Bethlehem Hotel Ziway | HD | 469469 | 875937 | 6 | 1.15 | 15.20 | 1,2 |
| Bakele Molla Hotel Ziway | BH | 468697 | 876048 | 36 | 4.54 | 34.40 | 1,2 |
| Yanet Hotel | HD | 468919 | 877927 | 15 | 4.86 | 34.90 | 1,2 |
| Ziway Caustic Soda Factory | BH | 467816 | 467816 | 63 | 4.60 | 33.80 | 1,2 |
| Dombosco Catholic School | BH | 467816 | 467816 | 80 | 4.65 | 34.40 | 1,2 |
| Ziway Brick Factory | HD | 468476 | 874721 | 23 | 3.86 | 30.20 | 1,2 |
| Pesticide Factory Adami Tulu | BH | 466599 | 870743 | 82 | 4.93 | 37.00 | 1,2 |
| Anano Shisho | BH | 465713 | 865438 | 84 | 4.38 | 33.65 | 1,2 |
| Korean No 6 Widena Town | BH | 465278 | 872955 | 97 | 5.25 | 39.20 | 1,2 |
| Korean well No 8 Boromo | BH | 461862 | 874063 | 111 | -3.50 | -18.00 | 1,2 |
| Lake Babogaya | LK | 499185 | 971422 | - | 6.70 | 42.50 | 1,2 |
| Alecu | BH | 465385 | 869197 | 68 | 5.13 | 38.30 | 1,2 |
| Shisho Tora | BH | 463179 | 867208 | 150 | 5.24 | 38.70 | 1,2 |
| Abussa Ol | BH | 469916 | 886327 | 44 | 5.51 | 39.50 | 1,2 |
| Tufa Spring | SP | 479266 | 847191 | - | -3.40 | -12.70 | 1,2 |
| Lake Hora | LK | 498819 | 968713 | - | 7.20 | 37.40 | 1,2 |
| Lake Ziway | LK | 476083 | 884242 | - | 6.70 | 49.00 | 1,2 |
| Lake Bishoftu | LK | 497994 | 966173 | - | 6.90 | 42.90 | 2 |
| Ketar River_ Assela | RV | 514542 | 880766 | - | -0.26 | 11.90 | 1,2 |
| Meki_Irenzaf | RV | 431210 | 898294 | - | 0.49 | 8.05 | 4 |
| River_Ziway town | RV | 468725 | 877076 | - | -0.70 | 12.85 | 2, |
| Bulbula River | RV | 461232 | 853940 | - | 5.29 | 39.00 | 1,4 |
| Woja_Akemuja | RV | 451466 | 897888 | - | 0.70 | 7.50 | 4 |
| Ketar River_kulumsa | RV | 511691 | 883239 | - | -2.03 | 0.10 | 1,2 |
| WL-1 | BH | 467974 | 863049 | - | 4.28 | 32.60 | 3,4 |
| WL-10 | BH | 482908 | 854827 | - | -2.40 | -8.00 | 3,4 |
| Chafe Jila | BH | 481995 | 863631 | - | -1.30 | -13.00 | 3,4 |
| Meki 01 | BH | 479438 | 899958 | 84 | -1.95 | -3.93 | 1,4 |
| Anano | BH | 467892 | 869314 | - | 4.45 | 32.38 | 1,4 |
| Abura | BH | 501935 | 888761 | 75 | -3.37 | -11.30 | 1,4 |
| Ziway Prison | BH | 467797 | 878153 | - | 5.04 | 36.20 | 1,4 |
| Meki 02 | BH | 479815 | 900819 | 82 | -2.73 | -8.10 | 1,4 |
| Ilala Gubiba | BH | 456844 | 884690 | 132 | -3.53 | -15.00 | 4 |
| Aluto_GWS | GW | 473069 | 857081 | - | 6.01 | 46.00 | 4 |
| Aluto_GWN | GW | 473130 | 861620 | - | 6.70 | 46.00 | 4 |
| WL-8* | BH | 484614 | 857721 | - | -1.40 | -8.00 | 4 |
| WL-9* | BH | 484888 | 854858 | - | -2.60 | 7.00 | 4 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| WL-I** | BH | 456844 | 884690 | - | -3.53 | -15.00 | 4 |
| Meki River @ Meeki | RV | 480300 | 901668 | - | 1.67 | 6.14 | 4 |
| Siltie Tebel Spring | SP | 428224 | 887304 | - | -2.44 | -3.70 | 4 |
| Butajira Spring | SP | 432113 | 898297 | - | -2.25 | -3.10 | 4 |
| Imba Koto -Hot spring | HSP | 428631 | 883578 | - | -3.66 | -15.60 | 4 |
| Koshe Well | BH | 448890 | 886031 | 115 | -3.53 | -15.00 | 4 |
| Lake Abijata | LK | 457292 | 835273 | - | 10.00 | 64.20 | 1,4 |
| Lake Langano | LK | 469819 | 836981 | - | 6.85 | 45.80 | 4 |
| Lake Shala | LK | 448182 | 825023 | - | 8.30 | 54.40 | 4 |
| Lake Shala Hot Spring | HSP | 455330 | 830112 | - | -1.97 | 1.90 | 1,4 |
| Germama_Kontela | BH | 467776 | 881478 | - | 5.14 | 32.27 | 1,4 |
| Weyo School | BH | 471669 | 891730 | 60.5 | 5.02 | 31.65 | 1,4 |
| Meja Shenen | BH | 496216 | 897505 | 64 | -3.35 | -13.70 | 1,5 |
| WL22 | BH | 462326 | 864828 | 96 | 1.45 | 6.92 | 4 |
| Note: BH :Boreholes; SP: Springs; LK: Lakes; GW: Geothermal wells | | | | | | | |
| Source: 1:This research 2018;2:Kebede,2004; 3:Ayenew,1998; 4:UNDP,1977; | | | | | | | |

## III. Piezometric Data

| Symbol | X | Y | Z | Depth | SWL | PS | Specific site |
|---|---|---|---|---|---|---|---|
| BH1 | 461636 | 885312 | 1715 | 140 | 102 | 1613 | |
| BH2 | 463216 | 867376 | 1675 | - | 75 | 1600 | |
| BH3 | 464718 | 883354 | 1676 | - | 60 | 1616 | Wege |
| BH4 | 468958 | 899334 | 1724 | 158 | 85 | 1640 | Meja |
| BH5 | 469942 | 895943 | 1711 | 128 | 80 | 1632 | Dodota |
| BH6 | 474128 | 894627 | 1675 | 63 | 30 | 1645 | Tepho Cheroke |
| BH7 | 478369 | 898541 | 1648 | - | 18 | 1630 | Wachu Girisa |
| BH8 | 489715 | 867833 | 1790 | - | 95 | 1695 | Chefe Burkitu |
| BH9 | 495889 | 895142 | 1644 | 79 | 33 | 1611 | Burqa BH |
| BH10 | 496131 | 897617 | 1677 | 42 | 30 | 1647 | |
| BH11 | 496211 | 897486 | 1676 | 64 | 30 | 1646 | |
| BH12 | 497543 | 892736 | 1705 | 81 | 44 | 1661 | Sengo |
| BH13 | 500516 | 889860 | 1685 | 202 | 26 | 1659 | Uhubo Berecha |
| BH14 | 501227 | 889154 | 1689 | 75 | 70 | 1619 | |
| BH15 | 496315 | 897541 | 1676 | 64 | 30 | 1646 | Meja Shenen |
| BH16 | 495889 | 895142 | 1644 | 79 | 33 | 1611 | Burqa BH |
| BH17 | 496970 | 878361 | 1719 | 80 | 46 | 1673 | Dobdobo |
| BH18 | 494507 | 874562 | 1724 | 60 | 44 | 1680 | Kiansho |
| BH19 | 492038 | 871194 | 1756 | 190 | 74 | 1682 | Kiyansho Kobota |
| BH20 | 494600 | 874770 | 1727 | - | 46 | 1681 | Kiyansho |
| BH21 | 483650 | 866279 | 1661 | - | 52 | 1609 | Chefe Jila 01 |
| BH22 | 488006 | 859301 | 1907 | - | 156 | 1751 | Adere Lepho |
| BH23 | 495587 | 871329 | 1827 | - | 107 | 1720 | Kobo Borera |
| BH24 | 494121 | 867777 | 1880 | - | 132 | 1748 | Abure |
| BH25 | 500516 | 889860 | 1685 | 202 | 26 | 1659 | Uhubo Berecha |
| BH26 | 501319 | 889352 | 1677 | 75 | 25 | 1652 | Ogolcho BH |
| BH27 | 497543 | 892736 | 1705 | 81 | 44 | 1661 | Sengo BH |
| BH28 | 489715 | 867833 | 1780 | - | 85 | 1695 | Chefe Burkitu |
| BH29 | 463008 | 873643 | 1667 | 98 | 56 | 1611 | Garb/wid/Boramo |
| BH30 | 445064 | 859096 | 1678 | 180 | 99 | 1579 | Urgo machefarra |
| BH31 | 471214 | 891136 | 1677 | 61 | 33 | 1644 | |
| BH32 | 472898 | 893416 | 1678 | 54 | 33 | 1645 | |
| BH33 | 474554 | 908761 | 1721 | 120 | 96 | 1625 | |
| BH34 | 477286 | 906903 | 1716 | 92 | 81 | 1635 | |
| BH35 | 479313 | 905790 | 1712 | 102 | 85 | 1627 | |
| BH36 | 478200 | 920000 | 1600 | 75 | 60 | 1540 | |
| BH37 | 483833 | 904045 | 1677 | 52 | 34 | 1643 | |
| BH38 | 469342 | 901807 | 1720 | 100 | 85 | 1635 | |
| BH39 | 479131 | 900450 | 1669 | 32 | 31 | 1638 | |
| BH40 | 479766 | 901046 | 1675 | 32 | 29 | 1646 | |
| BH41 | 498754 | 922389 | 1608 | 43 | 30 | 1578 | |
| BH42 | 469210 | 888248 | 1681 | 75 | 53 | 1628 | |
| BH43 | 481495 | 909593 | 1704 | 105 | 84 | 1620 | |
| BH44 | 477019 | 917872 | 1724 | 123 | 79 | 1646 | |
| BH45 | 480351 | 901718 | 1680 | 41 | 34 | 1646 | |
| BH46 | 480199 | 901430 | 1680 | 54 | 30 | 1650 | |
| BH47 | 480387 | 901435 | 1669 | 54 | 30 | 1639 | |
| BH48 | 471672 | 892227 | 1679 | 50 | 30 | 1649 | |
| BH49 | 467748 | 894665 | 1714 | 99 | 81 | 1633 | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| BH50 | 469725 | 895830 | 1716 | 110 | 79 | 1637 | |
| BH51 | 469886 | 886446 | 1654 | 81 | 31 | 1623 | Abosa town |
| BH52 | 479226 | 898332 | 1647 | - | 15 | 1633 | Wachu Girisa |
| BH53 | 484764 | 920771 | 1690 | 165 | 90 | 1600 | |
| BH54 | 483074 | 898580 | 1648 | - | 9 | 1639 | |
| BH55 | 474283 | 894973 | 1666 | 44 | 8 | 1658 | |
| BH56 | 492763 | 900233 | 1674 | 73 | 33 | 1641 | |
| BH57 | 496211 | 897486 | 1676 | 64 | 30 | 1646 | |
| BH58 | 467644 | 868349 | 1658 | 154 | 55 | 1603 | Adame Tulu |
| BH59 | 466561 | 870573 | 1644 | - | 28 | 1616 | Pesticide factory |
| BH60 | 480497 | 900763 | 1662 | 84 | 49 | 1613 | Meki 01 |
| BH61 | 466592 | 870790 | 1644 | - | 29 | 1615 | |
| BH62 | 468735 | 875680 | 1647 | - | 22 | 1625 | Elementary school |
| BH63 | 467744 | 876679 | 1652 | - | 29 | 1623 | Mission Sefer |
| BH64 | 475571 | 924071 | 1752 | 154 | 92 | 1660 | |
| BH65 | 480694 | 901824 | 1661 | 83 | 29 | 1632 | Meki 02 |
| BH66 | 478364 | 897796 | 1666 | - | 12 | 1654 | Kofe Bari |
| BH67 | 496131 | 897617 | 1677 | 42 | 30 | 1647 | |
| BH68 | 469448 | 901986 | 1721 | 100 | 85 | 1636 | |
| BH69 | 472425 | 902009 | 1656 | 80 | 28 | 1628 | Weyo Gebriel |
| BH70 | 477198 | 901824 | 1688 | 75 | 60 | 1628 | |
| BH71 | 473980 | 903130 | 1688 | 75 | 61 | 1627 | |
| BH72 | 469824 | 896035 | 1705 | 110 | 79 | 1626 | |
| BH73 | 470000 | 891000 | 1705 | 54 | 33 | 1672 | |
| BH74 | 471570 | 898358 | 1722 | 93 | 78 | 1644 | |
| BH75 | 490632 | 918070 | 1655 | 127 | 79 | 1576 | |
| BH76 | 476306 | 897835 | 1664 | 51 | 30 | 1634 | Giraba Korke Adi |
| BH77 | 472990 | 893601 | 1670 | - | 33 | 1637 | |
| BH78 | 472726 | 893351 | 1665 | - | 33 | 1632 | |
| BH79 | 471764 | 892451 | 1675 | 50 | 35 | 1640 | |
| BH80 | 471400 | 892500 | 1675 | 99 | 81 | 1594 | |
| BH81 | 471669 | 891730 | 1675 | 61 | 33 | 1642 | Weyo School |
| BH82 | 469500 | 889800 | 1687 | 75 | 53 | 1634 | Toch Dembel |
| BH83 | 469822 | 890935 | 1694 | 72 | 54 | 1640 | |
| BH84 | 471300 | 898200 | 1694 | 54 | 30 | 1664 | |
| BH85 | 470500 | 914200 | 1694 | 60 | 28 | 1666 | |
| BH86 | 493500 | 916800 | 1660 | 93 | 62 | 1599 | |
| BH87 | 472200 | 902400 | 1660 | 90 | 57 | 1603 | |
| BH88 | 474500 | 902500 | 1660 | - | 54 | 1606 | |
| BH89 | 481416 | 909593 | 1712 | 105 | 84 | 1628 | |
| BH90 | 470565 | 914133 | 1747 | 62 | 54 | 1693 | |
| BH91 | 487438 | 902563 | 1677 | 50 | 26 | 1651 | |
| BH92 | 477313 | 906916 | 1721 | 92 | 81 | 1640 | |
| BH93 | 480034 | 902598 | 1685 | 41 | 34 | 1651 | |
| BH94 | 465363 | 869206 | 1658 | 82 | 58 | 1600 | |
| BH95 | 456338 | 873026 | 1710 | 127 | 93 | 1617 | |
| BH96 | 462137 | 883385 | 1707 | 108 | 81 | 1626 | |
| BH97 | 472335 | 901797 | 1703 | 92 | 74 | 1629 | |
| BH98 | 468848 | 889123 | 1684 | 40 | 35 | 1649 | Megu |
| BH99 | 468604 | 886521 | 1669 | 40 | 30 | 1639 | Elka Metremofa |
| BH100 | 469440 | 886823 | 1671 | 51 | 32 | 1640 | |
| BH101 | 468446 | 885274 | 1663 | 45 | 35 | 1628 | Hizbawi Betele |
| BH102 | 469069 | 882869 | 1654 | 37 | 18 | 1636 | |
| BH103 | 468333 | 879382 | 1655 | 25 | 22 | 1633 | Ziway town |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| BH104 | 465797 | 875905 | 1661 | 60 | 45 | 1616 | |
| BH105 | 466857 | 876078 | 1660 | 56 | 42 | 1618 | |
| BH106 | 467526 | 877495 | 1658 | 50 | 34 | 1624 | Ziway prison |
| BH107 | 468215 | 876905 | 1658 | 60 | 33 | 1625 | Adame Tulu town |
| BH108 | 474683 | 942441 | 1710 | 80 | 65 | 1645 | |
| BH109 | 464718 | 883354 | 1676 | 295 | 270 | 1406 | |
| BH110 | 467945 | 869660 | 1654 | 66 | 30 | 1624 | |
| BH111 | 471448 | 898126 | 1706 | 93 | 78 | 1628 | |
| BH112 | 462137 | 883385 | 1707 | 108 | 81 | 1626 | Galo Fechase |

PS : Groundwater level or Piezometric Surface ; SWL :
Static Water level