APPLICATION OF STABLE ISOTOPES IN THE STUDY OF LAKE DYNAMICS

IN ZIWAY-SHALLA BASIN (ETHIOPIA).

A THESIS

SUMITTED TO SCHOOL OF

GRADUATE STUDIES ADDIS ABABA UNIVERSITY

IN PARTIAL FULFILLMENT OF

THE REQUIREMENT FOR THE DEGREE

MASTER OF SCIENCE IN GEOLOGY

ELENI AYALEW

JUNE 2003

ACKNOWLEDGMENTS

I would like to express my gratitude to my advisor Dr. Tamiru Alemayehu, for his approval and encouragement, which initiated me to work on the title. His comments and valuable assistance during the thesis work is appreciated. I am grateful for his help that enabled me to get an inland scholarship.

I am greatly indebted to my co-advisor, Ato Seifu Kebede, for his continuous guidance, support, comments, and priceless discussions and for all his inputs, which helped me to understand the science. His assistance in analyzing all the samples and consistent help during the field and paperwork despite his tight schedule is greatly appreciated. Many Many Thanks!

I would like to thank Dr. Bekele Abebe, for his cooperation in providing me the necessary financial and logistic support.

I am very much grateful to my friend, Khalid Adem for all his kind help and encouragement during the entire study period.

I acknowledge the institutions, Ethiopian Institute of Geological Surveys (EIGS), Ministry of Water Resources Development, National Meteorological Services (NMS) and others to let me use their materials and data as an input to my work.

TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

LIST OF ANNEXES

ABSTRACT

A thorough understanding of lakes hydrology is crucial before any usage of the lakes for different development works. In Ziway-Shalla basin where there is complex interaction between the lakes and groundwater system, stable isotope water balance method is employed in this work to estimate the groundwater exchange rate for the geographically clustered lakes of the basin.

Although the stable isotope water balance method has limitation due to lack of measurement of environmental parameters, the existence of terminal lake, Lake Abiyata in the basin gives a chance to estimate these environmental parameters that are important in groundwater quantification. These environmental parameters would have been difficult to measure. The unknown δ_A, isotopic composition of the atmospheric moisture for Ziway - Shalla basin is estimated to be -16.8‰ and the limiting isotopic composition (δ^*) determined to be 12.5 ‰. The lakes are evaporated with respect to the present day precipitation and the surface and groundwaters between the lakes are influenced by the lakes indicating the hydraulic link between surface and groundwater.

The result of stable isotope water balance shows that the lakes are influenced by different degree of groundwater flux .The groundwater inflow to lake Langano and Shalla is significant while the inflow to lake Abiyata is minimum. The groundwater outflow from Lake Ziway is significant which may become groundwater inflows to the two downstream lakes, Abiyata and Langano. Lake Langano is characterized by modest groundwater outflow next to the two terminal lakes in the basin.

CHAPTER I

1. INTRODUCTION

1.1. Background

The water and isotope balance of the four lakes of the Ziway-Shalla basin is studied using isotopes of water, hydrochemistry and hydrological approaches. The study site is located in Main Ethiopian Rift (**figure 1a**), which is part of the East African Rift system. Intra rift faulting and associated volcanic activities resulted in formation of structural depression which becomes sites of the present day group of lakes. The lakes form a chain of interconnected discrete set of drainage system isolated from each other by volcanic hills and ridges.

The basin comprises four permanent lakes. These are lakes Ziway, Langano, Abiyata and Shalla. These lakes have been used for long time for different purposes (small scale commercial fishing, recreation and small scale irrigation) and currently the most important abstraction of water from these lakes is being used for irrigation and soda ash production. Lake Ziway and its feeder have been targeted for irrigation development since 1970's. Lake Abiyata has been used for soda ash production since 1989 by evaporating lake water. On the other hand, the basin is characterized by significant ecological and wealth in biodiversity. Birds, wild life parks with big potential for tourism industry and fishery are the important natural resources.

Figure 1a. Digital terrain map of Ethiopia and location map of the area

The lakes are also of immense importance for scientific studies in disciplines such as paleoclimate reconstruction, water geochemical evolution studies, and human impact studies at regional or global scale. Furthermore the lakes may play a major importance not only from the point of view of using them directly for water supply (irrigation or domestic) but also they are important element of the water compartment of the basin that may recharge the groundwater aquifers adjacent to them in this water deficit zone of the country.

There has been reduction in the volume of lake Abiyata. The chemistry of this lake undergone considerable increase in ionic concentration (Tenalem Ayenew, 1998). The change in lake volume may be related to soda production or / and to abstraction of water from lake Ziway for irrigation. Lake Ziway is directly connected to Lake Abiyata by Bulbula River. The change may also be related to change in climate condition. In this lake system, if there is change in one of the lakes or their feeder rivers, the change will be manifested in the other lake as the lakes are connected to each other either by surface or groundwater flows.

The rapid population growth and associated water resource development works in the area may place a strain upon the water balance of the lakes. This may cause adverse impact on lacustrine ecological environment. So before any further expansion, the water balance of the regime of the lakes should be understood comprehensively so as to set an optimum condition to use the lakes with a minimum possible environmental impact.

1.2. Relevance of the study

The need for scientific understanding on the ways of using available water resource in a lake basin is unquestionable. This insures the health of natural environment by avoiding further change in hydrological regime of lakes and ecology of the lacustrine environment. To set an optimum condition for water abstraction in the basin, a very good understanding of lakes hydrology (i.e. the water budget of the lakes), understanding lake-groundwater interaction, interaction among the lakes, and understanding the chemical behavior and evolution of the lakes is very essential.

Previous works mainly used physical hydrogeological approaches and numerical modeling (Tenalem Ayenew, 1998) to understand the role groundwater plays in the water balance of the lakes. Using environmental isotopes and geochemistry, Tesfaye Chernet (1998) qualitatively shows the role the groundwater plays in the hydrology of the lakes. No previous attempt has been made to quantify the role of groundwater in the hydrology of the lakes using environmental isotopes. The goal of this work is to quantify the water budget of the lakes using isotopes of water. In addition, the results that will be obtained may be used in wider areas such as water resources development, fishery, agriculture and climate variability studies. A good understanding of the isotope hydrology of these lakes also provides a qualitative insight into hydrology of the lakes outside the basin. Isotopes and chemical analysis results and the interpretations that will be made from this work may also be used in defining the boundary conditions for a further numerical groundwater modeling works in the basin.

1.3. Objectives of the study

The major objectives of this work are a) to calculate water balance of the lakes using isotopes of water and to unravel the importance of groundwater in the hydrology of the lakes, b) to understand geochemical evolution of groundwaters to identify the causes of degradation of water quality in the basin.

The specific objectives of the study are:

- Showing the subsurface hydraulic link between the lakes
- Showing hydraulic link between lakes and surrounding aquifers.
- Comparing isotopic composition of meteoric waters of the study site with the Local Meteoric Water Line (LMWL) so as to grip a picture on water residence time, rate of evaporative concentration, hydraulic links between lakes, and sources of groundwater recharge etc.
- Recommending the suitability of the waters for different uses.

1.4. Methodology

To achieve the specified objectives geological, hydrometeorological, hydrogeological, and hydrochemical approaches with a special emphasis on isotope hydrological approaches were used. These were made through:

- Collection and analysis of existing geological, hydrogeological, hydrological, hydrochemical and hydrometeorological data from the basin.

- Collection of water samples for the lakes, wells, rivers, springs, etc. in both dry and wet seasons for chemical and isotope analysis.

1.5. Water sampling and analysis

Water samples were collected from lakes, rivers, bore wells, lakes and springs in leak proof plastic and glass bottles. Electrical conductivity, pH and water temperature were measured in situ. The samples were then analyzed within one month after sampling. The samples were stored under a standard condition of sample preservation before they were sent to the University of Avignon for Isotope and Chemical analysis. Major cations were analyzed using Atomic Absorption Spectrophotometer and Major anions were measured using DX600 Ion Chromatograph. Isotopes of Water were analyzed using standard procedure of isotope analysis using mass spectrometer.

1.6. Previous works

Research works in the study area dates back to 1628 when Portuguese missionaries *Manoel de Almedia* reported the existence of lakes in the northern part of the Main Ethiopian Rift. He wrote that 'Awash receives the water of big river named Meki coming from lake Ziway (Beckingham and Huntingford 1954 as cited in Street, 1982). The interrelationship of other three lakes and observation of lake level fluctuation is carried out by *Newman 1901(02), Omer-Cooper in 1926, and Eric Nelson in 1933.* The first bathymetric survey were carried out by *Vatova 1941*, and updated by Ital consultant 1970. Hunting Service took Arial photograph of the area in *1952 and 1972.* Late

Quaternary lake level fluctuation of the lakes in the basin is reconstructed by *Street, 1979.* The later work shows the dramatic change in lake levels during the quaternary and that the lakes formed one big water body before they shrunk to their present positions.

Studies by Talling and Talling *(1965);* Von Damm and Edmond, *(1984); Wood* and Talling (1988)*; Birhanu Gizaw (1996) and Tesfaye Chernet (1998)*; have focused on hydrochemical characterization of different water sources and groundwater and lake water geochemical evolution. Some of these studies qualitatively showed the role lake-groundwater hydraulic link plays in controlling the salinity of the lakes (Wood and Talling, 1988). *Von Damm and Edmonds (1984)* showed the importance of '*with in lake*' geochemical processes such as calcium carbonate precipitation and clay mineral formation (reverse weathering) as a principal control of chemical evolution of the lakes. However in there succeeding works, Wood and Talling (1988) disregard the importance of clay mineral formation in controlling the chemical evolution of the lakes. The role that mantle CO_2 plays in accelerating hydrolysis of silicate minerals and thus in imparting high salinity and alkalinity to groundwaters and lakes in discussed by *Birhanu Gizaw (1996)* and *Darling (1996).* A recent work by *Tesfaye Chernet (1998*) showed the role of evaporative enrichment in lakes as a principal control of chemical degradation of water quality in the lakes and groundwaters.

Studies on hydrogeology of Main Ethiopian Rift (Tesfaye Chernet, 1982; HALCROW, 1989 and Tenalem Ayenew, 1998*)* focused on quantitative hydrogeology. The later showed the importance of groundwater in the hydrology of the lakes after conducting numerical groundwater modeling.

Isotopic geochemical and hydrological study of geothermal water in Ethiopian Rift by Craig *et al.* (1977*)*, a study on geochemistry of liquid process in the eastern branch of east African rift by Darling *(1996)* and Isotope and Geochemical study of the Ziway Shalla lakes by Tesfaye Chernet (1998) were some of the most important studies that used isotopic approaches. These works showed the presence of surface water groundwater hydraulic links and attempted to identify the sources of recharge to geothermal waters. And much more recently Dagnachew Legesse (2002) studied the hydrologic response of Ziway-Shalla lake basin to different scenarios of changes in climate and human activities.

CHAPTER II

2. SITE DESCRIPTION

2.1. Location

The study site lies in the central sector of the Main Ethiopian rift, which is part of the East African Rift system (**figure 1a**). The basin covers an area of 13000 sq km and is bounded with in $38^0$00-$39^0$30 east longitudes and $7^0$00-$8^0$30 north latitude. The basin consist of four lakes: Ziway, Abiyata, Langano and Shalla with variable depth and salinity.

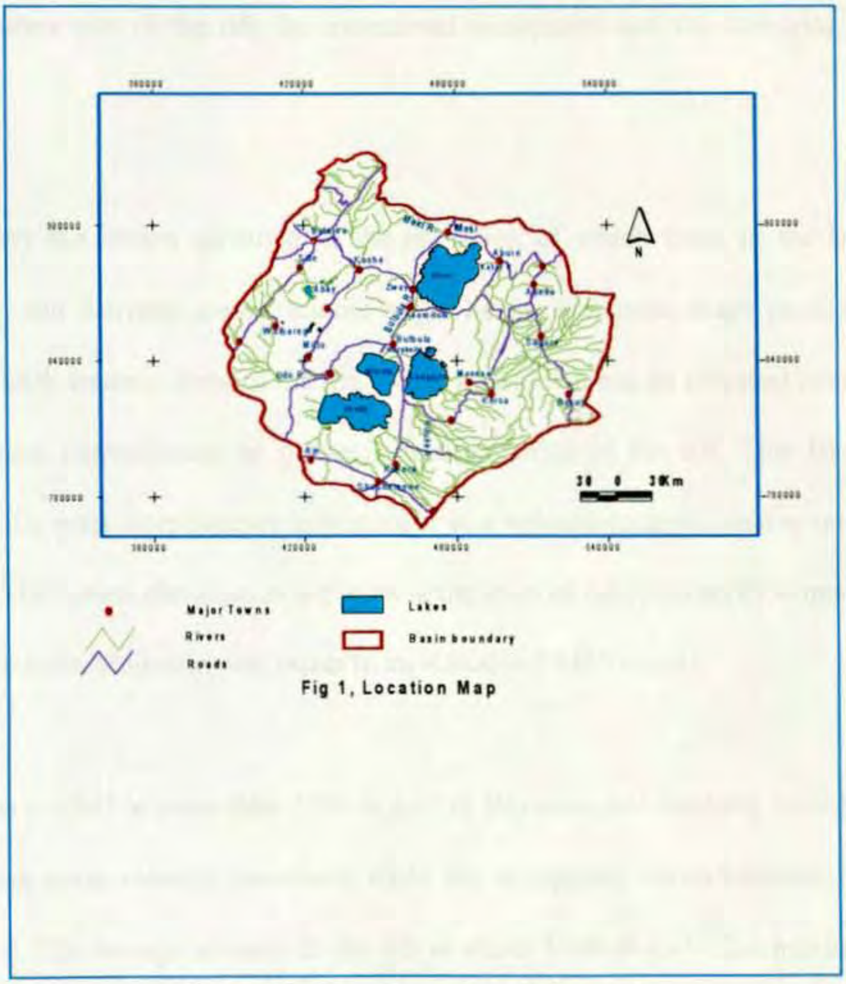


Figure 1b. Location map of the area

2.2. Topography

The Ziway-Shalla basin is bordered by Northwestern Ethiopian Plateau to the West and by the South Eastern Ethiopia Plateau to the east (**figure 1a**). The physiography of the area is chiefly determined by two geologic phenomena. These are the uplifting of Arabo-Ethiopian swell and its subsequent dissection by the rift system faulting. The elevation of the swell is manifested by the fact that most of the highest summit of plateau lies close to margin of rift system. The basin is divided into three-physiographic region, the high plateau on the either side of the rift, the transitional escarpment and the low-lying rift floor.

The Lakes occupy the lowest elevation of the rift floor, of which three of the lakes (Ziway, Langano and Abiyata) are of tectonic origin having elongated shape parallel to the major NNE-SSW tectonic trend of the rift. While lake Shalla has an elliptical contour with its major axis perpendicular to the main tectonic trend of the rift. This lake is characterized by its deep morphometry indicating it is a volcano-tectonic sinking on the floor of the rift. The lowest elevation in the basin is the level of lake Shalla (1550 m.a.s.l) and the highest is Kaka Mountain with raises to an altitude of 4245 m.a.s.l.

The highland has a relief of more than 2000 m.a.s.l in elevation and reaching more than 4000 m.a.s.l along some volcanic mountains while the escarpment varies between 1700 and 2000 m.a.s.l. The average altitude of the rift is about 1700 m.a.s.l. The maximum elevation of the rift floor is about 1800 m.a.s.l at north of Ziway at the watershed between Meki and Awash River.

The structural irregularities of the faulted rift floor have been smoothed out by deposition of lacustrine sediments and recently by volcanic lava and pyroclastic materials during the quaternary. However the recent intensely faulted belt called 'the Wonji fault belt' formed new structural irregularities. The eastern margin is well developed and defined by more or less continuous system of boundary fault where as the western border is marked by few major faults.

2.3. Climate

The climate is humid to sub-humid in the highland and semi-arid in the rift valley. The average rainfall varies from about 1150 mm in eastern and western highlands to about 650 mm in the rift. The mean annual temperature is about 15 C^0 is the highlands and around $20C^0$ is the low land. In the basin temperature and rainfall show strong altitudinal variation. There are three main seasons: the summer (Kirmet), the spring (Belge) and the dry season (Bega). The seasonal drifting of the Inter Tropical Convergence Zone (ITCZ) **(figure 2)** mainly controls the seasonal variation in rainfall.

During the long rainy season is the boreal summer (June- September) the ITCZ lies north of Ethiopia. During this time the Atlantic Ocean and the southern Indian Ocean plays a major role as sources of the monsoon moisture (Daniel Gemechu, 1977). This rain represents 50-70% of mean annual total rainfall. The highland flanking the rift valley intercepts most of monsoonal rainfall resulting in the strong moisture deficit at the rift floor.

The dry period extends between October and February when the ITCZ lies south of Ethiopia during which northeasterly trade wind traversing Arabian continent dominates in the region. Occasional rain during this period brings 10-20% of the annual mean rainfall.

The 'small rain' (that is 20-30 % of the annual amount) occurs during March and May. It coincides with diminution of the Arabian high as it moves toward the Indian Ocean causing warm moisture air with southerly component to flow over most of the country. This small rain is extremely important from the point of view of agriculture in many part of the country where it is the major rainfall especially in southeastern parts of Ethiopia.

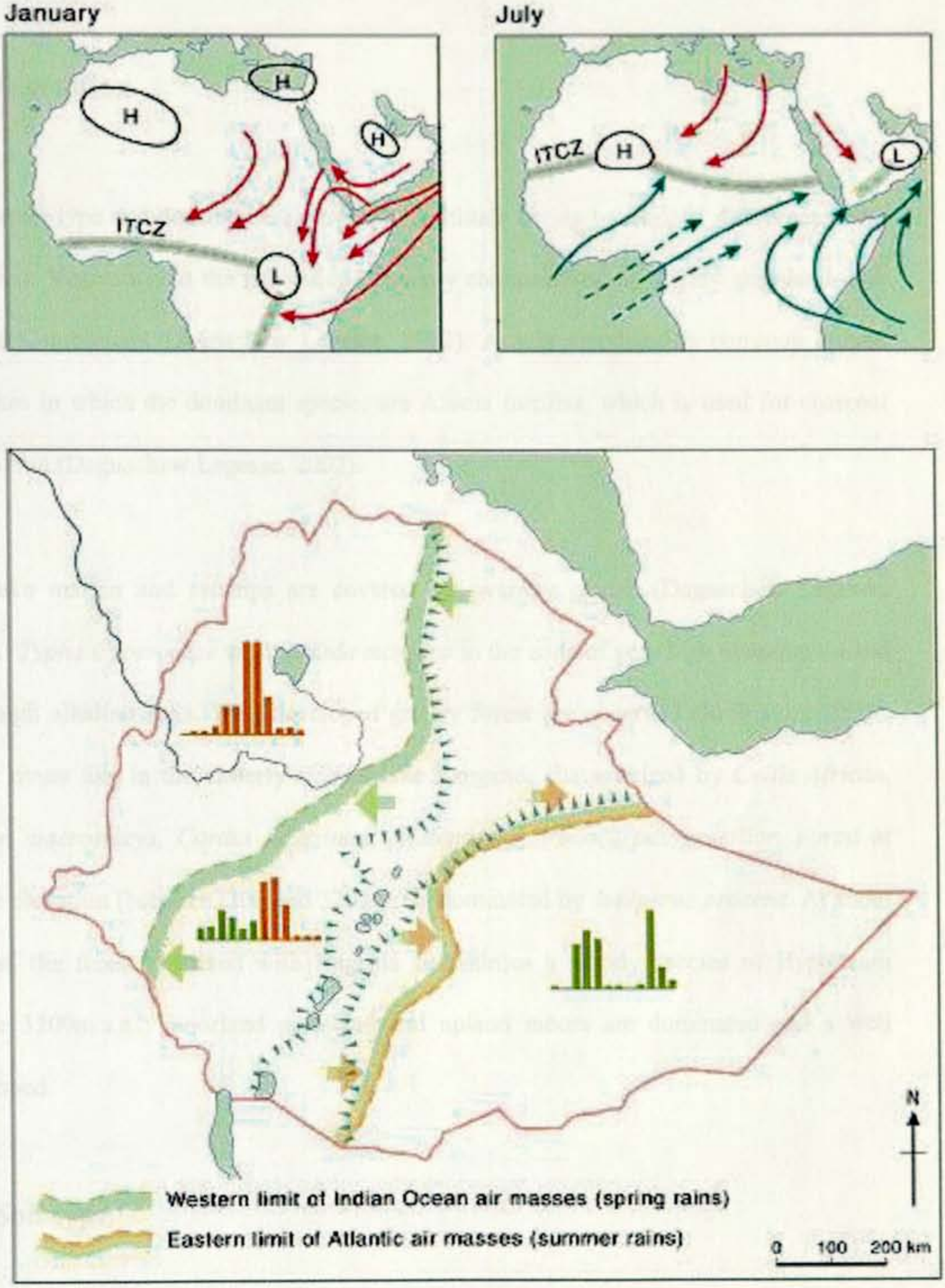


Figure 2. Seasonal drifting of the ITCZ and its control on the rainfall regime

2.4. Vegetation

Vegetation type and density are controlled by altitude owing to climatic differences with elevation. Vegetation in the rift valley is mainly characterized by woody grassland with Acacia Combretum (Dagnachew Legesse, 2002). Acacia woodland is common around the lakes in which the dominant species are Acacia tortillas, which is used for charcoal production (Dagnachew Legesse, 2002).

The lake margin and swamps are covered by swampy genera (Dagnachew Legesse, 2002). *Typha Cyperoceae* with *Suaeda monoica* in the zone of very high evaporation and very high alkaline soils. Well developed gallery forest are observed along some of the major rivers like in the easterly side of lake Langano, characterized by *Celtis African*, *Croton macrostacys, Cordia abyssinica ,Matenus sp, Podocarpus gracilior.* Forest at higher elevation (between2200 and 3200 m) is dominated by *Juniperus procera.* At about 3200m, the forest is mixed with Hagenia absyssinica a woody species of Hypericum Above 3200m.a.s.l, moorland grassland and upland moors are dominated and a well developed

2.5. Soil type

Soils of the basin are derived from three main sources. These are weathering of the bedrocks, from volcanic activity and from the deposition of sediments in the valley bottom. The soil type is the rift valley is closely related to soil parent material and the degree of weathering. The main parent materials in the basin are basalts, ignimbrites, acidic lavas, volcanic ash and pumice, riverine and lacustrine alluvium. From a general soil map of Matkin *et al.* (1975), there are four main types of soil in the basin: Lateritic clay loam, dark clay soil, sandy loam soil, and lithosols/regosols.

The highlands and escarpment above 2000 m.a.s.l elevation on either side of the rift are characterized by reddish clay loam or lateritic clay developed mainly from weathered basalt and ignimbrite. These soils occupy areas that are well drained and often covered by trees.

The black clay mostly occupies relatively flat areas and the poorly drained water logging sites. They are black in color due to their high organic matter content, as the soils have developed on paleo-swamp areas with little or no oxidation.

Much of the rift floor is covered by soil developed on recent volcanic deposit of ignimbrite, ash, lava, and tuff, which form the gently undulating plain of the area. The soils, which develop in these types of rocks, are dark grayish, coarse-textured, free draining and lack any distinct soil profile development. Around the lakes they are developed on lacustrine deposits inter-bedded with pumice.

Poorly developed thin layers of soil characterize areas above 3500-4000 m.a.s.l. These soils do not have diagnostic horizon.

CHAPTER III

GEOLOGY

3.1. General Geology

The geology of the area is mainly controlled by activities, which control the geology of the country. These geologic activities are, the formation of the Precambrian basement and associated deformation, the deposition of Mesozoic sedimentary succession, the uplifting-volcanism and rifting of the Cenozoic and much more recently the quaternary climate variation and associated lake level changes. All these geologic activities leave their imprint in the geology of the study area (**figure 3**).

The Cenozoic uplift and associated rifting have been associated with volcanic activity. This activity leads to the eruption of volcanic rocks such as basalts (the older trap series basalt and the much more recent basaltic scoria cones), ignimbrite, trachyte, rhyolite and pumiceous and pyroclastic. The faulting also formed structural depressions and calderas, which are later, filled by lakes. The lakes occupied a wide area in the quaternary before they shrunk to the present day size due to climate change. The shrinking lakes left behind lacustrine sediments that cover the low-lying plain. Nevertheless, the dominant rocks in the study sites are volcanic products of the Cenozoic and the quaternary to recent fluvio-lacustrine sediments.

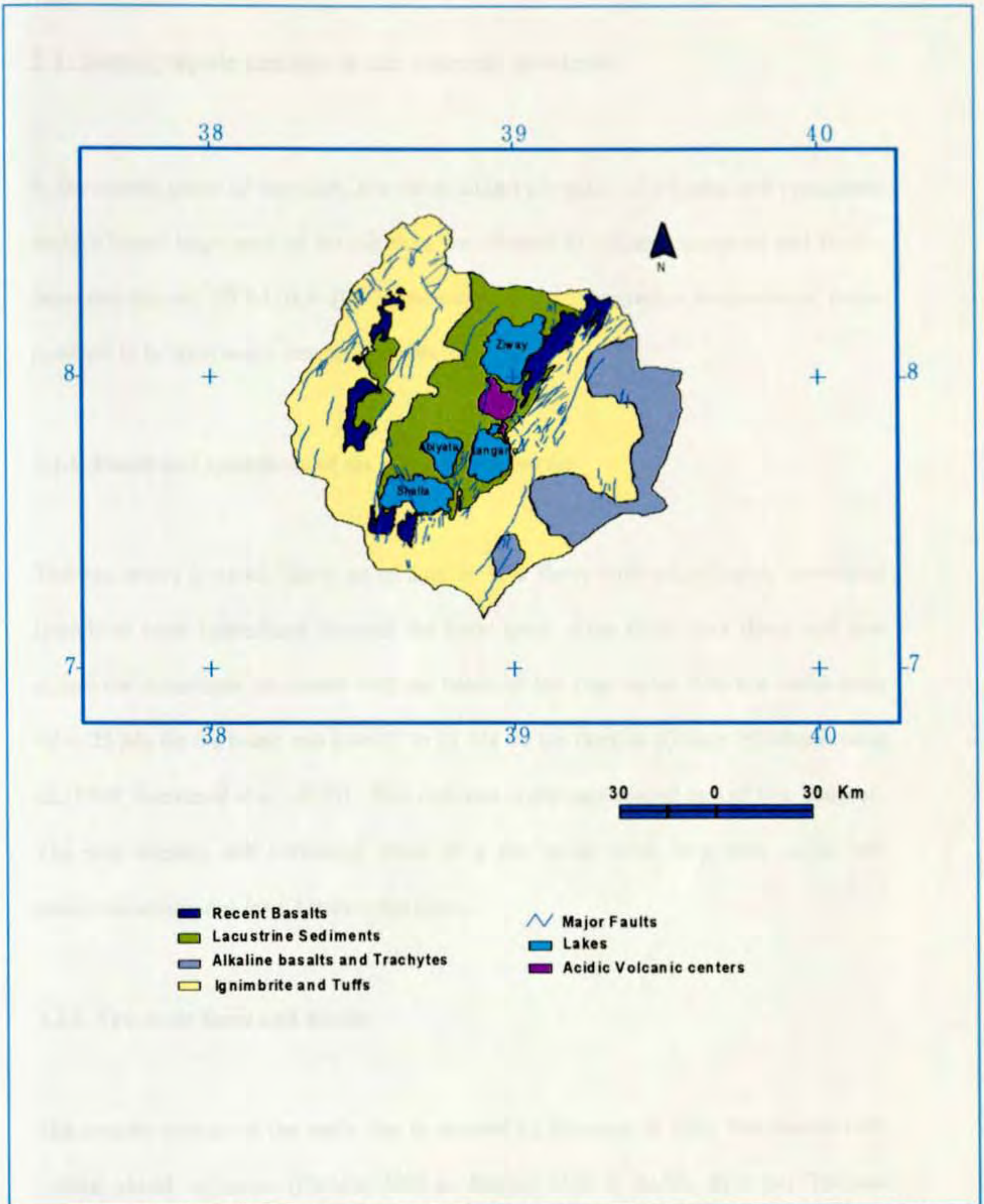


Figure 3.Geological map of the Ziway- Shalla basin, (after Tesfaye Chernet, 1985).

3.2. Stratigraphic outline of the volcanic products

In the central sector of the MER, the rift shoulders are made of volcanic and pyroclastic rocks whereas large areas of the rift floor are covered by volcano-lacustrine and fluvio-lacustrine deposit. DI PAOLA (1972) reconstructed the stratigraphic succession of major products in to eight major categories (**table 1**).

3.2.1. Basalt and ignimbrite of the plateau Trap series

The trap series is mostly made up of basaltic lava flows with subordinately associated ignimbrite units intercalated between the basic lavas. Also silicic lava flows and lava domes are sometimes associated with the basalt of the Trap series. The age varies from 40 to 25 Ma for the basalt and from 37 to 27 Ma for the rhyolite (Gidaye Woldegabriel *et al.*, 1990; Benvenuti *et al.*, 2002). This rock unit is exposed around east of lake Langano. The unit consists sub horizontal flows of a few meter thick lava with rather well preserved scoraceous level between the flows.

3.2.2. Trachytic flows and domes

The eastern plateau of the study site is covered by Pliocene to early Pleistocene (4.6-1.6Ma) shield volcanoes (Chilalo, 4005 m, Kecha, 4245 m Badda, 4170 m). The unit consists of trachyte with subordinate basalts and mugearites (Di Paola, 1972; Gidaye Woldegabriel *et al.*, 1990; Benvenuti *et al.*, 2002)

3.2.3. Rift pyroclastic formation

The formation covers most of the rift floor and includes three principal rock types: typical ignimbrite, sillar and layered pumice. They are the most ancient formation outcropping on the floor of the rift valley. They are Early to Middle Pliocene (4.3-3Ma) formations (Gidaye Woldegabriel ***et al.***, 1990).

Typical ignimbrite is hard, well welded rock with nicely developed fiammae coating small inclusions of foreign rocks. Sillar ignimbrite is a coarse and less welded ignimbrite, which is well presented around Lake Shalla, western shore of Lake Langano and East Ziway. It is poorly welded ignimbrite, rich in big pumice fragments and generally forms horizontal layers and the thickness can reach 150 m.

Another important pyroclastic formation is a layered pumice formation, which is constituted by unwelded pumice of small size and each layer is generally thin and interbeded with thin layers of lacustrine deposit, ashes and paleosoils. Ignimbrites are intensely faulted and it is possible to observe the formation almost everywhere and its thickness exceeds 200 m on the West and East of lake Shalla.

3.2.4. Old Rhyolitic lava flows and Domes

These are alkaline and per alkaline rhyolitic lava flows and domes which was erupted later as viscous lava after the magma has lost its gases during previous explosive activity. Thin and subordinated layers of unwelded pumice and ash are often found interbeded in these silicic lava flows and domes. This lava was erupted from late Pliocene to middle Pleistocene and in some places crop out as remnants of large calderas and often shows vertical sheeting or flow folding.

Stratigraphic unit	Geological time
Alluvium and lacustrine sediments	Recent Pleistocene
Recent alkaline and peralkaline rhyolite pumice, ashes and lava flows	Holocene
Alkali Trachytic lava flows and domes	Recent Pliocene
Recent basaltic lava flow and spatter cone	Recent Pleistocene
Basaltic hyaloclastites	Recent Pleistocene
Old alkaline and peralkaline rhyolitic lava flows and domes associated pumice and ashes	Early Pleistocene, Late Pliocene
Alkaline and peralkaline ignimbrite associated to pumice and ashes	Pliocene
Tertiary basalts and ignimbrite and plateau Trap series	Pliocene, Early Eocene

Table 1. Stratigraphical succession of the Ethiopian rift by DI PAOLA

3.2.5. Basalt Hyaloclastites

Limited occurrences of sub aqueous basaltic volcanism are found in the rift valley. Hyaloclastite occur both as small monogenic rug and as horizontal layer of local extension. They are exposed around lake Chitu on the southwestern shore of lake Shalla and around lake Ziway. These rocks consist of fine glassy material, generally yellowish to brown in color. They contain small boulder of basaltic lava.

3.2.6. Recent Basalt

Recent basaltic cones are elongated parallel to the man tectonic trend of the rift and were produced by fissural eruption. The alignment of the spatter cones parallel to the rift marks the feeding fissures. These flows consist of lots of scoria cones. Two main field of recent basalt having an area of about 800 km^2 are located close to western and eastern escarpment. The lava fields close to the Butajira-Silte in the west and the spatter cones east of Lake Ziway in the east.

3.2.7. Recent rhyolitic pyroclastic and obsidian lava flows

These rocks are the latest volcanic products in the region. Many young volcanoes and calderas such as the Bora-Bericco complex, the Alutu volcano and Chabbi volcanoes that grew inside the Corbetti caldera, are made up of rhyolitic lava flows, pumice flows, pumice falls and ashes. Only the Aluto Langano complex is located in the study basin.

Obsidian flows represent the final product of the volcanic activity. These volcanoes started to be active from the middle Pleistocene with intermittent Late Holocene activity. Obsidian flows and pumice were dated 2000 y before present and very recent ash deposits 1500 and 230 y BP occur in the area.

3.2.8. Lacustrine Sediments

Lacustrine sediments are common in the rift valley. They are the result of drying up of a big lake that occupied the floor of the rift valley during pluvial periods. The lacustrine sediments include silts, clays, diatomites and volcanoclastic sediments. However silts and clays are dominated. Significant outcrop of diatomite is located between lakes Shalla and Abiyata.

3.3. Structure

Two main fault systems have been distinguished in the Main Ethiopian Rift. These are the $N30^0E$- $N40^0E$ trending fault system, which characterizes mainly the rift margins and N-S to $N20^0E$ trending faults system, which are often termed as the Wonji Fault Belt **(figure 3)**. The later obliquely cuts the rift (Boccaletti et al., 1998). The rift is asymmetric in the study area due to the difference in faulting characteristics on the two rift margins. The western margin of the study area is well represented by the $N35^0E$-$N40^0E$ trending and ENE dipping high angle faults, while to the south the margin is marked by N-S to

N20^0 E trending faults and covered by the later volcanic products. The vertical throw of the western faults can reach values up to 1000 m.

There is a change in tectonic style as one proceeds from the margin of the rift. The rift margin is characterized by few widely spaced faults with large vertical displacements while the rift floor is affected by dense fault swarms exhibiting relatively small throws (<100 m). Late Pliocene-Quaternary volcanic and sedimentary rocks of the rift floor are affected by this fault system.

CHAPTER IV

HYDROLOGY

4.1. General

The Ziway-Shalla basin is characterized by internal drainage as all rivers flow into the lakes (**figure 4**). No surface water outflow exists out of the basin currently. Awassa lake basin to the south, the Bilate river basin to the west, the Awash River basin to the north and Wabishebelle river basin to the east border the basin.

The major rivers rise from the plateau on either side of the rift valley and tend to follow generally southern direction into permanent and terminal lakes on the floor of the rift valley. The major rivers in the basin include Ketar and Meki that flows to lake Ziway, Jido River that flows to Lake Shalla, and Gedemso, Lepis and Hulka rivers that feed lake Langano. Bulbula and Horakello rivers in the rift floor are drain of Lake Ziway and Langano respectively into lake Abiyata.

Ketar and Meki rivers dominate the water balance of the basin as they drain about 42.5% of the Ziway-Shalla basin. Meki River originates from the Gurage highland and drains the western mountains and escarpment with high gradient and flows through swampy areas while 50% of tributaries of Ketar River starts from Chilallo volcano and they form radial pattern. Rift faults have affected the drainage of the area by determining the river course and by impounding river water and causing local marshy areas.

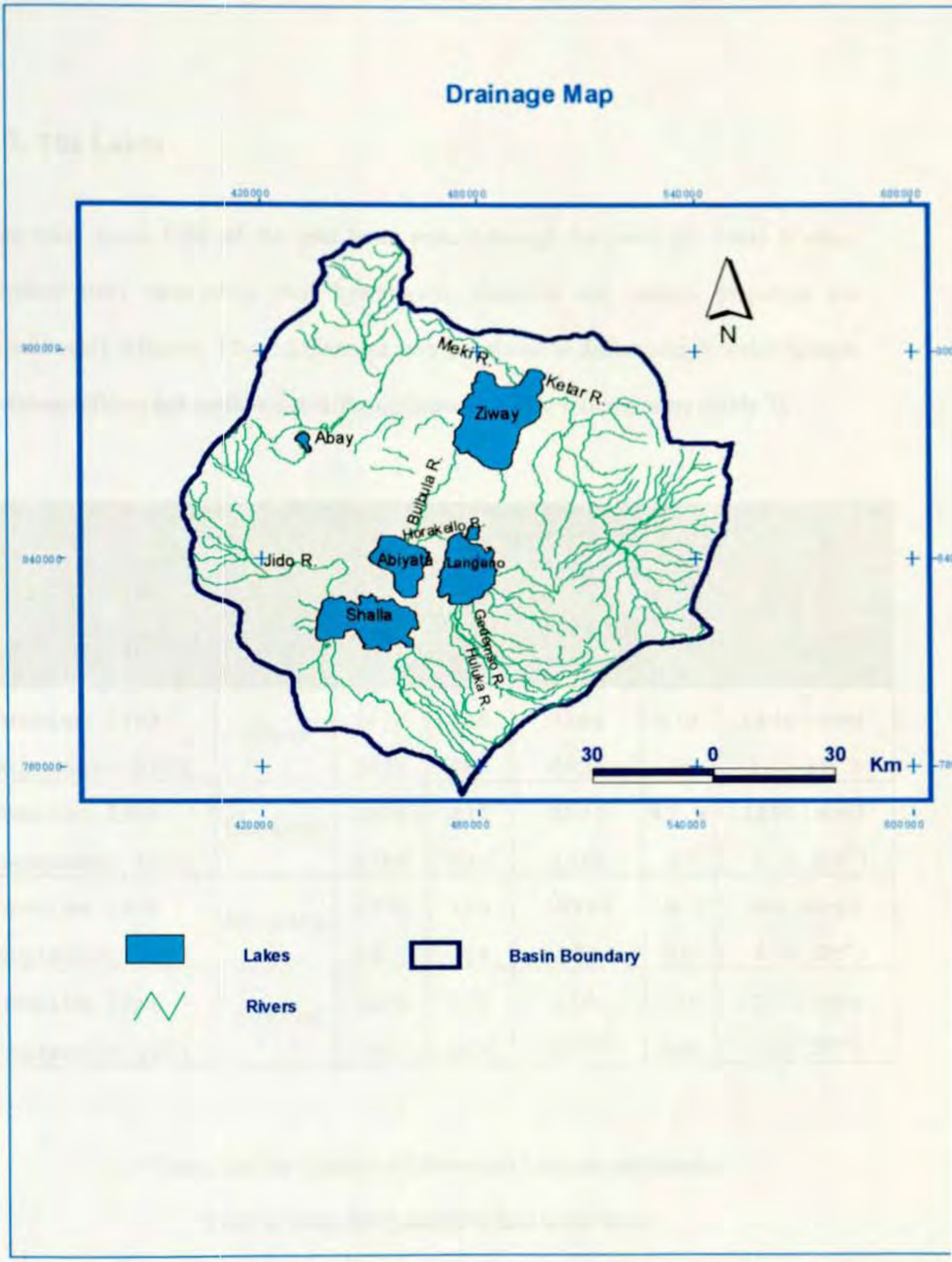


Figure 4. Drainage map of the basin showing major rivers and lakes

4.2. The Lakes

The lakes cover 8.5% of the total basin area. Although the lakes are found at close distance from each other, their hydrological, chemical and isotopic properties are considerably different. These differences may be related to differences in water balance between inflows and outflow and to the differences in their morphometry **(table 2).**

Paper	Lake	Altitude (m.a.s.l)	Lake area (km^2)	Catchment area (km^2)	Max depth (m)	Volume
Tenalem 1998	Ziway	1636	440	7380	8.9	1466(mcm)
Dagnachew 2001		1636	485	6834	9	1.7 KM^3
Tenalem 1998	Langano	1585	230	2000	47.9	3800(mcm)
Dagnachew 2001		1585	226	1750	47	4.8 KM^3
Tenalem 1998	Abiyata	1578	180	10740	14.2	954(mcm)
Dagnachew 2001		1577	159	1100*	10	0.8 KM^3
Tenalem 1998	Shalla	1550	370	2300	266	37000(mcm)
Dagnachew 2001		1557	318	3297	266	34 KM^3

* Excluding the upstream of Ziway and Langano catchments

Table 2. Basic Morphometric data of the lakes

4.2.1. Lake Ziway

Lake Ziway is the shallowest and largest lake in the basin. It is located at the highest altitude compared to the other lakes. It lies in shallow faulted basin. The lake level is maintained at 1636 m.a.s.l. It is drained by Bulbula River and fed by River Ketar and River Meki. It is a fresh water lake with short water residence time (about 1.5-2 years). The lake has a potential for irrigating 1700 hectare (Halcorw, 1989) but currently 1200 hectare is being irrigated. The Lake is used for commercial fishing and has a potential of 3000 tones of fish per year (Atkins & Partners, as cited in Tenalem Ayenew, 1998). The lake has eleven Islands of various size formed of scoria or hyaloclastites.

4.2.2. Lake Langano

The lake occupies the large depression bounded by well-defined major faults. The escarpments to the east and important faults on the west tectonically determine the shape of Lake Langano. Streams that fed the lake drain the southeastern highland. It is relatively saline compared to Lake Ziway owing to its longer water residence time, which ranges from 3 to 5 years. This gives some time for evaporation before it flows out via Harakello River into Lake Abiyata. It is currently used as a recreational center.

4.2.3. Lake Abiyata

Abiyata is the smallest lake of the basin. As it has more restricted catchment, its water balance depends on the overflow from the other two lakes and from direct rainfall. As it is a terminal lake without surface water outlet, evaporation is the only way of losing water. The water residence time is high (10 to12 years). Owing to this the lake is characterized by very high salinity. Due to its terminal position in the drainage, it is easily affected by inter-annual or seasonal climate changes in rainfall in the plateau. Currently it has shrunk dramatically in its size. The lake is being used for soda ash production.

4.2.4. Lake Shalla

Lake Shalla is the deepest lake in Ethiopia with a maximum depth of 266 m. It occupies a caldera with steep rims. The lake receives water from Jido River that drain western escarpment and by intermittent Adobar River derived from southeastern escarpment. The lake is also fed by hot spring mainly from southern and eastern shore. It is a closed lake without surface outlet with a water residence time of about 150 years and as a result the water is extremely saline.

4.3. Hydrological data

River discharge and lake level data were obtained from Ethiopia Ministry of Water Resources. Monthly discharge data of the major rivers is plotted **(figure 5)**.

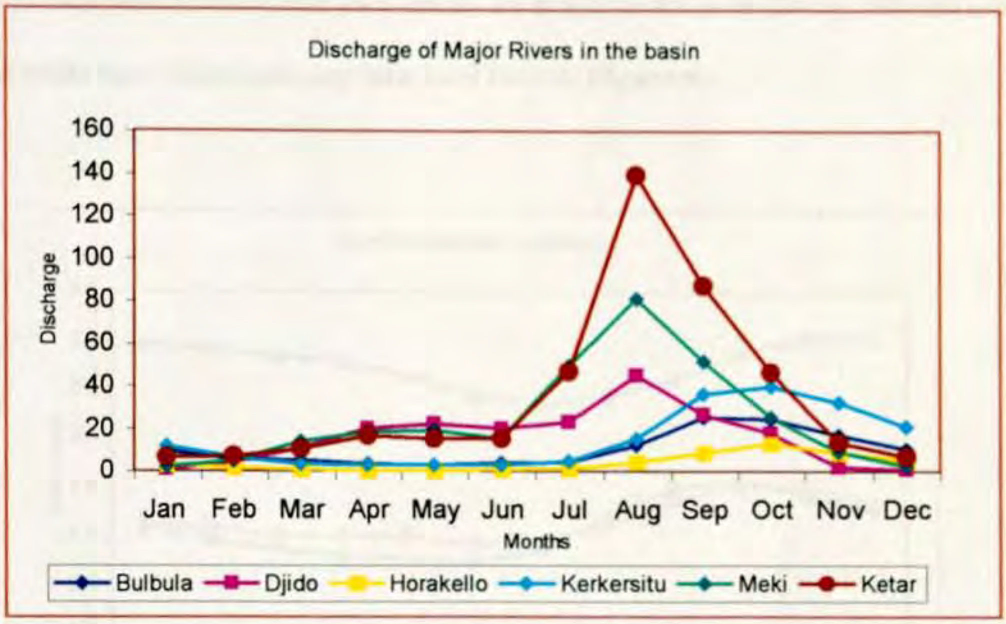


Figure 5. Mean Monthly discharge of the major rivers in the basin

Figure 5 shows that the rivers that arise from the highlands (Ketar, Meki and Jido) are characterized by the highest discharge in the months of July through September. This may be related with the major rainfall event during this season.

River which drains the lakes (Bulbula and Horakello) show a major peak after one or two months lag time as they have to wait until the river in the highland arrive in the rift floor to a shift in reference datum and error in recording. Lake Abiyata shows strong lake and feed the lakes and the lakes must be filled before they flow to their respective outflows.

During the field visit in February 2003, Bulbula River was dry. Big rivers from the highland like Ketar, is not affected by the drought as base flow sustain the discharge. Lake level data relative to the reference datum are available for lakes Ziway, Abiyata and Langano while lake Shalla lacks any lake level records **(figure 6)**.

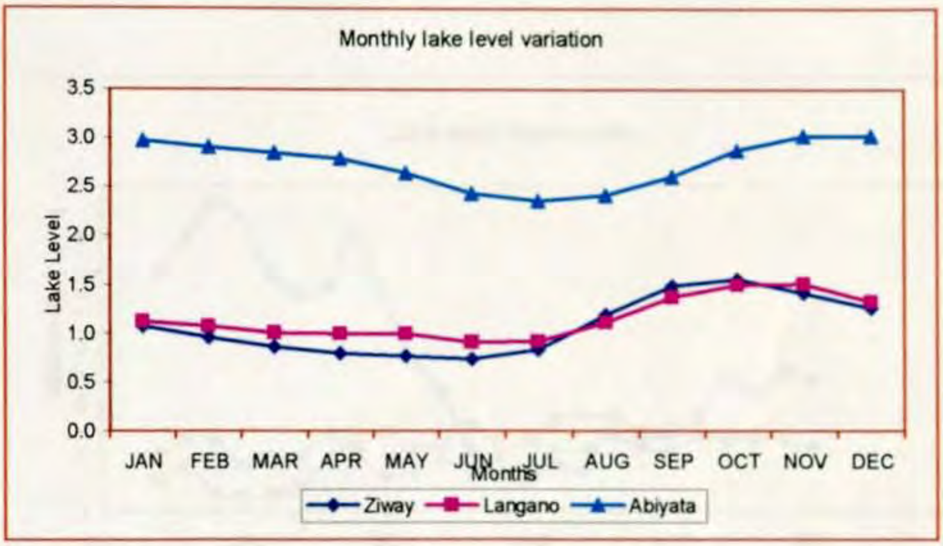


Figure 6. Monthly lake level fluctuation

Mean monthly lake level variations of lakes the three lakes (**figure 6**) shows that they are characterized by minimum lake level for the month of June to July and start to increase in August when the rivers from the highland reach the floor of the rift. For lakes Ziway and Langano, the lakes attain maximum level in September while lake Abiyata is still increasing in size. Lake Abiyata reaches its maximum height around November after three to four months of lag time after the main rainy season.

From the lake level curves it may be possible to observe that the discharge from the rivers of the highland is more important to the hydrology of the lakes than the non canalized flood inflows, which occurs in the rainy season. The precipitation on the rift floor and the resulted surface runoff that may occur from it during the same period are not significant in affecting the lake level compared to the river discharges.

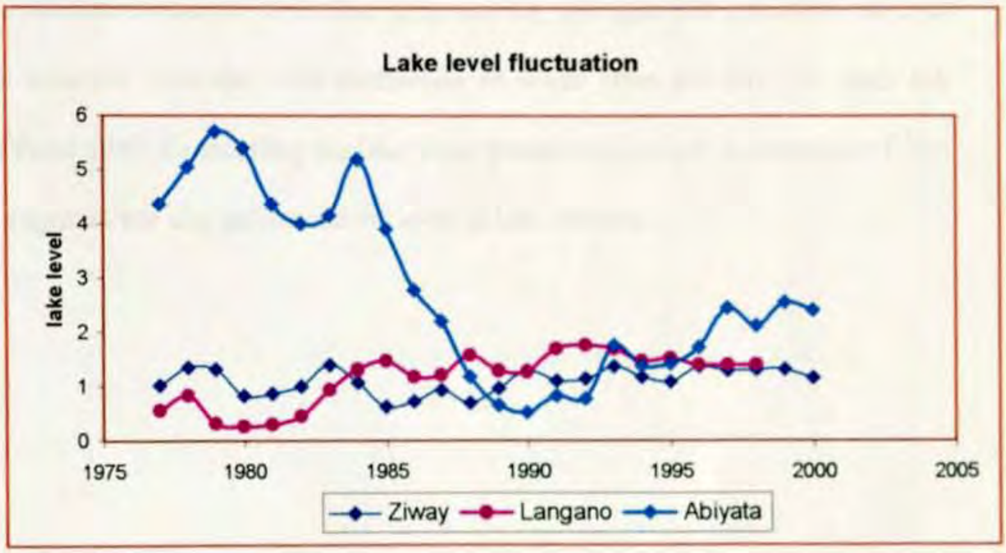


Figure 7. Annual lake level fluctuation

Annual Lake level fluctuation of the lakes **(figure 7)** indicates that Lakes Ziway and Langano are characterized by more or less constant trend compared to lake Abiyata. In the lake level record of Langano, there is a discrepancy between the 1977 to 1983 records and those of 1983 to recent times. Dagnachew Legesse (2002) attributes this discrepancy to a shift in reference datum and error in recording. Lake Abiyata shows strong lake level fluctuation due to its shallow depth and its terminal location in the basin. This lake started to decline since 1984 and gets its minimum value around 1990's and started to increase then after.

The initial decrease in height of Lake Abiyata in 1984 and 1985 which is also observed in lake Ziway, may be explained by change in climate pattern particularly due to change in precipitation in adjacent highland. Although Lake Ziway started to recover by the year 1986, Lake Abiyata continues to decline progressively and gets it's minimum value at 1990. This situation coincides with abstraction of water from the lake for Soda ash production since 1989. Evaporating the lake water produces soda ash. Abstraction of lake Ziway for irrigation has also influenced the level of lake Abiyata

CHAPTER V

HYDROMETEOROLOGY

5.1. The Hydrometeorological data

In order to estimate the water budget of lakes meteorological data is indispensable. Some of the meteorological variables such as river discharge and rainfall amount were used directly in the water budget calculation. Data on wind speed, air temperature, relative humidity etc were used to determine rate of open water evaporation. The long term mean monthly metrological data of precipitation, temperature, wind speed, relative humidity and sun shine hours were collected from National Metrological Service Agency (NMSA) of Ethiopia. In addition, data from different papers (Tenalem Ayenew 1998, Tesfaye Chernet 1998 and Dagnachew Legesse, 2002) have been used to supplement the missing information. The data, which are used in this work, is compiled and tabulated (**Annex 1**).

5.2. Precipitation

As precipitation is one of the major inputs, which control the water balance of the lakes and lake level records, it is important to recognize its spatial and temporal distribution in the catchment for a good understanding of rainfall pattern. The amount of rainfall for the given point is influenced by the location of the area in relation to the sources of moisture, direction of the wind and topography. Long term mean monthly rainfall records for about 30 stations have been used to characterize the rainfall pattern in the basin. **Figure 8** shows, the highest rainfall is recorded at Silte station in the western highland while the lowest rainfall record is obtained at Abiyata station in the rift floor.

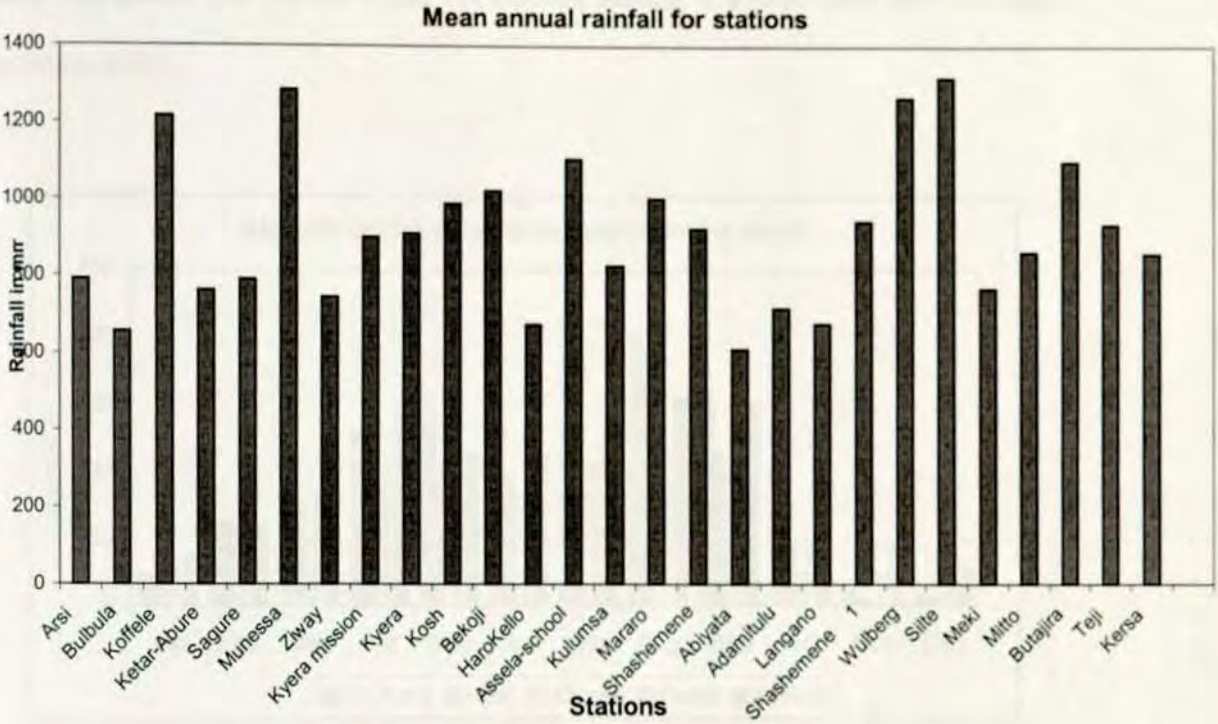


Figure 8. Mean Annual rainfall stations in the basin

5.2.1. Spatial variation of precipitation

The spatial variation in precipitation in the basin is controlled by topography. The long-term mean annual precipitation increase with elevation.

As it can be seen from Isohyetal map in **figure 10,** the low lying rift floor is marked by the lowest mean annual precipitation, which varies from 600 to 800 mm while it reaches up to 1200 to 1350 mm in the highlands in either side of the rift. This may be due to the fact that the rift floor is found in the leeward side of both moisture sources. The plateau captures the two moisture sources from the Indian and the Atlantic oceans and the air mass that passes into the rift valley is often hot making it arid to semi arid with high moisture deficit.

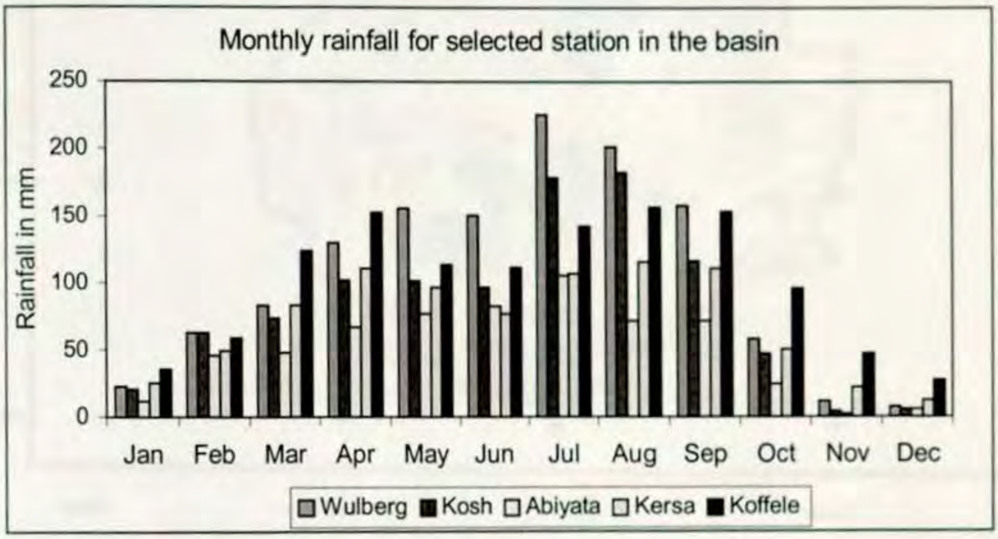


Figure 9. Rainfall amount from selected stations from highland, escarpment and rift floor

Rainfall amount from selected stations from western highland (Wulberg), escarpment (Kosh), rift floor (Abiyata) and from eastern escarpment (Kersa) and highland (Koffele) were plotted in **figure 9** to show spatial variation of rainfall for the three different topographic regime of the basin.

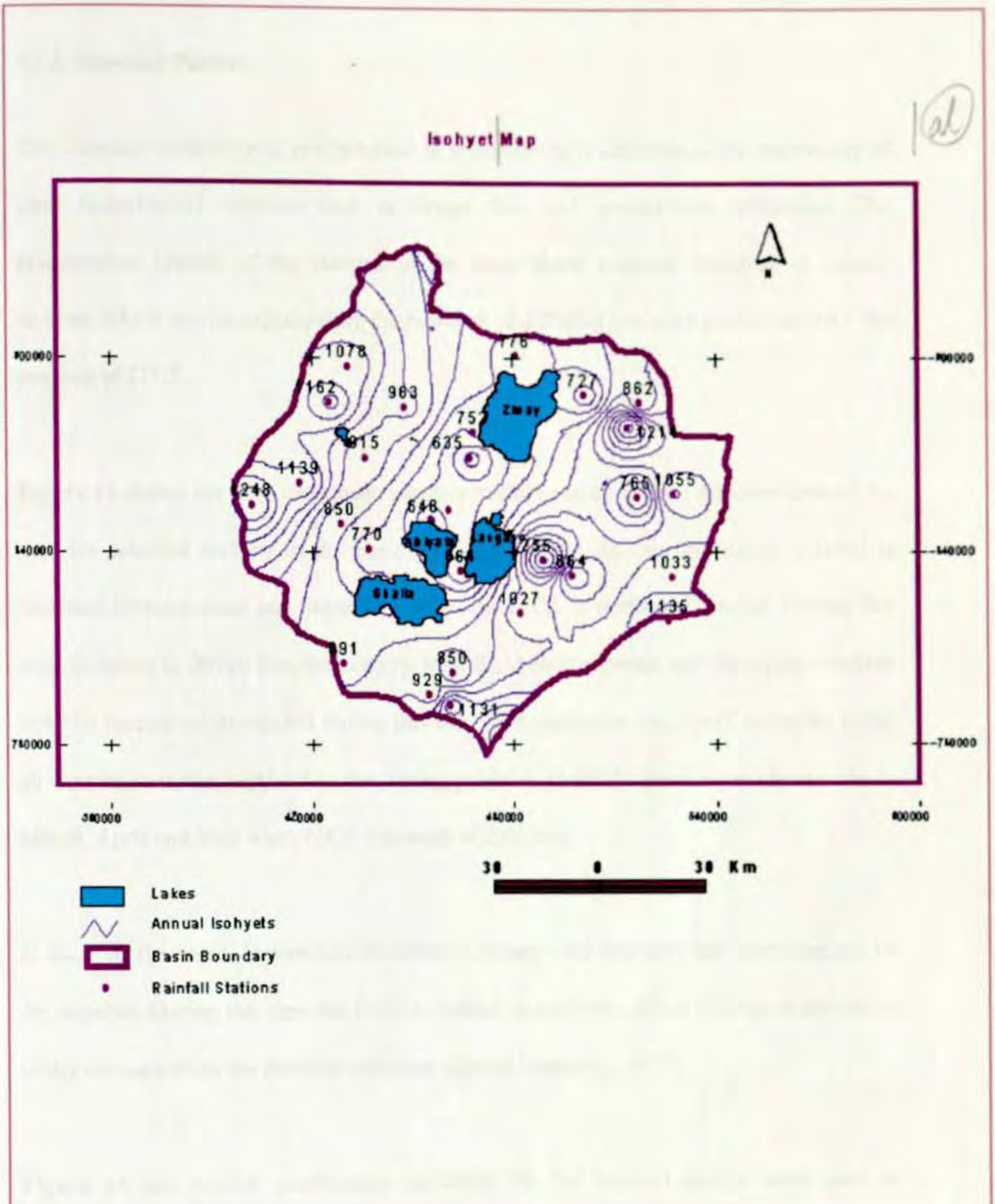


Figure 10. Isohyetal Map

5.2.2. Seasonal Pattern

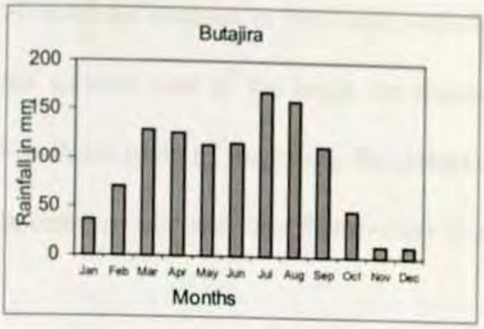
The seasonal variability of precipitation is important as it determines the seasonality of other hydrological variables such as stream flow and groundwater infiltration. The precipitation records of the stations in the basin show seasonal variation in rainfall amount, which can be explained by the presence of different moisture source and by the position of ITCZ.

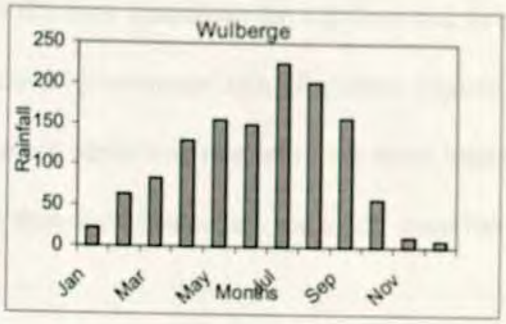
Figure 11 shows the long-term mean monthly rainfall variation with different time of the year for selected stations in the basin. For most of the station, the highest rainfall is recorded between June and September when the ITCZ is north of Ethiopia. During this time moisture is driven into the country from the Atlantic Ocean and the region receives over 70 percent of its rainfall during this time. The easterlies and south easterlies moist air current over the highland in the Spring produce relatively small to moderate rain in March, April and May when ITCZ lies south of Ethiopia.

In most of the cases, November, December, January and February are characterized by dry weather. During this time the ITCZ is located in southern Africa leading to derivation of dry air mass from the Arabian continent (Daniel Gemechu, 1977).

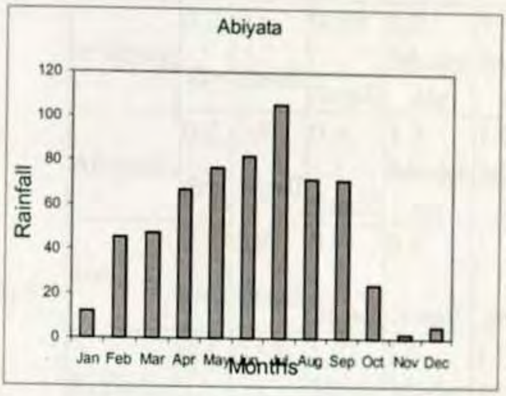
Figure 11 and rainfall coefficients calculated for the selected station were used to determine the type of rainfall distribution and the results are reported in **table 3**.

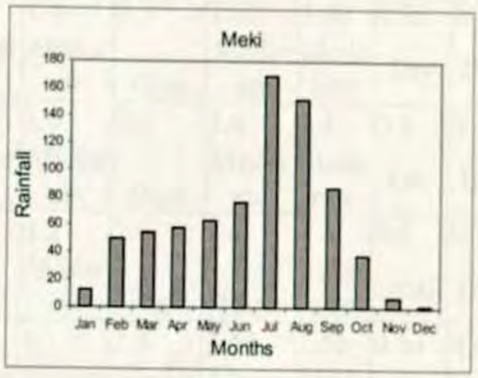
Station from Western highland, Butajira and Wulberg



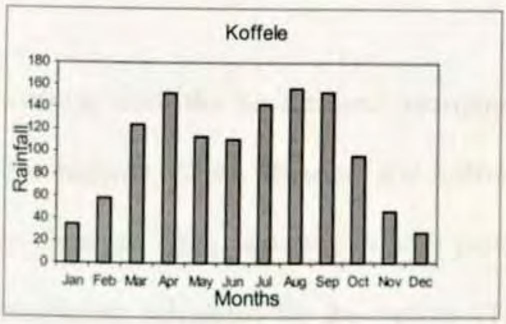


Station from the rift, Abiyata, Meki





Station from the Eastern highland, Koffele, Kersa



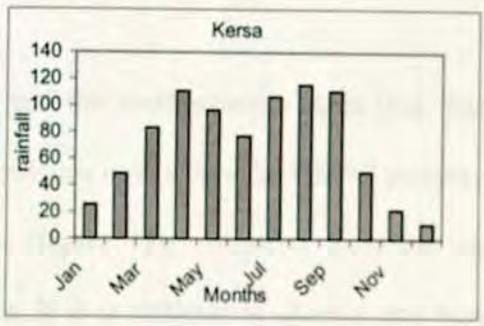


Figure 11. Mean monthly rainfall variation of different station in the basin

Most of the stations in the basin, especially the ones located on the rift floor and those in the western part of the basin are characterized by unimodal rainfall pattern (**figure 11**). For those parts of the basin, the Atlantic Ocean equatorial westerlies are more important in terms of intensity and distribution of rain than that of easterlies and south easterlies.

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Butajira	0.4 Dry	0.8 Small	1.4 Moderate	1.4 Moderate	1.2 Moderate	1.3 Moderate	1.8 Moderate	1.7 Moderate	1.2 Moderate	0.5 Dry	0.1 Dry	0.1 Dry
Wulberg	0.2 dry	0.6 small	0.79 Small	1.2 Moderate	1.5 Moderate	1.4 Moderate	2.1 High	1.91 Moderate	1.49 Moderate	0.55 Dry	0.11 Dry	0.1 Dry
Abiyata	0.2 dry	0.9 Small	0.9 Small	1.3 Moderate	1.5 Moderate	1.6 Moderate	2.1 High	1.4 Moderate	1.4 Moderate	0.5 Dry	0 Dry	0.1 Dry
Meki	0.2 Dry	0.8 Small	0.9 Small	0.9 Small	1 Small	1.2 Moderate	2.6 High	2.4 High	1.4 Moderate	0.6 Small	0.1 Dry	0 Dry
Koffele	0.4 Dry	0.58 Dry	1.22 Moderate	1.5 Moderate	1.1 Moderate	1.1 Moderate	1.4 Moderate	1.54 Moderate	1.51 Moderate	0.94 Small	0.46 Dry	0.3 Dry
Kersa	0.4 Dry	0.68 Small	1.16 Moderate	1.6 Moderate	1.4 Moderate	1.1 Moderate	1.5 Moderate	1.62 Moderate	1.55 Moderate	0.7 Small	0.3 Dry	0.2 Dry

Table 3. Rainfall Coefficient of some of selected stations

Stations from the Southeastern escarpment and the southeastern plateau (e.g. Kuyera, Shashemene, Kersa, Munessa, and Koffele) practice nearly bimodal rainfall pattern, as it is observed from two-peak rainfall patterns (**figure 11**). However from the rainfall coefficient calculated for the stations (**Table 3**) it is difficult to observe this bimodal pattern. Therefore it can be concluded that the southeastern part of the study site experiences a single rainy season from March to September from different moisture sources.

5.2.3. Rainfall-altitude relationships

As it has been discussed previously the amount of precipitation is strongly controlled by topography in the study basin. The relation between rainfalls with increasing elevation is not strong if all the stations in the basin were used in **figure 12**. This is because the region is affected by two different moisture sources at different intensity. Stations from the eastern and southeastern side of the rift and those from the Northwestern part of the study site were plotted separately to clearly understand the relation between altitude and amount of rainfall. The relation between altitude and rainfall amount is weak for the stations in the southeastern escarpment and the southeastern plateau **(figure 12 left)** while stations in the western escarpment shows a good correlation **(figure 12 right)**.

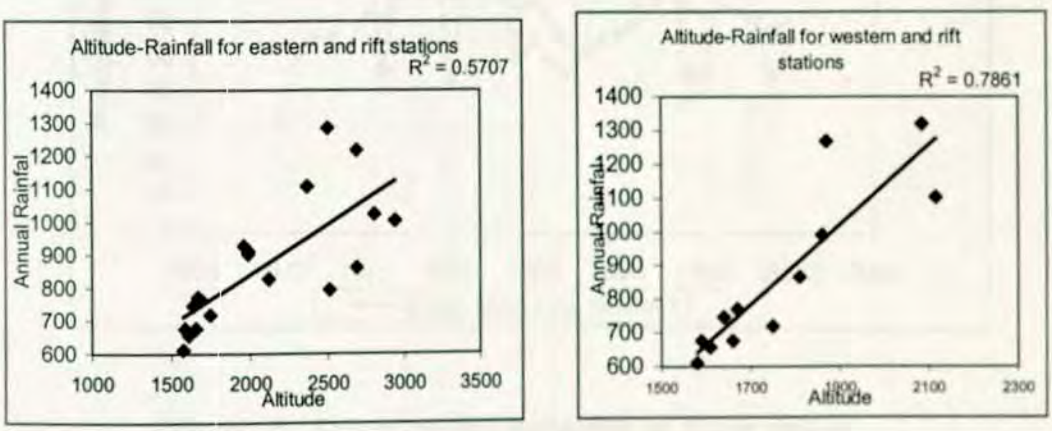


Figure 12. Altitude Rainfall plot for eastern station and western station from left to right

As it can be seen from **figure 12,** part of the basin that is characterized by nearly bimodal rainfall pattern, show poor Rainfall-altitude relation compared to those that show unimodal pattern. When the area is influenced by two different moisture sources at equal weight, the first pattern masks the altitude-rainfall relation of the second.

The five-year moving average at Ziway station shows that rainfall in the rift had an increasing trend and gets its maximum at the end of 1970's and at the very early of 1980's.Then it showed a decreasing trend and got it's minimum at the end of 1980's. It started inclining and gets its maximum value all over again at early 1990's and starts to decline.

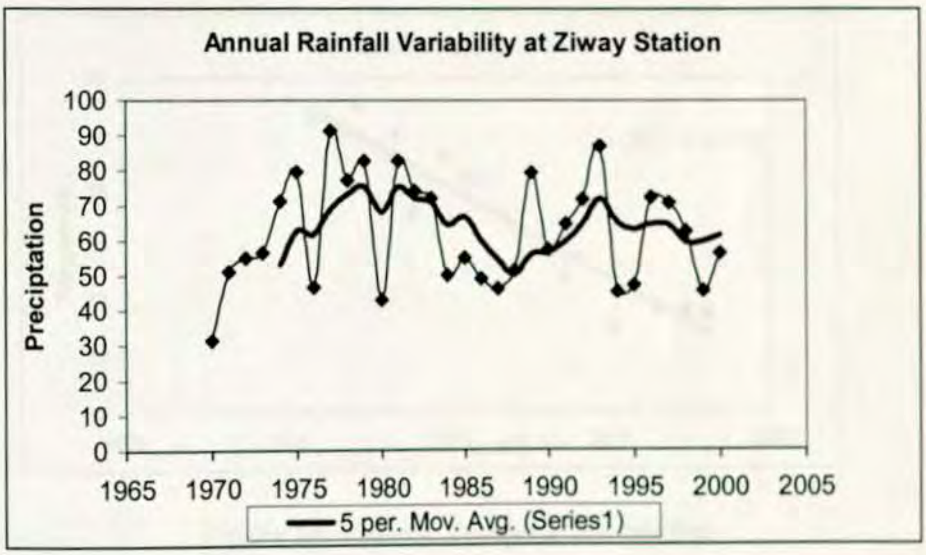


Figure 13. Annual rainfall variability at Ziway station

5.3. Temperature

The solar radiation absorbed by atmosphere and the heat emitted by the earth increase the air temperature. The maximum and minimum air temperatures of the air are measured in the meteorological stations of the basin and the data has been averaged and used for analysis.

The temperature records of the basin indicate that it is controlled by the topography and they are inversely proportional, as it is being the highest in the rift floor and progressively decrease through the escarpment to the highland in either side of the rift. **Figure 14 and 15** indicates that the altitude and temperature relation is very strong with correlation coefficient of 0.91.

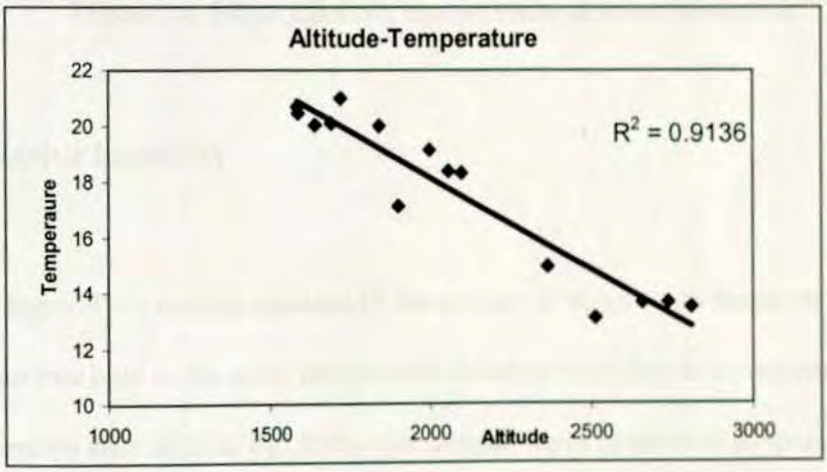


Figure 14. Altitude Temperature relation

Mean annual temperature for stations in the rift floor is about 20^{0}C and decreases up to 13 ^{0}C in the highlands. Generally March, April and May have highest average temperature while July and August are characterized by the lowest temperature.

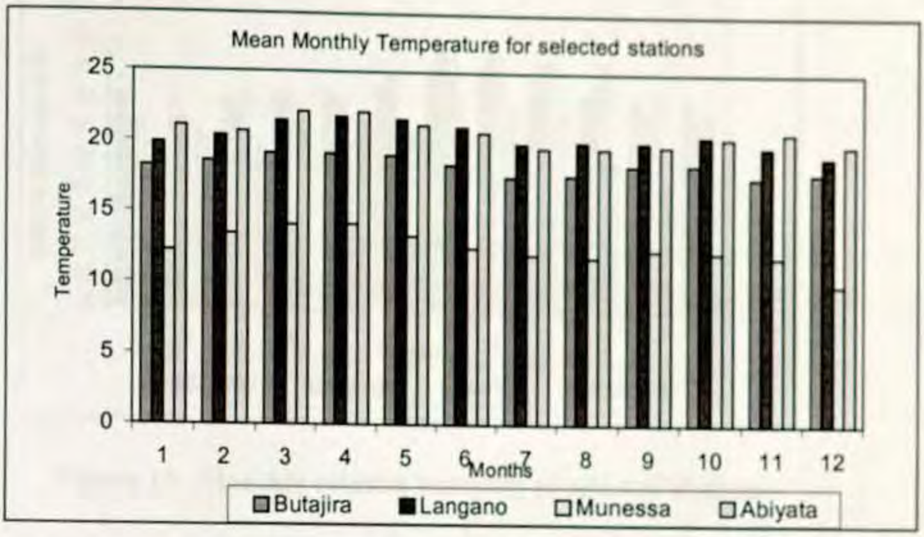


Figure 15. Mean Monthly temperature of selected station

5.4. Relative humidity

Relative humidity is relative measure of the amount of moisture in the air to the amount that the air can hold at the same temperature. Relative Humidity is an important variable in Evaporation estimation as the difference between vapor pressure at evaporating surface and the surrounding air is a driving force for evaporation of water from evaporating surface. Relative humidity record at 0600, 1200, and 1800 hours are available for some of stations in the basin and they are averaged to calculate mean monthly relative humidity of the region **(Annex 1)**. As it can be shown from **figure 16** June, July and August are the most humid months.

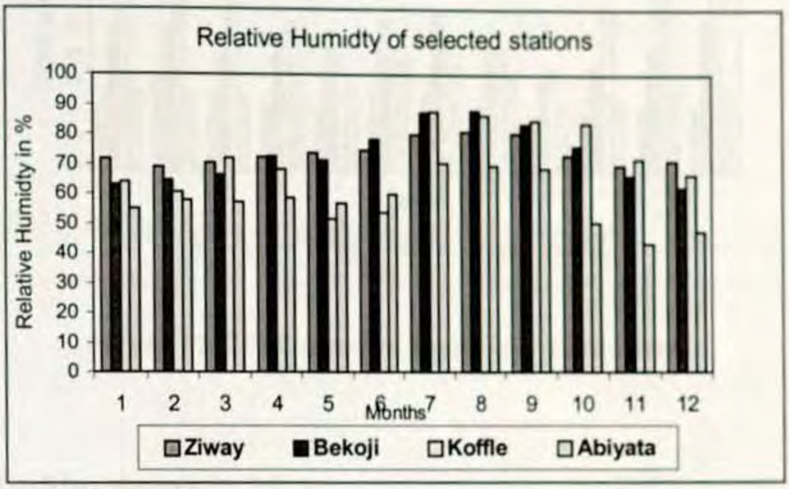


Figure 16. Monthly relative humidity of selected stations

5.5. Wind Speed

Wind Speed is another important variable in estimation of Evaporation. As the process of vapor removal depends on wind and air turbulence, which transfer large amount of air over the evaporated surface when vaporizing water becomes gradually saturated with water vapor. Monthly mean wind Speed (m/s) at 2 m is available in some of the stations (**Annex 1 and figure 17**).

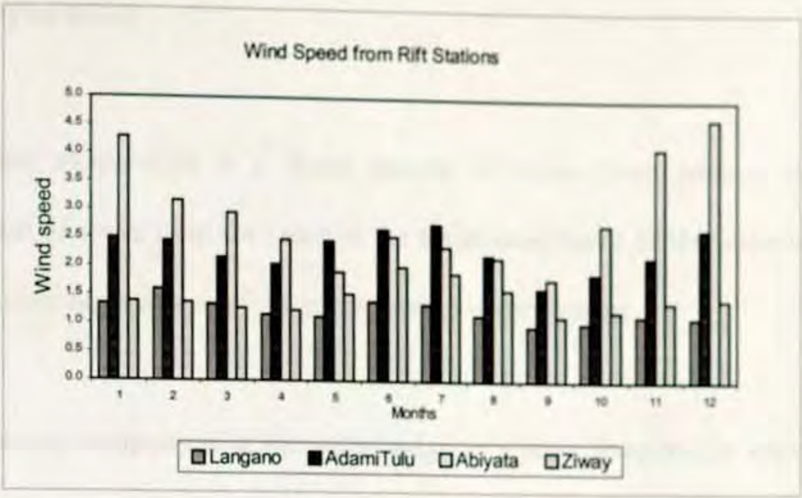


Figure 17. Wind speed at 2m/s from rift stations

5.6. Sunshine hours

Records of sunshine hours for the basin indicate that, it is maximum for the months of October to January and gets minimum in the months of July to September **(figure 18).**

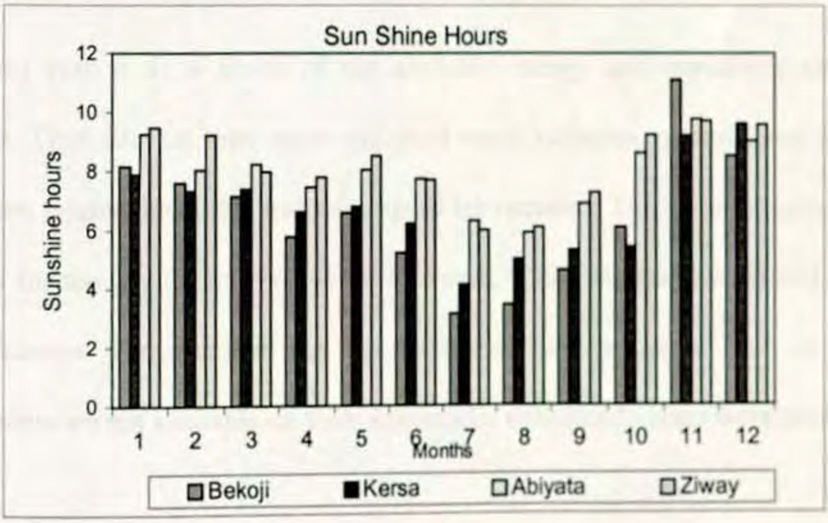


Figure 18. Sunshine hours of the selected stations in the basin

5.7. Evaporation

Open water evaporation is a direct transfer of water from surface water bodies. Evaporation of water from the Lakes is the major component of the water budget of the lakes and their basin as a result its quantification is very crucial.

Among several components of the water budget in a basin, evaporation amount is one of the most difficult to quantify. Three methods namely the Mass transfer, the Energy balance and the Penman approaches were used to estimate open water evaporation for lakes in the study area. Meteorological stations near or around Lake Ziway, Abiyata and Langano are used while average value of the nearby stations are used for lake Shalla to get the required meteorological variables for the computation of evaporation.

5.7.1 The required data

Evaporation rate is as a factor of net available energy and prevailing metrological conditions. Thus data on long wave and short wave radiation, metrological data on air temperature, relative humidity, and wind speed are required. The meteorological data that were used for the calculation were given in **Annex 1**. As the Long-wave and the Short-wave radiations were required for the estimation of evaporation and as no direct measurements are not available on them empirically calculated values were used.

5.7.2. Mass transfer approach

The method makes use of bulk aerodynamic equation found by Dalton, which consider evaporation as diffusive process. It has the form of:

$$E = (b_o + bV_a)(e_s - e_a) \qquad \textit{Equation 5.1.}$$

Where, E is rate of open water evaporation, b_o & b_1 are empirical constants, e_s *is* vapor pressure of the evaporating surface, e_a vapor pressure of the overlying air, and V_a is wind speed at a given height.

b_0 and b mainly depend on the height at which wind speed and vapor pressure of the air measurement is taken. Theoretical analysis indicate that $b_0 = 0$ and $b = K_E$ (Dingman, 1994) if wind speed is measured at 2 m above the ground.

Equation 4.1 can be rewritten as:

$$E = K_E V_a (e_s - e_a) \qquad \textit{Equation 5.2}$$

Where E is in cm/day and the vapor pressures are given as:

$$e_a = W_a e_{sat}(T_a)$$

$$e_s = 6.11\exp\left(\frac{17.3T_a}{Ts + 237.3}\right) \qquad \textit{Equation 5.3}$$

T_s and T_a are lake surface and air temperature respectively, W_a is relative humidity.

Lake surface temperature for the lakes is estimated by assuming that it is greater than air temperature by an order of 3^0C, i.e. ($T_s = T_a + 3^0 c$) which is characteristic feature of tropical lakes (Yin & Nicholson, 1999).

After inserting the necessary variables from **Annex 1** into equation 5.2, the annual evaporation values for Lakes Ziway, Abiyata, Langano and Shalla are found to be 784.8, 1897.9, 672.8 and 1122.8 mm respectively. The relatively low evaporation value of Lake Langano is perhaps due to the low wind speed recorded at a nearby station. This is perhaps because of measurement error and scarcity of wind speed data around lake Langano.

5.7.3. The Energy budget approach

This method is based on heat balance by considering the principle of conservation of energy that come into and go out of the system in the form of energy and change in energy stored in the water body over a time period of Δt. The energy balance method can be written as:

$$E = \frac{K + L - G - H - A_w - \Delta Q / t}{\rho_w \lambda_w} \qquad \textit{Equation 5.4}$$

Where E is in cm/day and sensible heat loss rate H, can be replaced by:

$$H = B\lambda_v \rho_w E \qquad \textit{Equation 5.5}$$

By substituting Equation 5.5 into Equation 5.4, the Energy balance can be expressed as:

$$E = \frac{K + L - G + A_w - \Delta Q / t}{\rho_w \lambda_w (1 + B)} \qquad \textit{Equation 5.6}$$

Where,

G: heat exchange by conduction between lake and surrounding sediment assumed to be negligible

K: the net short-wave radiation

L: the net long-wave radiation

B: Bowen's ratio

Short-wave radiation, K can be empirically obtained from the equation, $K = K_{in}(1\text{-}a)$ Where K_{in} is incoming solar radiation and K_{in} for a region is estimated from the clear- sky solar radiation K_{cs} and the fraction of sky covered by cloud C as in the following equation of Koberge, as cited in Dingman (1994).

$$K_{in} = [0.355 + 0.68\,(1\text{-}C)]\,K_{CS}$$

An empirical relation for albedo of water surface is given as function K_{in}

a is albedo or reflectivity of water and it is estimated:

$$a = 0.127\, exp\,(\,-0.00108\, K_{in})$$

Net long-wave radiation L, is equal to incoming atmosphere long-wave radiation flux, L_{at}, minus the portion of L_{at} reflected and the radiation flux emitted by water surface, L_W. Long-wave reflectivity of the surface equals $1\text{-}\ \varepsilon_w$, where ε_w is emissivity of the water surface

$L = L_{at} - (1-\varepsilon_w) L_{at} - L_w$ *Equation 5.7*

Thus L_{at} and L_w are calculated from relation based on the Stefan-Boltzmann equation and L is calculated as

$L = \varepsilon_w \varepsilon_{at} \sigma (T_a + 273.15)^4 - \varepsilon_w \sigma (T_s + 273.15)^4$ *Equation 5.8*

Where:

ε_{at} is effective emissivity of the atmosphere

σ Is the Stefan-Boltzmann constant, $\sigma = 1.17 \times 10^{-7}$ cal cm^{-2}day^{-1}K^{-4}

$\varepsilon_w = 0.97$ and temperature in ^{0}C.

$\varepsilon_{at} = (0.53 + 0.065\ e_a^{0.5})(1+0.40C)$

B: is the ratio of sensible heat exchange to latent- heat exchange

$$B = \frac{H}{LE} = \frac{CaP(T_s - T_a)}{0.622\lambda_v(e_s - e_a)}$$ *Equation 5.9.*

Where Ca is the heat capacity of air which is equal to 0.24 cal g^{-1} C$^{0-1}$, P is atmospheric pressure, $\lambda_{v\ is}$ latent heat of vaporization and A_w: is the water advected energy is assumed to be negligible

$\Delta Q/\Delta t$: change in stored energy over the time Δt is assumed to be negligible

By inserting all the necessary metrological variables in the *equation 4.5*, the annual evaporation of lake Ziway, Abiyata, Langano and Shalla is found to be 2012.4, 1980.1, 2011.2 and 1985.7 mm respectively.

5.7.4. The Penman (combination) approach

Penman (1948) developed a formula by combining mass transfer and energy balance approaches to arrive at an equation which enables widely available metrological observation to be used and which does not require surface temperature data and the method become the standard hydrologic method for determining free water evaporation (Dingman 1994). The penman equation is given as

$$E = \frac{s(T_a)(K+L) + \gamma K_E \rho_w \lambda_v \left[e_{sa}(T_a)\right](1-W_a)}{\rho_w \lambda_V \left[s(T_a)+\gamma\right]} \qquad \textit{Equation 5.10.}$$

E is evaporation in cm/ day

K_E a coefficient that reflects the efficiency of vertical transport of water vapor by the turbulent eddies of wind and is equal to 1.26×10^{-4} if wind speed is in cm/s at 200cm,

ρ_w is mass density of water, 1gm/ cm^3

λ_v latent heat of vaporization of water, 586 cal/g

V_a is wind speed in cm/s in meteorological data

W_a is relative humidity, from meteorological data

S (T_a) is slope of saturation vapor pressure vs. temperature of the air. It can be given as:

$$S(T_a) = \frac{25083}{T+237.3}\exp(\frac{17.3T}{T+237.3)})$$

Where

γ is psychrometric constant, about 0.66mbc$^{0-1}$

Inserting the relevant meteorological variables into the equation 5.9 the annual open water evaporation is found to be 1739.3, 1679.4, 1701,and 1683 mm for lakes Ziway, Abiyata, Langano and Shalla respectively.

Evaporation estimates using the three approaches for the four lakes is given in **table 4**.

Lake evaporation in mm / year				
Approch	Ziway	Abiyata	Langano	Shalla
E energy	2012.38	1980.11	2011.25	1985.70
E mass	784.84	1897.98	672.79	1122.84
Penman	1739.32	1679.44	1701.12	1683.13
Average	1875.85	1829.78	1856.18	1834.41

Table 4. Open water evaporation of the lakes

As it can be seen **table 4,** except for Lake Abiyata where there is considerably high wind speed, the Mass transfer approach underestimates evaporation rates of all the lakes. This can be due to the fact that mass transfer equation gives an instantaneous rate of evaporation under a given instantaneous value of wind speed and vapor pressure differences. This is because the vapor pressure used in equation 5.1 is determined from measured temperature via non linear equation of Equation 5.3. Therefore it may unreasonable to assume that the method give time-averaged rate of evaporation when time-averaged temperature and wind speed are used as independent variables. Therefore results from Mass transfer approach method will not be considered in the water budget estimation that ensues.

For water budget evaluation of lakes and for further analysis, the arithmetic mean of Energy budget and Penman combination approaches was taken and mean annual evaporation is estimated to be 1875.8 mm for lake Ziway, 1829.8 mm for lake Abiyata, 1856.2 mm for lake Langano, and 1834.4 mm for lake Shalla.

CHAPTER SIX

HYDROGEOLOGY

6.1. Introduction

In the study basin ample data on pumping test is lacking. This is one of the predicaments to evaluate the aquifer characteristics and storage. Understanding the hydrogeological characteristics of the rocks in the basin on one hand gives a clue about the validity of the isotope balance and groundwater-surface water interaction results obtained during this work. On the other hand information on groundwater flow, storage, and recharge may be obtained from such a data. In such a case of lack of hydrogeological data a through look at the lithological characteristics may help in gaining qualitative information on the aquifer characteristics.

6.2. Hydrogeological characteristics of volcanic rocks: general

Volcanic rocks include materials having a wide range of hydrologic properties. This property is due to differences in mineralogy, chemistry, texture, structure, etc. Hence, their ability to store and transmit water varies accordingly. The storage and flow of groundwater in volcanic rocks is governed by a number of geological factors. These factors include primary and secondary structures, and the rock texture. The porosities due to primary structures are vesicles, flow contacts or interflow spaces, lava tubes or tunnels, clinker or rubble layers, shrinkage cracks or columnar joints etc. Whereas the porosities due to secondary structures include inter-trappean beds, weathering zones, paleosoils, faults and tectonic fractures, etc.

The most important features governing the groundwater flow and storage in volcanic rocks are vertical permeability due to primary and secondary fractures, horizontal permeability due to horizons containing openings due to the lava flow and gas expansion during solidification, occurrence of impervious horizons and dikes.

All fractured and porous volcanic rocks do not always serve for groundwater circulation. In this regard the main controlling factors are type, frequency and distribution of the fractures, degree of the fracture and pore interconnection, thickness of the lava flow, occurrence of cementing material and their hydraulic characteristics, constitution of the soil cover, the depth of the lava flow. Groundwater circulation and storage in the volcanic rocks depend on the type of porosity and permeability formed during and after the rock formation.

Some recent basalt aquifers have close to the highest transmissivity known. This is in contrast with tuffs that generally have high porosities but very low permeabilties or dike rocks that have low permeabilties and low porosities.

The porosity of unfractured volcanic rock bodies from less than 1 percent in dense basalt to more than 85 percent in pumice. Typically, rocks within dikes and sills will have less than 5 percent porosity, dense massive flow rock will have values ranging from 10 to 50 per cent. Although porosity may be quite high, the permeability is largely as a function of other primary and secondary structures within the rock. In addition to the features causing permeability, the porosity may be increased locally in the rock by weathering. Buried soils are a common feature of thick sequences of volcanic rock.

Pyroclastic rocks associated with lava flows are generally porous but not very permeable. Exceptions are blocky, coarse material near volcanic vents and tuffs, which have been reworked by water. Welded tuff can transmit the most water because of its tendency to develop joints and other fractures, which will remain open at considerable depths.

6.3. Hydrostratigraphy

Based on the few data available on the hydrogeological properties (permeability, transmissivity, aquifer storage, porosity etc) of the different rocks in the basin and from geological characteristics, the rocks have been classified into five hydrostratigraphic units by Tesfaye Chernet (1982).

6.3.1. Alkaline basalt trachyte and trachybasalts

These rocks are generally massive and they have a low permeability and productivity except where a few faults cause localized fracturing. The borehole around Asella have low yield of less than 0.5 liters /sec. A number of small discharge but perennial stream start from Trachytic Chilallo Mountains. As the underlying formation is mostly massive, shallow groundwater in the upper weathered parts provide small perennial flows to the streams.

6.3.2. The ignimbrite and pumice of the rift floor

In most cases the ignimbrites are well jointed while in some cases it is massive and pumiceous. Where it is well jointed, it has a high or moderate permeability, but in the rest it has low permeability. Hydraulic conductivity of ignimbrite varies between 0.02 m / day of well in Waji, north of Sagure to 41.6 m/day well in Gora, south of Kulumsa. On average the formation may be taken to have a moderate permeability and productivity. It has also different depths to groundwater; mostly 20 m to 100 m, but in some cases it is greater. When dense Wonji fault belt cuts these rocks, the degree of jointing increase and their permeabilties also increase at the same time.

6.3.3. Basaltic lava flows

Includes basaltic lava flows connected to volcanic centers and young lava field from aligned spatter cones, with a thickness less than 100m. The main areas of basalt flows are east of Lake Ziway, south of Lake Shalla, and along the major fault east of Butajira. These basalts are highly fractured and in several places they are scoriaceous. The scoria cones around Butajira show no drainage on their slope as they have the highest permeability in the area. Recent basalts have in general moderate to high permeability and productivity. Borehole at recent basalt yields 5.8 liters /sec at Abure School.

6.3.4. Pumice falls and acidic volcanic

Pumice fall are characterized by high inter-granular permeability, which become highest when sorted. Unaltered pyroclastic rocks, like alluvium, have porosities and permeabilties directly related to fragment size, sorting, and degree of combination. Poor sorting and abundance of fine material cause most widespread pyroclastic deposits to have low permeabilties but moderate to high porosities.

Acidic volcanoes are lava domes, lava flows and are silicic center of rhyolitic composition. Silica-rich lavas are more viscous and will be erupted in thick, dense flows. Their permeability is as a factor of extent of jointing and generally they have low permeability and productivity.

Obsidian, which is the last product of rhyolitic centers such as, Aluto is often associated with fumarolic activity. They occur in small outcrops mostly in the main geothermal areas.

These rocks are the latest volcanic products in the region. Many young volcanoes and calderas such as the Aluto volcano are made up of rhyolitic lava flows, pumice flows, pumice falls and ashes. When they are fractured and broken up they have moderate permeability. However the underlying formations, ignimbrite and basalt acts as aquifer in these areas while the overlying recent permeable rocks act only as avenues for infiltration or recharge.

6.3.5. Lacustrine sediments

Lacustrine sediments are common in the rift floor especially between lakes. They are the result of drying up of a big lake that occupied the floor of the rift during pluvial period. They overly the ignimbrite and they consist of alternating fine and coarse beds. The permeability of the lakes sediments become higher when there is higher proportion of coarser materials like pumice sand beds. Thickness of lake sediments range from 40 meter to more than 200 meters. The hydraulic conductivity of the lacustrine sediments varies from 2.94 m/day to 18.57 m /day for wells between the lakes.

6.4. Groundwater flow and Dynamics

Generally volcanic rock of the rift floor is characterized by fissural basaltic lava and acidic lava with pyroclastics erupted by central volcanoes. The axial part of the rift is dominated by acidic volcano that mainly erupted along tectonic line. The rift is affected by fault, which aligned in NE-SW and N-S direction. In the basin, the potential aquifers are fractured basalt and fresh jointed ignimbrite found at a moderate depth and most wells are located in these units.

The weathered tuff and paleosoils are impermeable layers inhibiting vertical movement thus forming perched water bodies. While silicic rich lavas such as rhyolites are more viscous and erupted in thick, dense flow so the flows are usually restricted around the source. Rhyolites are characterized by low permeability unless they are affected by fractures While the permeability and porosity of the pyroclastic rocks directly related to fragment size, sorting and degree of cementation.

The topographic and head difference between the highland and rift floor and the existence of suitable geological structures resulted in occurrence of local, intermediate and deep groundwater at different elevations (Tenalem Ayenew, 1998).

Shallow groundwater flow system is confined to the upper permeable zone, weathered and fractured rock. Extensive permeable zones occur at fairly shallow depth from the surface and consist of soil, weathered and fractured volcanic rock and forms unconfined aquifer. The thickness and hydraulic nature of the top zone change from place to place in relation to degree of weathering and fracturing.

Immediately below this zone, intermediate groundwater flow system is found in fractured volcanic rocks and the depth of this zone depends on the degree of fracturing. While the lower zone is massive volcanic sequence, which are locally fractured by deep faults.

6.5. Groundwater Recharge and discharge conditions

Recharge in the highland is mainly from direct precipitation as annual rainfall is higher than that of annual evapotranspiration. As a result waters in these areas are characterized by lower TDS and EC. On the escarpment recharge is facilitated by the presence of fractures and fault systems, mainly in eastern escarpment. Although recharge from intense storm in short duration is possible in the rift floor, recharge from channel loss of major rivers through lacustrine sediments is important.

Many discharging sites like cold springs, hot springs, swamps are found at different elevation in the basin and indicate the existence of different groundwater flow systems.

6.6. Thermal water

A relatively high temperature is characteristic of the entire rift due to due to intensive central type volcanic activity. Crustal thinning and ascension of magma chamber make the heating of groundwater possible in much higher magnitude than under normal geothermal gradient. The intense tectonic and volcanic activity in Ethiopian Rift caused the geothermal gradient to rise as $6m/^{0}C$ (Tamiru Alemayehu and Vernier, 1997 as cited in Tamiru Alemayehu, 2000).

Ziway-Shalla basin is an important geothermal energy exploration area within which sub areas such as Aluto volcanic centers, Lake Shalla shores, Lake Ziway area and Butajira-Silte areas are found. It has been found from Langano test wells that the high temperatures are due to high thermal fluid which rise from depth through permeable structures such as the SSW-NNE trending fault zone and dissipate heat through the basalt and ignimbrite rock units indicating that heating is not due to depth of the formation but due to rising fluid.

The existence of a geothermal system needs heat source, a permeable reservoir rock recharge of the groundwater and cap rock. In continental rift zone CRZ such as Ethiopian rift there can be many areas that have big heat source but usually one of the above mentioned parameters are lacking and the natural geothermal system remain infeasible. The most common factors for low success or failures of geothermal exploration in Ethiopian rift are absence of a permeable aquifer and lack of groundwater recharge (Tsegaye Abebe, 2000).

Geothermal field are associated with acidic center as heat source is acidic volcanism. Due to different in viscosity, basaltic magma tend to flow out totally to the surface while rhyolitic magma tend to retain residual shallow intrusive magma chamber which become source of tremendous geothermal energy (Tesfaye Chernet,1982).

The reservoir rocks are the Pliocene basalts and ignimbrite while some fine-grained Pleistocene and recent sediments, volcano-sediments and tuffaceous flows are taken to be confining cup rocks (Tsegaye Abebe, 2000).

Lack of recharge condition is one of the reason which limit geothermal system in rift zone the other limitation in continental rift zone is the block forming nature of the fractures or faults that allows fluid circulation only along weak zones. As these fluids are not gravity type and they need tectonic discontinuities for their flow.

CHAPTER SEVEN

WATER CHEMISTRY

7.1. Introduction

Data on major and trace element composition of water bodies in the basin is important not only form the point of view of determining the quality of water for different uses but also it gives a good picture on the hydrologic and hydrogeologic characteristics of the basin. From the analysis of the chemical data the sources of the undesirable constituents such as the high salinity, the high alkalinity, and the high fluoride in the lakes regions may also be unraveled. The objective of this chapter is to try to characterizes the chemical composition of water bodies and use it to gain an insight into the hydrology of the lakes. The suitability of the waters for different uses will also be addressed.

New major element chemistry of the water bodies in the basin were collected in leak proof plastic bottles. The samples were analyzed form major element using Atomic Absorption Spectrometers for cations and Ion chromatograph for anions. The new chemical data obtained during this work and data from previous sources were complied and presented in **Annex 2**.

7.2. Lake Chemistry

The chemistry of the lakes in Ziway-Shalla basin is mainly controlled by their hydrological characteristic. The notable difference between the salinity of the lakes despite their proximity is a matter of balance in water input and output.

In lakes with no surface and ground outflow evaporation is the only way of water loss to balance the total inflow to the lake. As such a lake lacks outlet for the solutes it becomes saline and the extent of salinity is the function of the length of the time since the lake has been closed. In the case of open lakes where there is outflow from the lake solutes loss may be possible from the lake. Such lakes are often characterized by low salinity. The extent of salinity of a given open lake is also as a factor of the amount or discharge of outflow, which determine the residence time of the water in the system.

Lake Ziway has outflow through Bulbula River, which keeps a lower water residence time. Therefore the lake is characterized by moderate salinity that is comparable to the geochemistry of the catchment. The lake is dominated by sodium and calcium. Bicarbonate is the dominant anion. The pH of the lake is around 8.4 and its TDS is 375 mg/L.

Lake Langano flows out through Horakello River but as the discharge of the river is not high and as the lake is occasionally closed during dry seasons, the residence time of the water in the lake is high. Therefore the lake is characterized by slightly higher salinity relative to its inflows. Sodium is the dominant cation and bicarbonate is a dominant anion followed by chloride. The Lake is characterized by pH of 9.2 and TDS of 1375.

Lake Abiyata is final evaporating basin for Lakes Ziway and Langano and has no surface and ground outflows. The lake is very saline. Its salinity is estimated to be fifteen and sixty times than lakes Langano and Ziway respectively. Precipitation of trona ($Na_2HCO_3.NaHCO_32H_2O$) is well marked around the margin of Lake Abiyata. Sodium is a dominant cation. Bicarbonate is the dominant anion followed by chloride. The Lake is characterized by pH of 10.1 and TDS of 19,848 mg/L.

Lake Shalla is the other terminal lake in the basin. It is characterized by the highest salinity, alkalinity and contains greater stock of solute. Chloride in lake Shalla shares about 97 % of the total quantity present in lakes region (Damm & Edmond, 1984). Sodium is a dominant cation that accounts for 95.57 % of the total cation and bicarbonate accounts for 77.64 % of the total anion and chloride accounts for 18.99 % of the total anion. The Lake is characterized by pH of 9.94 and TDS of 21,835 mg/L. Although the amount of discharge of hot springs to lake Shalla may be inconsiderable their solute contribution may be significant.

The low concentration of dissolved calcium and the increase in alkalinity during evolution from dilute lake Ziway to the saline lake Shalla was observed. Due to the alkaline characteristics of the lakes water the pH reaches a value of 9 to 10. Sodium increase continuously from 62.8 % of lake Ziway to 95 % of lake Shalla of the total cations. When the salinity of the lakes increase as a factor of their water balance, the importance of chloride increase from 5% of lake Ziway to 21.25% of lake Abiyata.

Although all the lakes are dominated by Sodium and Bicarbonate, their salinity and pH are significantly different. This is perhaps related to their hydrological setting. The salinity and pH of the lakes increase as the tightness of the lake increases. This is because evaporative concentration leads to a continuous build up of sodium, loss of calcium carbonates, consumption of dissolved carbondioxide (CO_2) and the increase in residual alkalinity. The alkaline nature of the waters and the increase in bicarbonate despite calcium bicarbonate precipitation may be explained by the presence of a positive alkaline residual of calcite. This process was discussed by (Tesfaye Chernet, 1998). The residual alkalinity of calcite is positive, as alkalinity is greater than the equivalents of calcium. When the water concentrates, alkalinity increases despite the precipitation of calcite.

Calcium and Magnesium are also important cations in open lake Ziway but their concentration decrease and become insignificant in the other alkaline and saline terminals lakes in the basin. This is due to the fact that in closed lake, water can escape only through evaporation and the residual water is expected to change in composition in well-defined pattern. The less soluble calcium carbonates are expected to precipitate first. As it can be observed (**figure 19**) the calcium content of the lakes is significant when the chloride concentration of the lakes is not high with respect to the rain. When the chloride becomes significant owing to evaporative, the calcium content progressively decrease and disappear from the lake water indicating loss of calcium via carbonate precipitation.

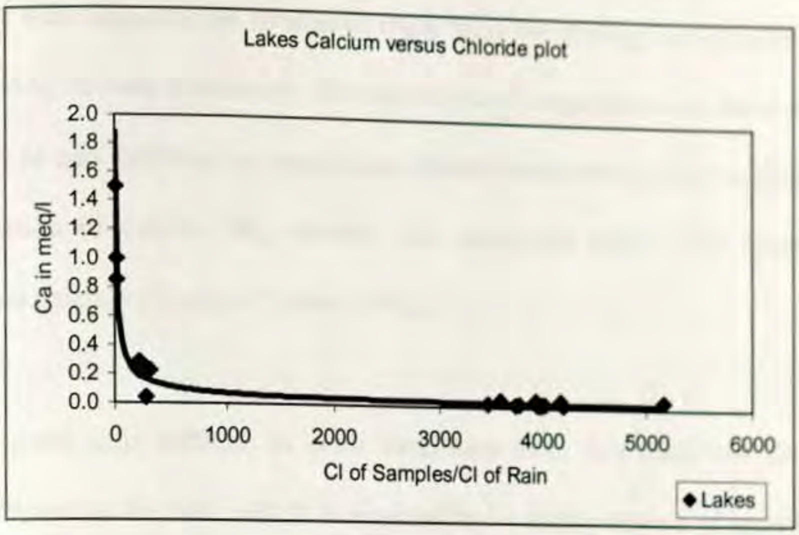


Figure 19. Calcium-chloride plot of the lakes

The importance of inflows to the lake is not only restricted hydrologically but also in transporting solutes from the drainage areas. As the basin is covered primarily by alkaline and peralkaline acidic rocks, rivers, which drain the weathered part of these rocks are charged with solutes in which sodium is dominant.

The progressive decrease and low content of magnesium in saline lakes and absence of simple salt that contain magnesium in lake sediments is an interesting characteristic of the basin. It is considered that the major possible sink of magnesium is aluminosilicates by von Damm and Edmond 1984. These authors suggest reverse weathering i.e. the neo formation of smectite and net removal of one or more base cation and silicates is possible in the closed lakes of the basin. The presence of smectite in the sediments of lake Shalla (Bauman 1975) may support this hypothesis.

Bauman found smectite in Lake Shalla but reported it as poorly crystallized and the smectite was suggested as weathered input from the drainage area rather than material produced by reverse weathering. The association of magnesium and silica precipitation at the time of neo synthesis of magnesium silicates such as Mg clays conforms successive precipitation of calcite, Mg silicates and amorphous silica. This hypothesis is also suggested recently (Tesfaye Chernet, 1998).

At this point it is difficult to draw conclusion from this study but there must be a phase/process in the lake, which is responsible for disappearance of magnesium. Uptake of Mg by algae may also be a possible sink for Mg.

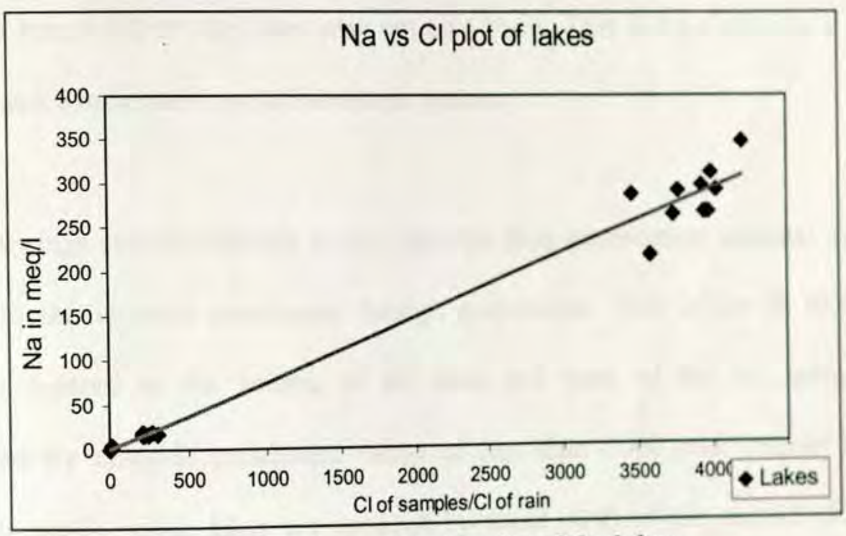


Figure 20. Sodium- chloride plot of the lakes

Sodium, which is mainly contributed from the drainage area through the inflows to the lakes progressively, increases in the lakes proportionately with chloride enrichment because saturation for sodium is not yet reached. It is clearly seen in **figure 20** that the two open lakes (Ziway and Langano) are characterized by relatively lower sodium and chloride due to their lower residence time. The closed lakes Abiyata and Shalla are characterized by significant enrichment of sodium and chloride ions as they lack outflow and therefore by considerably high water residence time.

Initially chloride content of terminal lakes may also be contributed from hydrolysis volcanic rocks. Then it enters into the lakes via surface water or geothermal water inflows although their concentration is progressively enriched as a response of the evaporation of the lake water. At the present condition, the presence of a process or a mineral phase that removes chloride form the lakes is not evident. Once it enters into the lakes from dissolution of biotite and hornblende of the glassy volcanic rocks such as obsidian its removal from the lakes may not take place. That is why chloride is often considered as a conservative ion in hydrologic systems.

These hot springs provide chloride to the lakes but their contribution may not be high compared to the chloride enrichment through evaporation. This is due to their low discharge compared to the volume of the lakes and most of the hot springs are characterized by chloride enrichment factor of less than 1000 with respect to the precipitation while saline lakes are enriched by about 4000 of the rainfall chloride. Besides Lake Abiyata, which is not fed by hot spring is characterized by similar chloride enrichment pattern as that of Lake Shalla. Lake Shalla is fed by many high chloride hot springs.

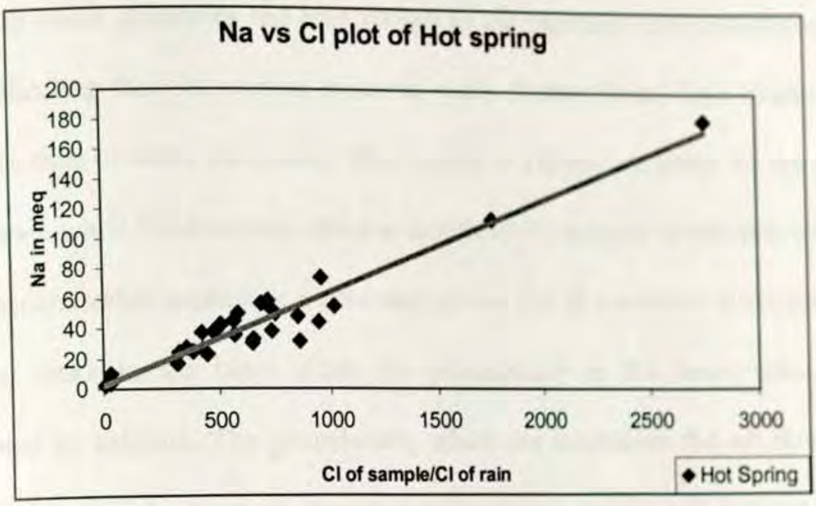


Figure 21. Sodium versus Chloride plot of Hot Spring

Although the water balance between inputs and outputs and geochemical processes of the lakes mainly control lakes chemistry in the basin, the geology of the drainage area and the input from thermal water seems to play a role in determining the chemistry of the lakes.

7.3. Groundwater chemistry

The groundwater chemistry of the basin shows variation from the highland and escarpment toward rift floor. The alkalinity and salinity of the groundwater tend to increase near the rift because of the influence of the alkaline lakes, due to the fact that rift floor is acting as evaporating pan for the basin and due to evolution of groundwater from the highland to the rift floor.

Hand dug wells, boreholes and cold springs of the highlands are characterized by lower TDS indicating that the present meteoric water flushes them. This illustrates the low residence time of water the system. Bicarbonate is a dominant anion for the groundwater of the basin while the dominant cation is as a factor of the type of volcanic rock. For most of the groundwater, sodium is a dominant cation due to extensive distribution of acidic volcanic rocks in the basin while the groundwater in the basic volcanic rocks is dominated by calcium. The groundwater, which are located on the rift floor around the lake and between the lakes are characterized by higher salinity and dominated by sodium bicarbonate. This is either due to influence of the lakes or due to the groundwater chemical evolution as it moves from the recharge area in the highland to the discharge area in the rift.

Wells, which are found south of Lake Shalla, are characterized by higher salinity that is comparable to the lake chemistry but it is unlikely to have southward groundwater movement from lake Shalla, as it is the deepest and the most terminal lake of the basin. This might be due to the groundwater inflow from the most alkaline Crater Lake Chitu.

Generally the groundwaters of the Rift floor are highly alkaline and are characterized by Na-HCO3 type waters compared the Ca-Mg-HCO3 type of waters in the bordering plateau which is also the recharge zone. This may be explained by a continuous geochemical evolution as the groundwater moves from the escarpment towards the rift. The geochemical reaction mainly hydrolysis of volcanic rocks may be accelerated by the presence of carbondioxide (CO2) as in the following reaction which leads to high Na and HCO3 in groundwaters.

$$CO_2 + H_2O + Na, K \text{ silicates} \Leftrightarrow HCO_3 + Na, K + H\text{- silicates}$$

Darling 1996, noted that in addition to the atmospheric or soil zone, CO_2 is produced from the mantle beneath the rift as ubiquitous carbon dioxide in Eastern Rift demonstrates. The partial pressure of CO_2 in Aluto-Langano reservoir is three times that of Broadland geothermal field in New Zealand, which is considered to be CO_2 rich system (Birhanu Gizaw, 1996).

There for it can be concluded that the presence of CO_2 diffusion from mantle sources accelerate the rate of chemical weathering leading to the degradation of water quality in the Ethiopian rift groundwaters.

7.4. Water type

From the Piper trilinear plot (**figure 22**), waters in the region can be broadly divided into the following groups:

Group1, Na-HCO_3 type

Group 2, Na-HCO_3-Cl type

Group 3, Na-Ca-HCO_3 type

Group 4, Ca-Na-HCO_3 type

Group 5, Ca-Mg-HCO_3 type

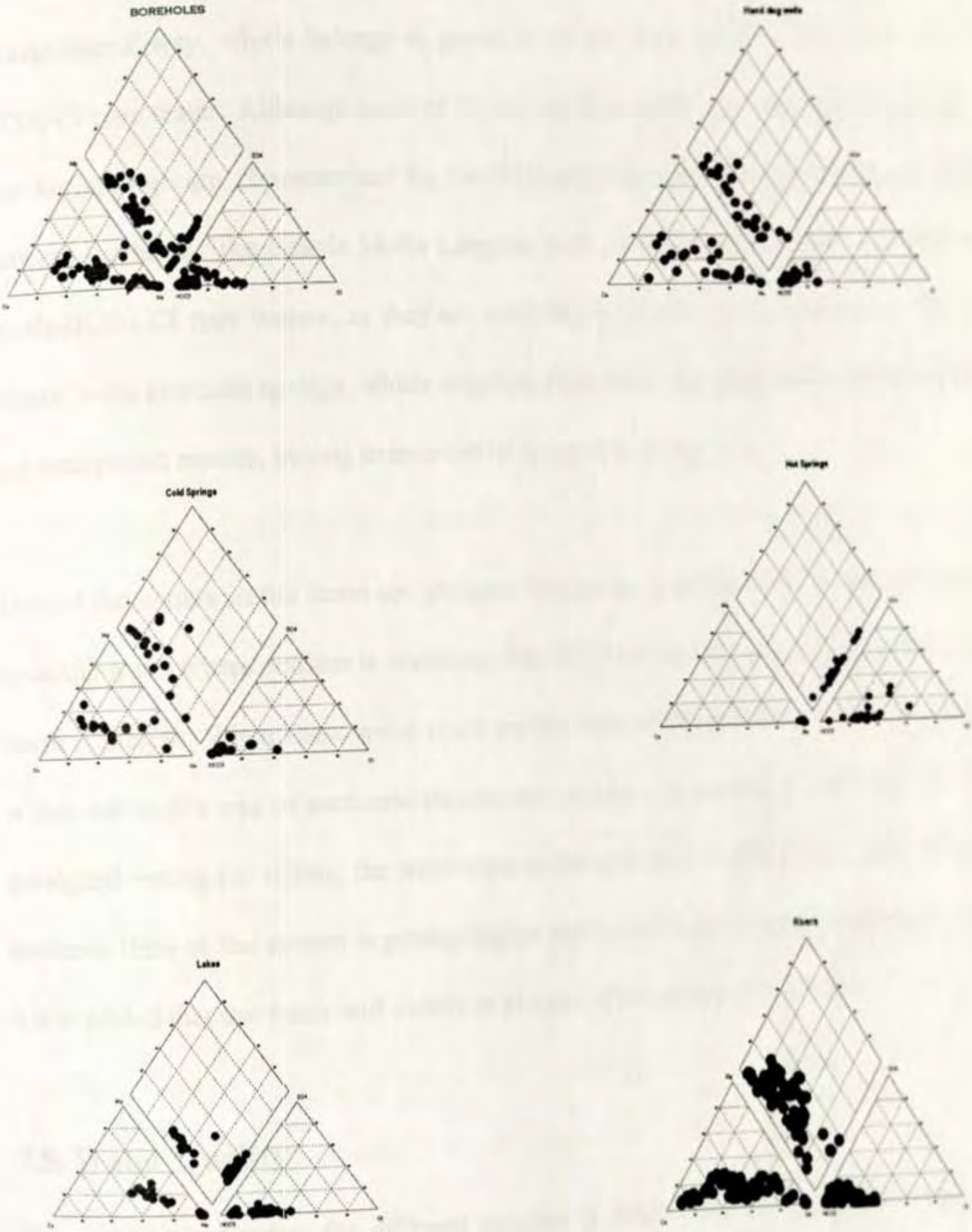


Figure 22. Piper plot

Most of the waters in the area i.e. rivers, wells and cold spring belong to group 1 and 3. Except lake Ziway, which belongs to group 3, all the three lakes in the basin are Na-HCO_3-Cl type water. Although most of the hot springs in the area are found in-group 2, few hot springs are characterized by Na-HCO_3-Cl-SO_4 type. Wells, which are found between the lakes, like Bekele Molla Langano well and soda ash well are characterized by Na-HCO3-Cl type waters, as they are most likely influenced by lake water. Most of Rivers, wells and cold springs, which originate from basic volcanic rocks of the highland and escarpment mostly, belong to in either of group 4 or group 5.

Most of the waters in the basin are grouped into group 1, as the basin is mainly covered by acidic rocks where sodium is dominate, but still calcium type water is observed where basalt is present. When these water reach on the floor of the rift floor where evaporation is high due to it's arid or semi arid climate and presence of several hot springs, due to its geological setting i.e. rifting, the water type is changed into Na-HCO3-Cl type. When the residence time of the system is getting higher and continuously modified by evaporation, it is expected that the water will evolve in to more alkaline and saline water.

7.5. Water Quality

The suitability of water for different purpose is determined by its quality. One basic measure of water quality is its TDS, total dissolved solid in water. As the amount of TDS increases, the quality of water for utilization for drinking and irrigation degrades. In the bordering highlands and the escarpments the TDS is lower than 500 ppm. This is acceptable for any use (irrigation, domestic water supply etc). The TDS varies from 500 to 1500 ppm in the rift floor and attains it maximum value for the two terminal lakes Abiyata and Shalla.

7.5.1. Drinking water quality

High Na, HCO3 and Fluoride content characterize are the three most important treats of water quality in the Ethiopian rift water bodies. Although fluoride is important for tooth formation in the early ages, prolonged intake of water cause adverse effect on dental and skeletal fluorosis if the fluoride content of the intake exceeds the optimal range for drinking water, that is 0.7-1.5 mg/l (WHO, 1984). The main factors, which determine the extent of adverse effects, are the concentration of fluoride in water, the quantity of water consumed, the length of consumption time, the temperature, the nutritional economic status and physical activities (Birhanu Gizaw 1996).

Rivers have acceptable fluoride concentration unless they are influenced by lake or thermal waters. In Lakes region where Na-HCO3 type water dominates the lakes waters very high fluoride contents are associated with high salinity of the lakes (Tesfaye Chernet, 1998) owing most probably to evaporative concentration.

The spatial distribution of fluoride follows the TDS pattern, as the lowest fluoride content characterize the highland and escarpment while the concentration of fluoride increase around the lakes on the rift floor and become highest up to 300 mg/l for the terminal Abiyata.

This is due to the fact that the chemistry of groundwaters and rivers in the higher elevation are as a factor of the geology of the reservoir and the waters are characterized by lower residence time as they are continuously flushed by relatively intense rainfall of the area. While in the lower elevation as there is no outflow from the closed basin, all the solute inflows from different part of the basin feed the lakes where they are continuously evolve as a response of the evaporation.

7.5.1.1 Origin of Fluoride concentration

Different authors have suggested the origin of high fluoride content in the Ethiopian rift. Leaching of fluoride from volcanic rocks especially from acidic and alkaline rocks by surface and groundwaters has been mentioned as potential source of fluorides. This is confirmed by very high concentration of fluoride and chloride in Gedemsa acidic lavas (North of the study basin). Some pumiceous rocks show low fluoride and strong decrease in sodium and moderate depletion in Cl, which may be interpreted as the interaction of pumice with waters and have already lost their fluoride and sodium content together. The high concentration of Na and F in Ethiopian rift valley waters mirror the composition of altered pumices (Gegahgne Yirgue *et al.*, 1999).

Concentration of F may also be related to the permeability of rocks. The differences in F concentration in groundwater from pumice compared F concentration in groundwater from ignimbrite and obsidian testifies the dependence of F leaching on permeability (Gegahgne Yirgue *et al.*, 1999). The strongly vesicular glassy pumice is characterized by much larger surface interaction than obsidian and ignimbrite although the original F content of these rocks is comparable.

Fluoride content in the water could be also limited by thermodynamic control (Tesfaye Chernet, 1998). When the solution in the water is saturated, the equilibrium relation controls the fluoride concentration; all changes in Ca^{2+} activity are liable to modify the amount of fluoride in solution. The solubility of CaF_2 increases with temperature and at the same time the solubility of calcium carbonate decrease so calcium content of the water become relatively low. When calcium is precipitated hence there is no enough Ca^{2+} to fix the F^-, therefore F become mobile component in the acid volcanic system of the rift. This explains the high value of fluoride in certain thermal spring. When lakes water is affected by evaporation, the precipitation of calcium carbonate resulted in low content of calcium in lake water, which provoke the occurrence of high fluoride content.

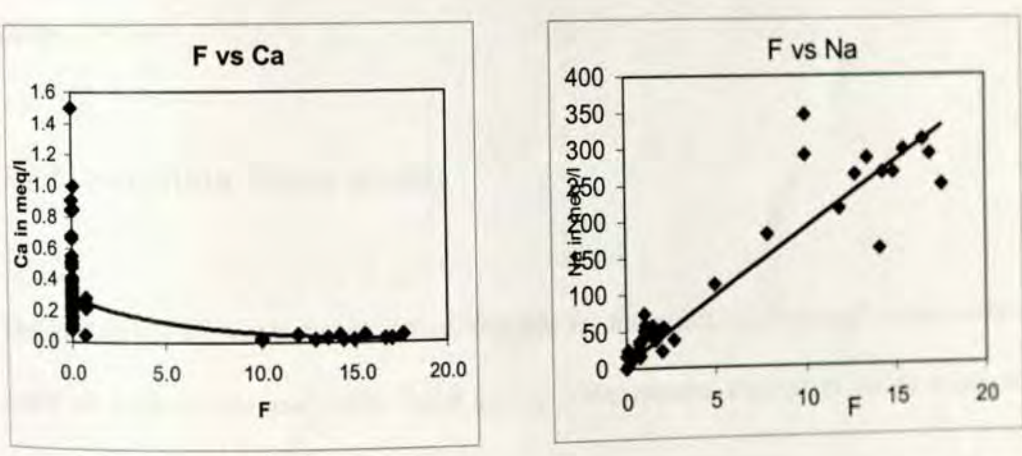


Figure 23. Fluoride versus calcium and Fluoride versus sodium plot from left to right

As it can be seen from **figure 23** at low fluoride content the calcium content is variable. This is most likely a factor of the geology of the volcanic rocks. While with increasing fluoride, calcium content of the water starts to decreases regularly which can be attributed to precipitation of calcite.

There is strong correlation between the increase of fluoride with sodium and they are correlated in the above figure with correlation coefficient of 0.92. The leaching of both elements from acidic rocks of the basin and their progressive increment in water is uniform in response to evaporation and interaction to thermal waters. This is because as both elements are not affected by mineral precipitation as the system is under saturated with respect to their respective phases.

It has been also suggested that fraction of the total F is likely to be contributed by deeper fluid as F is added from magmatic sources in the form of neutral molecule HF (Birhanu Gizaw, 1996).

7.5.2. Irrigation Water quality

The suitability of water for irrigation depends on the effect of chemical constituents of water on both plants and soils. Good quality water permits maximum yields consistent with proper soil and water management.

SAR (sodium adsorption ratio) is often considered to characterize the quality of water for irrigation by assessing the sodium hazard. SAR is given as

$$SAR = \frac{Na}{\sqrt{\frac{Ca + Mg}{2}}}$$ Where cations are in meq/l

When sodium rich water is applied to soil, as a result of base exchange with clays, the physical properties of soil changes. As the soil become sticky and slick when wet with low permeability and it becomes hard clods when it dries and makes the soil unsuitable for agriculture.

Source	EC	SAR	Water class	% Na	Water class
Ziway	420	3.50	Good	68.85	Doubtful
Abiyata	15000	969.22	Bad	99.95	Unsuitable
Langano	1850	31.53	Bad	96.82	Unsuitable
Shalla	18230	1189.98	Bad	99.96	Unsuitable

Table 5. Irrigation water Quality

It is only the water from lake Ziway that can be used for irrigation and it has been used for irrigation for a considerable time. The lake has a potential for irrigating 1700 hectare (Halcorw, 1989) but currently 1200 hectare is being irrigated.

Due to the closed nature of the basin, it is characterized by intense evaporation, high salinity occurs in the plain of closed basin. Salinization is a problem in Ziway irrigation farm especially during drought time and they either abandon the soil until the next rain season or use the land to plant salt resistant vegetables like onion.

The increase in alkalinity and pH induce problems of insolubility and deficiency of mineral nutrient for plants such as phosphorus and zinc as well as phenomena of toxicity of sodium (Valles, 1987 as cited in Tesfaye Chernet, 1998)

It is very unfortunate that, despite the large volume of open water bodies available in the basin, due to their poor water quality i.e. sodification and alkalinization, the lake waters are unsuitable for irrigation and domestic water supply at the present day technology. Under an improved economic condition however economical desalinization of the lake waters would be possible.

CHAPTER EIGHT

ISOTOPE HYDROLOGY

8.1. Introduction

A sound understanding of hydraulic interconnection between lakes and the surrounding groundwater is important for the proper management of lakes. Isotope hydrology is one of the chemical approaches, which is widely used to understand lake-groundwater interaction by taking an advantage that lakes and their surrounding groundwater are isotopically distinct. This chapter will entertain the qualitative analysis of isotopes in precipitation, runoff, groundwater and lakes so as to capture a good picture on factors that control isotopic composition of the meteoric waters and to grip an idea about groundwater recharge sources, surface water groundwater interactions and the degree of evaporative concentration etc.

8.2. Theoretical background

Isotope Hydrology is based on the fact that different isotopes of the same element differs slightly in chemical and physical properties due to their mass differences. Certain thermodynamic properties of molecules depend on the mass of the atoms. As a result, isotopic fractionation between heavier and lighter isotopes of the same element takes place. The consequences of these mass differences are two fold: -

1. The heavier isotopic molecule have lower mobility as velocity of molecules are inversely proportional to square root their mass
2. Heavier molecules have higher binding energy so that the bonds, which are formed by lighter isotopes, are weaker and easily broken and more reactive.

There are two types of fractionation, Equilibrium and Kinetic fractionation. Equilibrium fractionation involves redistribution of isotopes of an element and the forward and backward reaction rate are equal. In equilibrium fractionation, the difference between the isotopic compositions of any compound is largely a function of chemical composition and temperature. In general the difference between the equilibrium isotopic compositions of any compound decrease as temperature increase due to the fact that as temperature increase the relative difference in vibrational frequencies between isotopic species decrease.

Kinetic fractionation involve unidirectional if reaction product become physically isolated from reactant. The reaction rates depend on the ratio of the mass of the isotope and their vibrational energies.

Stable isotopes in water are fractionated in different hydrological compartment and provide characteristic fingerprint of their origin. Isotope of oxygen and hydrogen are useful tracer of water source as they are constitute of water molecules itself and are conservative in aquifer.

Stable isotopes of oxygen and hydrogen are commonly reported in delta (δ) values in parts per thousand (‰) that quantify enrichment or depletion with respect to a standard called Standard Mean Oceanic Water (SMOW)

$$\delta = \left[\frac{R_{sample}}{R_{standard}} - 1 \right] * 1000$$

Positive value indicates the sample is 'enriched' in heavy isotopes than does the Standard and negative value indicate that sample is 'depleted' in the heavy isotopes relative to the standard.

8.3. Isotope data and analysis

Water samples were collected in August 2002 and February 2003 and stored in refrigerator before they were sent for analysis at the University of Avignon, Laboratory of Hydrogeology, France. The water samples were treated with Zinc at 500 ^{0}C to generate hydrogen for D/H analysis and equilibrated with CO_2 for $^{18}O/ ^{16}O$ analysis. Mass Spectrometric determinations were performed on a VG SIRA + ISOPREP 18 in conjunction with laboratory standard calibrated against VSMOW scales. The results are reported in δ notation per mil (‰) versus these standards. The data obtained from this work and previous stable isotope data is compiled and tabulated **(Annex 3)**.

8.4. Isotopic composition of precipitation

The transformation of atmospheric water vapor to precipitation depends on several climatological factors. The most important factors that determine isotopic composition of rainfall are temperature of condensation and degree of rainout. Craig (1961) noted a linear relation between δD and $\delta^{18}O$ values for precipitation from various part of the world. The liner relation is termed as the Global Meteoric Water Line and is defined by the relation:

$$\delta D = 8\delta^{18}O + 10$$

The observed strong relation between δD and $\delta^{18}O$ is due to the fact that the formation of water droplet in a cloud is an equilibrium controlled process as of 100 % or greater water vapor saturation in air mass and fractionation is only as a function of ambient temperature.

The GMWL is an average of many Local Meteoric Water Lines (LMWL) each of them controlled by local climatic factors such as source of vapor mass, secondary evaporation during rainfall and seasonality of precipitation. As these local factors affect both the slope and deuterium excess (d-excess=δD-$8\delta^{18}O$), it is essential to set LMWL for a given region and compare the ground and surface water with this local meteoric water line. As there is no continuous record isotopic composition of rainfall for the study area, we used isotopic composition of the Addis Ababa rainfall to detect the seasonal variation of the rainfall as they are under the same moisture source.

8.5. Isotopic pattern of the Addis Ababa rainfalls

The International Atomic Energy Agency (IAEA) in cooperation with world Meteorological Organization (WMO) has been conducting a worldwide survey of isotopic composition of H and O of precipitation in East Africa including Ethiopia since 1961. The $\delta^{18}O$ and δD data of Addis Ababa station plot along the LMWL defined by

$$\delta D = 6.95\delta^{18}O + 11.51 \text{ with } r^2 = 0.92$$ (Rozanski *et al.*, 1996)

Dansgaard (1964) showed that temperature is a major parameter that controls isotopic composition of precipitation. Rozanski *et al.*, (1996) indicated that in subtropical stations, temperature has minor importance in controlling isotope variation in rainfalls and that the seasonal variation of $\delta^{18}O$ for tropical station correlate poorly with temperature as it is correlated with strong seasonality of the landward displacement of ITCZ. The seasonal variation in $\delta^{18}O$ (**figure 24**) perhaps demonstrates the importance of seasonal drifting of the ITCZ in controlling the $\delta^{18}O$ variations. In spring when the moisture is driven from the Indian Ocean the rainwater are characterized by enriched $\delta^{18}O$. This is perhaps related to the fact that moisture is driven from North Indian Ocean, which is characterized, by high sea surface temperature (SST). In summer when the moisture is driven into the region from the Atlantic Ocean $\delta^{18}O$ is relatively depleted owing to the low SST of the ocean. As the amount of rainfall reaches its maximum, the local factors like the amount effect and temperature effect also leads to depleted $\delta^{18}O$ composition of the summer rainfall.

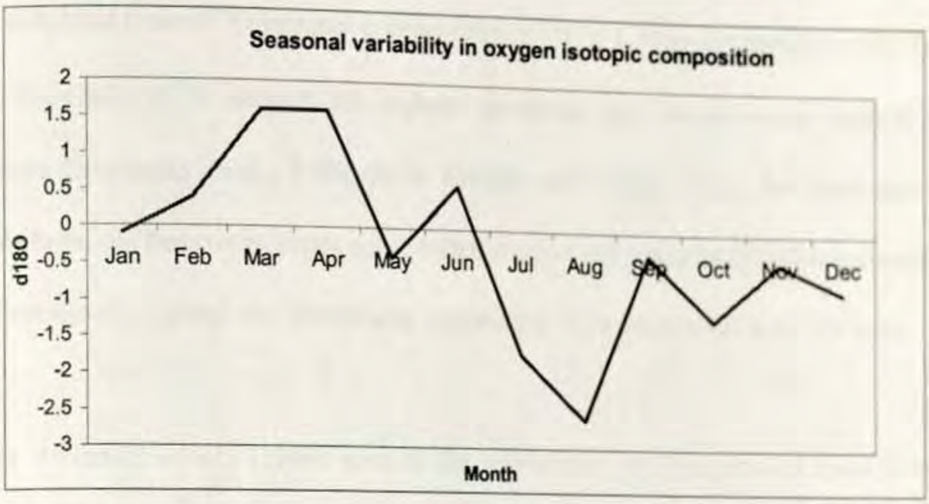


Figure 24. Seasonal variation in $\delta^{18}O$ of Addis Ababa Rainfall

The heavy summer rain is characterized by lighter isotope than that of smaller spring rain, and this seasonal dependence of the $\delta^{18}O$ variation on the amount of rainfall is termed as the Amount Effect (Dansgaard, 1964). His explanation for the existence of 'Amount effect' is that as the falling raindrops undergo partial reevaporation this enriches the isotopes and this effect is more severe when the ambient temperature is high and when the amount of rain is small.

As it can be seen from **figure 24**, the depleted $\delta^{18}O$ value of the rain also persists through the months of October to December although they are characterized by low rainfall amount. This may be due to the fact that the source of moisture is still from Atlantic Ocean, indicating the isotopic composition of Addis Ababa rainfall is the result of both local and regional factors.

Addis Ababa is located at the elevation of between 2360 m.a.s.l and characterized by heavier weighted mean $\delta^{18}O$ isotopic composition ($\delta^{18}O$ = -1.3‰) compared to other East African Rainfalls $\delta^{18}O$ despite its highest elevation and lowest mean annual air temperature (Rozanski *et al.*, 1996, Seifu Kebede and Travi, 2002). As cloud rise up higher altitude, the heavier isotopes are distilled and the residual precipitation is expected to gets isotopically lighter. No satisfactory explanation is so far available on this issue.

However Rozanski *et al.* (1996) evoked the importance of transpiration from Congo basin vegetation as playing a role in modifying the isotopic composition of the Atlantic Ocean Monsoon. While Seifu Kebede *et al.*, (2003) indicated the importance of local soil moisture-rainfall feed back mechanism as an important control of isotopic signal of the Addis Ababa rainfall and the Ethiopian Highlands.

8.6. Isotopic composition of rainfalls in the Ziway-Shalla basin

Rainfall samples have been collected in the study area in non-systematic manner at scattered localities of the basin by different researchers. Data from IAEA 1995, Tenalem Ayenew 1998; Tesfaye Chernet, 1998 and others were plotted along the LMWL of the basin **(figure 25)**. There is questionability of using the rift rainfall isotope data to calibrate a representative LMWL. Most of the data are collected in individual rainfall event and the result may give widely differing isotopic result, as evaporation and temperature effect are different for different rainfall event. In addition to this the basin is influenced by two moisture sources so seasonal rainfall data should be collected in consistent manner for a considerable time for sound understanding of isotopic pattern of the rainfall in the basin. However the range of $\delta^{18}O$ and δD composition of these rainfall events is similar to the range of values of the Addis Ababa rainfall composition testifying similarity in sources of moisture (**figure 25**).

$$\delta D = 6.08\delta^{18}O + 8.94 \text{ with } r^2 = 0.87$$

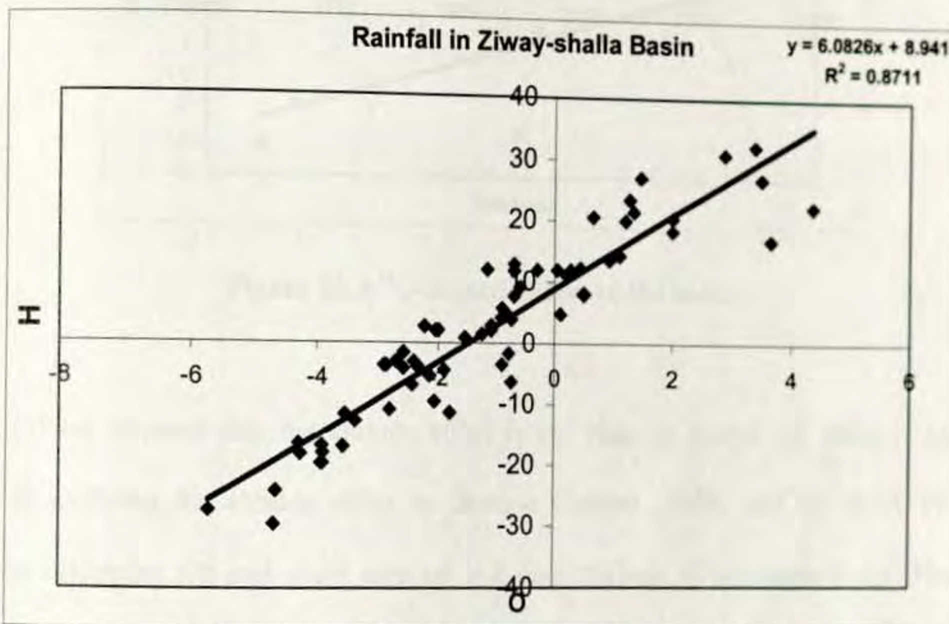


Figure 25. Rift rainfall isotope data in Ziway-Shalla basin

8.7. The Altitude effect

The altitude effect is one of the geographical variations in isotopes, which is widely used in groundwater recharge source estimation. From the scare data so far available a very poor $\delta^{18}O$-altitude relation is obtained (**figure26**). This can be due to the limited number of samples or from the fact that the basin is under the influence of two moisture sources that may complicate the altitude effect.

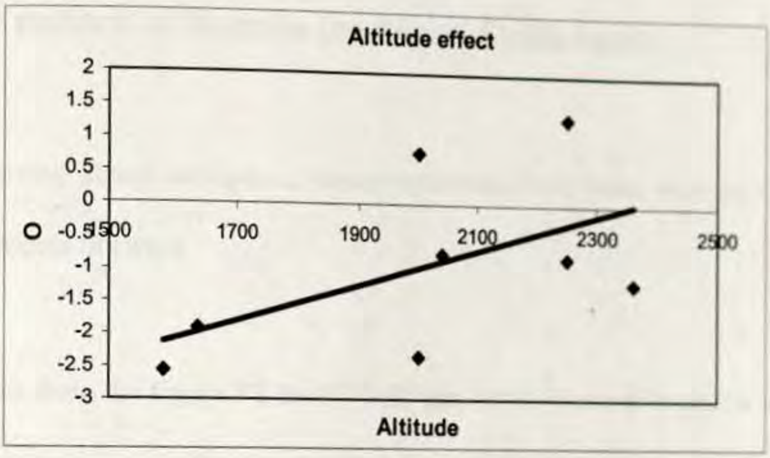


Figure 26. $\delta^{18}O$-altitude effect in the basin

Darling (1996) showed that the altitude effect is not clear in Kenya rift valley. An attempt to calibrate the altitude effect by Tesfaye Chernet (1998) and by IAEA TC project in Ethiopian rift and show reversal and poor altitude effect respectively. The altitude effect of –0.5‰/100m has been recently calibrated by McKenzie *et al.* (2001) for Abay-Chamo basin from cold springs. Although it is controversial, cold springs may be used to calibrate the altitude effect because they may represent isotopic composition of rainfalls under favorable conditions of short subsurface residence time and absence of evaporation prior to recharge.

Recently Seifu Kebede and Travi (2002) indicated that the altitude effect is subdued by the rain shadow effect in the Ethiopian rift, as it is located on the leeward side of the two moisture sources. It is important to have continuous seasonal data at different altitudinal transect of the basin to calibrate a valid altitude effect in the basin and the Ethiopian rift as a whole.

8.8. Isotopic pattern of Rivers in the Ziway- Shalla basin

Naturally occurring stable isotopes of water molecules have been used to study the hydrological process of rivers.

As it can be seen from the **figure 27**, the $\delta^{18}O$-δD plot of the rivers of the basin coincides with the local meteoric water line showing that the isotopic composition of river water is similar to that of precipitation. This rules out the importance of en route evaporation of river waters.

Bulbula and Horakello rivers are highly enriched relative to other rivers ($\delta^{18}O$ of 5.2‰ and 6.85‰ respectively) as they are outflows from Lake Ziway and Langano respectively. The isotopic composition of outflow from a given well-mixed lake is expected to be equal to the isotopic composition of the lake itself. Jido River that drains into Lake Shalla is slightly enriched ($\delta^{18}O$ of 0.58‰) may be due it's transporting distance or season of sampling.

Small rivers that drain into Lake Langano which vary from ($\delta^{18}O$ = –2.93‰) of NE Langano stream to ($\delta^{18}O$ = –0.59‰) of Gedemso river and small rivers which drain into

Lake Shalla like ($\delta^{18}O$=-2‰) of Debaba river and ($\delta^{18}O$ =-0.65‰) of Melka Oda are characterized by isotopically lighter water and they all plot above or near the LMWL.

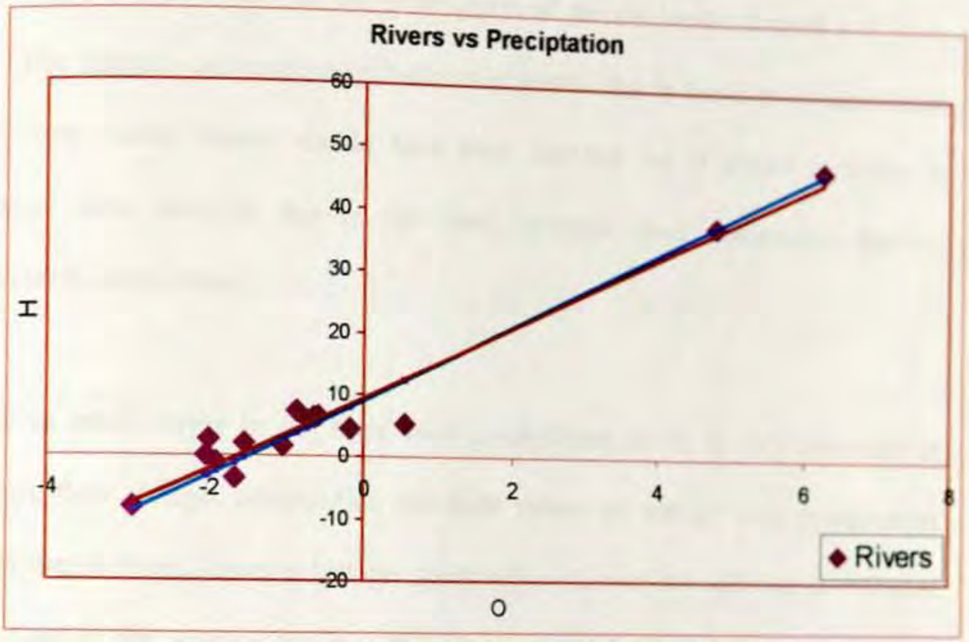


Figure 27. δD-δ^{18}O plot of Rivers in the basin with respect to the LMWL

This may be an indication that the isotopically depleted summer rain is more important in feeding small rivers while the enriched spring rainfall which occur just after the dry season is used in replenishing soil moisture deficit and used for transpiration of the plant than in flows into the rivers.

Meki River is characterized by lighter $\delta^{18}O$ in its headwater like Ereshea River ($\delta^{18}O$=-2.8‰) and slightly enriched down stream to about ($\delta^{18}O$ =-0.41‰). This may be due to the input from swamp areas and also from its long river course, which enhances en route evaporative enrichment.

Ketar River is characterized by longer river course and larger catchment area. A sample from Aleltu Sagure river at the middle of the catchment has a $\delta^{18}O$ of -2.67‰ and the only sample from Ketar river at the downstream of the catchment showed a $\delta^{18}O$ =-2.37‰. The isotopic composition of Ketar river sample that is found at a considerable distance from Aleltu Sagure should have been enriched but it shows depletion in downstream. This may be due to the input of water from isotopically depleted groundwater in downstream.

Generally in small rivers in the basin local precipitation event is very important in determining their isotopic composition and these values are not far from precipitation value. For larger rivers however isotopic composition of local precipitation is reflected near the head of the streams but near their downstream ends modification of $\delta^{18}O$ is observed perhaps owing to inflow of tributaries with different isotopic composition or due to groundwater influx in to them.

8.9. Isotopic pattern of Lakes

During an open water body evaporation into unsaturated atmosphere, kinetically controlled isotopic fractionation is significant in most evaporation process that lead to an isotopic fractionation exceeding which is predicted by equilibrium fractionation. Kinetically controlled fractionation result from the fact that light isotope species have greater free air diffusion rates than heavier isotopes thus the light species are preferentially transported away. This kinetic fractionation is controlled by diffusion of isotopically different water molecule through air, the moisture deficit (1-h) over the evaporating surface.

The net result of evaporation is isotopic fractionation of lake water is the water mass, which is not in isotopic equilibrium with its water source. Therefore isotopic composition of lake water is enriched with respect to its inputs. The mean oxygen isotopic composition of the lakes in the basin are +5.26‰for lake Ziway +6.71‰ for lake Langano +7.64 ‰ for lake Shalla and +8.19‰ for lake Abiyata. All the lakes are enriched which respect to LMWL. This indicates that they undergone intensive evaporation with respect to the present day precipitation.

Lake Abiyata is the most enriched lake in the basin due to its terminal position and its shallow depth. As evaporation is the only way of water loss from the lake, its residence time is higher than the nearby Ziway and Langano lakes. The later two lakes are characterized by considerable surface and ground outflows. Lake Shalla is the other terminal lake in the basin. The isotopic composition of lake water plot below the LMWL on a line called the Local Evaporation Line (LEL). The lakes plot on a LEL defined by:

$$\delta D = 5.75\delta^{18}O + 8.63 \text{ with } r^2 = 0.96$$ **(figure 28)**

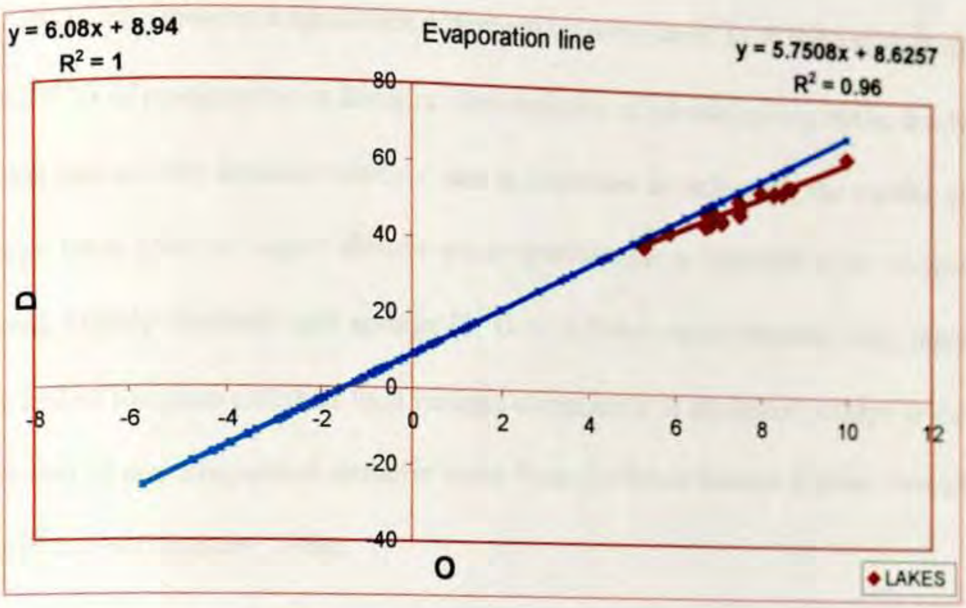


Figure 28. δD-δ^{18}O plot of lakes in the basin with respect to the LMWL

As it can be seen from the above figure, the LEL line represent the isotopic evolution of lake water from its source water and the slope of evaporation line is as a function of humidity, temperature and isotopic composition of atmospheric moisture above the lakes.

8.10. Lake Groundwater Interaction

Groundwater samples from hand dug wells, boreholes and cold springs were used to study the groundwater-lake interaction. All the cold spring samples plot near the Local Meteoric Water Line as they are depleted relative to the mean precipitation (figure 24). The δ^{18}O of groundwaters of the basin vary from -2.55‰ of Butajira cold spring to -1.62‰ of Shalla cold spring. The isotopic composition of Silte cold spring (δ^{18}O = -2.44‰) is comparable to average isotopic composition of the precipitation at Silte (δ^{18}O

= -2.14‰) while there is a significant difference between the $\delta^{18}O$ of Butajira cold spring and the $\delta^{18}O$ of precipitation at Butajira. The depletion of all cold spring can be due to the fact that isotopically depleted summer rain is important in recharging the aquifer or the recharge takes place in higher altitude where precipitation is expected to be isotopically depleted. Highly depleted cold springs ($\delta^{18}O$ = -3.38‰) were observed along marginal faults east of Langano and their light isotopic composition is attributed perhaps to the fast circulation of non evaporated meteoric water from the South Eastern Plateau through the faults (Tenalem Ayenew, 1998).

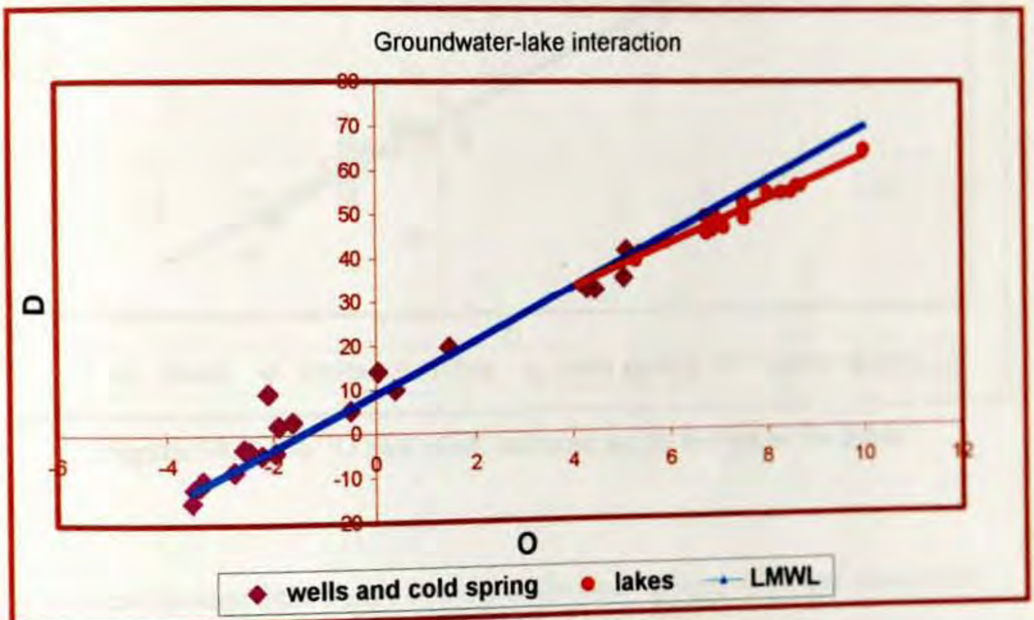


Figure 29. Groundwater –lake interaction

Hand dug wells of Butajira, Koffele, Abure are depleted with respect to LMWL and plot along with cold springs as they are not influenced by secondary process such as evaporation prior to infiltration or mixing with lakes. Wells, which are found between the lakes in the rift floor like Ziway South Well ($\delta^{18}O$ = 5.04‰), Adamitulu well ($\delta^{18}O$ =

4.45‰), Ziway Debritu hand dug well ($\delta^{18}O$ = 5.08‰), Oxfam Well ($\delta^{18}O$ = 4.03‰), Soda ash bore well ($\delta^{18}O$ = 1.44‰) Langano Bekele Molla ($\delta^{18}O$ = 0.39) etc are enriched with respect to their inputs and plot on groundwater- lake mixing line **figure 29**. This mixing line is observed due to the fact that there is significant hydraulic connection between the lakes and the nearby aquifers.

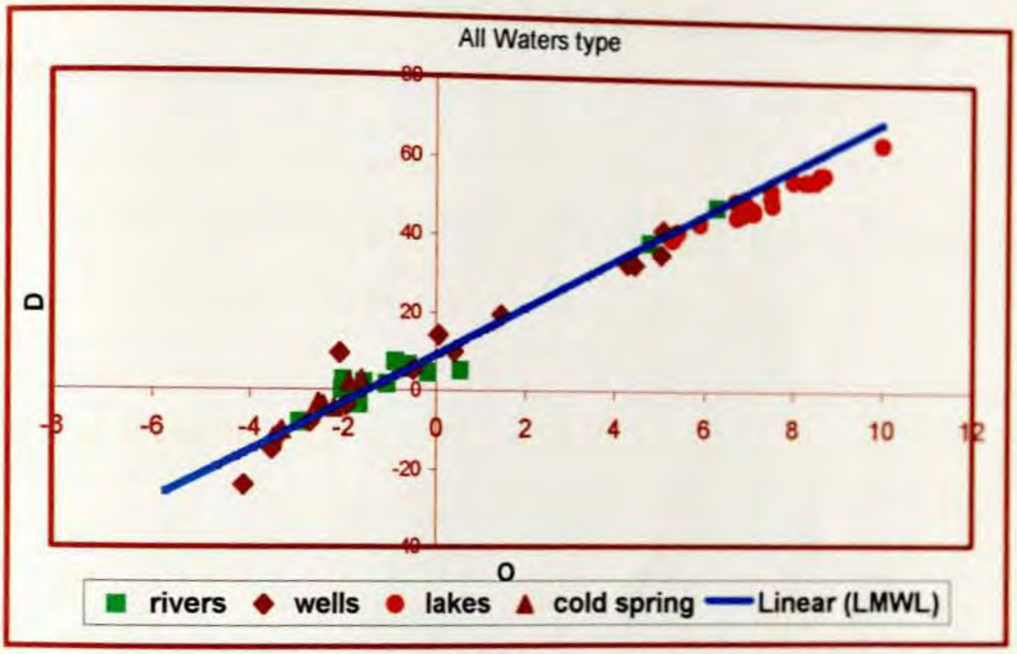


Figure 30. δD-$\delta^{18}O$ Plot of all meteoric water bodies in the basin

Generally as it can be seen from **figure 30** most of the clod springs, rivers and some wells plot on and towards the depleted end of the LMWL indicating that the hydrology of both surface and groundwater is controlled by the input from isotopically depleted heavy summer rain or recharge of groundwater and feeding of rivers takes place in the highland where isotopic composition of the precipitation is expected to be depleted. The four lakes are enriched with respect to the LMWL as they are in the state of evaporation with respect to their inputs.

Exceptions are observed on water bodies in the rift floor where the groundwaters and rivers are influenced by evaporated lake water through surface and groundwater outflows from the lakes and plot along mixing line and indicating the hydraulic interconnection between surface and groundwaters.

CHAPTER NINE

Water and Isotope budgets of the Lakes

9.1. Theoretical Background

Lakes are complex dynamic system interacting with local environment and connected to water cycle through both surface and groundwater inflows and outflows as well as through precipitation and evaporation fluxes. It is important to quantify all the hydrological inputs and outputs for a sound understanding of Lakes Water budget and their proper management. Water budget components of a lake is schematically shown in **figure 31,**

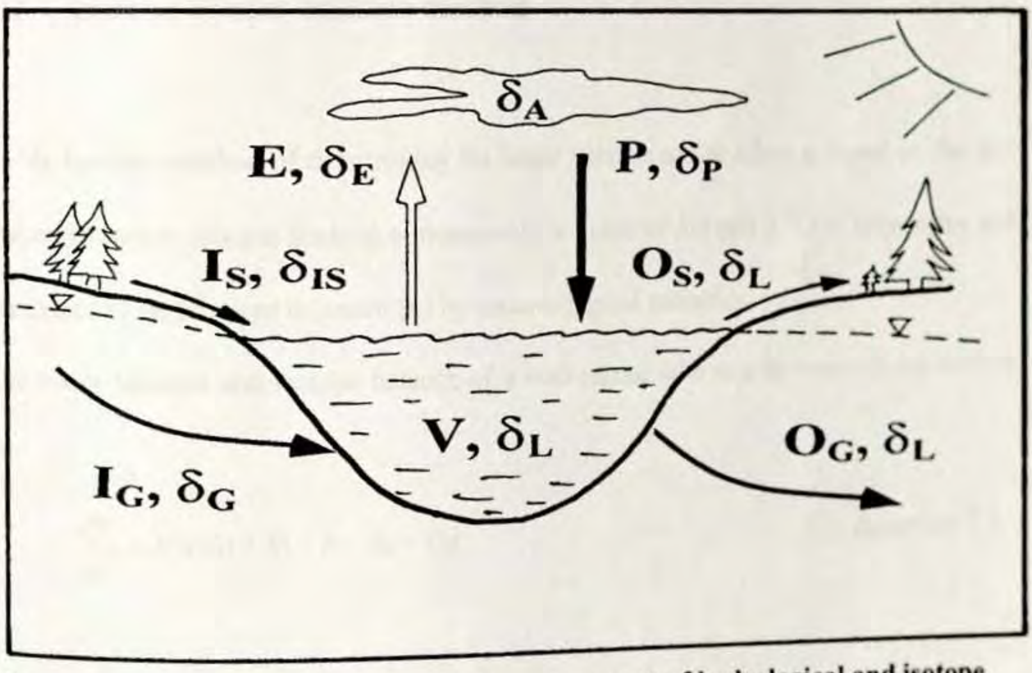


Figure 31. Schematic diagram depicting components of hydrological and isotope budget of a lake system.

It may possible to measure directly the precipitation flux, surface inflows and outflows but it is often difficult to measure the groundwater and evaporation fluxes for a given lake. Groundwater component of the lakes water budget are commonly calculated as the residual of average precipitation, evaporation fluxes and change in lake storage. This type of budget calculation provides only an estimate for net ground flow as the calculation never separate the inflow and outflow component.

Stable Isotopes will be used to separate the net groundwater flux into its inflow and outflow components. The Stable Isotope approach is based on the fact that mass conservation is applied to trace constitute of the water molecules.

9.2. Isotope Water balance method

Stable Isotopic method of determining the water balance of the lakes is based on the fact that evaporation process leads to a measurable increase of δD and $\delta^{18}O$ of lake water and the extent of enrichment is controlled by meteorological variables.

The water balance and isotope balance of a well-mixed lake can be respectively written as:

$$\frac{dV}{dt} = P + Gi + Si - E - So - Go \qquad \textit{Equation 7.1.}$$

$$\delta_L \frac{dV}{dt} + V_L \frac{d\delta V}{dt} = \delta p P - \delta_E E + \delta_R Si - \delta_L So + \delta_G G_{in} - \delta_L G_o \qquad \textit{Equation 7.2.}$$

Where,

P is precipitation on the lake

E is evaporation from lake surface

S_i is surface runoff to the lake from the catchment

S_o is lake out flow via surface water

G_{in} and G_o are groundwater inflow and out flow respectively

δ Is isotopic composition of each flux with which it are associated

.

Assuming that a given lake is in hydrological and isotopic steady state ($dV/dt = d\delta_L/dt = 0$) and that it is a well-mixed lake ($\delta_{GO} = \delta_L$), the equations 7.1. and 7.2. can be solved simultaneously to derive both groundwater fluxes independently. An equation of the following form can be obtained:

$$G_{in} = S_{in}\left(\frac{\delta s - \delta_L}{\delta_L - \delta_G}\right) + P\left(\frac{\delta_P - \delta_L}{\delta_L - \delta_G}\right) + E\left(\frac{\delta_L - \delta_E}{\delta_L - \delta_G}\right)$$ *Equation 7.3.*

The most difficult parameter to quantify in above equation is isotopic composition of net evaporation flux δ_E as it cannot be directly measured. The boundary layer flux model developed by Craig and Gordon (1965) can be applied to estimate the isotopic composition of evaporating water as a function of other more readily determined physical parameters as in the following model equation.

$$\delta_E = \frac{(\alpha^* \delta_L - h\delta_A - \varepsilon)}{(1 - h + 10^{-3} \Delta\varepsilon)}$$ Equation 7.4

Where $\alpha^*(=1/\alpha)$ is the equilibrium liquid-vapor isotope fractionation at the kinetic temperature of evaporating surface (α is equal to 1.0098 for $\delta^{18}O$ at 25°C. δ_A is the isotopic composition of ambient moisture, and h is relative humidity normalized to kinetic temperature of the evaporating surface; ε is total isotopic separation factor which is the sum of the equilibrium (ε^*) and the kinetic ($\Delta\varepsilon$) separation factors.

The above equation requires the knowledge of isotopic composition of atmospheric moisture (δ_A) above the lake, air temperature, lake surface temperature and relative humidity. The isotopic composition of atmospheric moisture (δ_A) can be determined through different available method depending on local geographic and climate conditions and the time availability and financial conditions.

The other method of evaluating δ_E is by using a terminal lake that has no surface and groundwater outflow. The isotopic composition of a given lake is not only controlled by meteorological factors but also by hydrology of the given lakes.

Of the four permanent lakes in the basin lake Abiyata is used as a terminal lake for the study area as it lacks any considerable surface and ground outflows and evaporation is the only way of water loss from the lake. The terminal feature of the lake Abiyata is also evidenced by its highly enriched $\delta^{18}O$ and its very high salinity.

The application of index lake method is valid only for lakes, which are in hydraulic and isotopic steady state. A hydrologic steady state may be a valid assumption if a long-term (example annual) water budget is sought for-as it is done in this work.

It is also proper to apply the index lake method to geographically clustered lakes that meet the requirement of being isotopic steady state. They should plot along the same evaporation line if they are indeed affected by the similar atmospheric conditions and similar hydraulic residence time. Lakes in the Ziway-Shalla basin meet these conditions as it can be seen from **figure 32** where the average isotopic composition of the lakes in the basin plot along the evaporation line at regression coefficient of r^2=0.997.

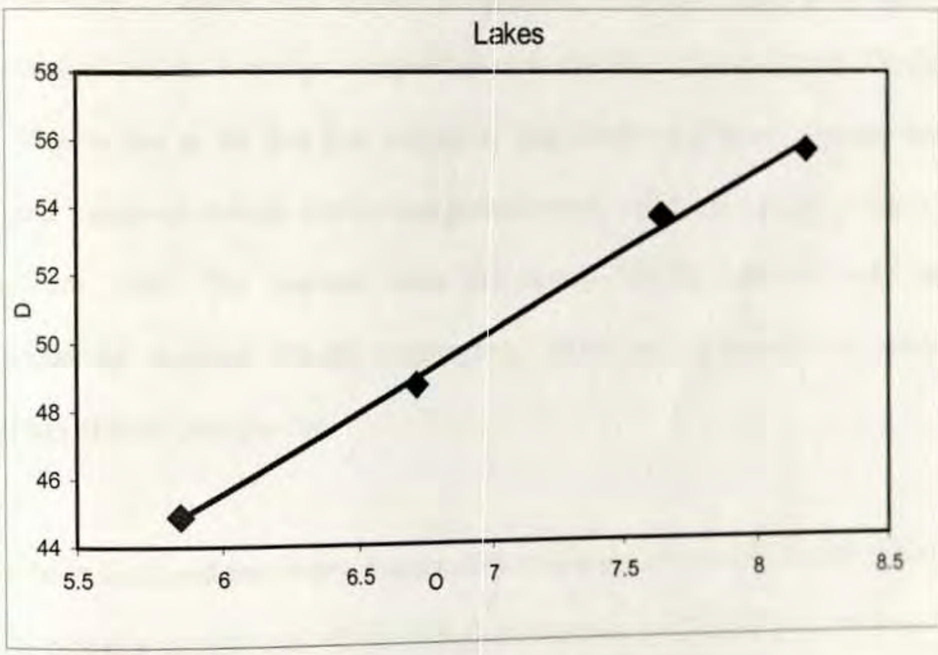


Figure 32. Evaporation line of the four lakes in the basin

Therefore Index lake method may be suitably applied to constrain the water budget of the lakes by using terminal lake Abiyata as Index Lake. This provides an opportunity to solve the isotope balance with out measuring the necessary environmental parameters.

Total inflows to lake Abiyata are equal to total output through evaporation and the isotopic composition such a terminal lake is in balanced state of total inflows and outflow and approach steady state value so that

$$\delta_E = \delta_I \quad \text{(Dincer, 1968)}$$

Where δ_I is weighted isotopic composition of total inflows.

The weighted average of $\delta^{18}O$ composition of all inputs to lake Abiyata is computed and it is found to be +2.32‰. The isotopic composition of average inputs to the lake is highly enriched relative to isotopic composition of local precipitation and most of surface waters. This is due to the fact that Abiyata is interconnected to both upstream lakes (Ziway and Langano) through surface and groundwaters, which are already enriched in the upstream lakes. The upstream lakes are mainly fed by meteoric water and characterized by depleted isotopic composition, which are comparable to isotopic composition of local precipitation.

As it has been discussed previously, fractionation of isotopes of the same elements during evaporation is due to combined effects of both equilibrium and kinetic fractionation. So total isotopic separation factor is the sum of the equilibrium (ε^*) and the diffusion controlled kinetic ($\Delta\varepsilon$) separation factors.

$$\varepsilon = \varepsilon^* + \Delta\varepsilon$$

ε^* Is a convenient way to express fractionation factors (α^* or α) in per mil,

$\varepsilon^*=1000\ (1-\alpha^*)$.

The kinetic fractionation factor is given by the relation $\Delta\varepsilon = K\ (1-h)$. Where K has been empirically determined to be 14.3‰ (Gonfiantini, 1986) for $\delta^{18}O$ and h is relative humidity normalized to kinetic temperature of the evaporating surface.

By using the weighted isotopic composition of inflows to lake Abiyata (δ_I = +2.32‰= δ_E) and inserting it in to the above equations the required environmental parameters were constrained.

By inserting δ_E = +2.32‰ into equation 7.4, the unknown δ_A, isotopic composition of the atmospheric moisture is estimated to be -16.8‰. Seifu Kebede *et al.* (2002) estimated δ_A to be –12‰ for the Ethiopian highland region and Gonfiantini *et al.*, (1973) found a value of δ_A to be -15‰ for the Afar depression by using lake Giulietti as a terminal index lake. The isotopic composition of atmospheric moisture (δ_A) in the lakes region is reasonably closer to the values, which was determined for Afar. The δ_A value of this work is relatively depleted compared to previous works.

This may be due the fact that the basin is characterized by large open water bodies (i.e. 8 % of the total area) which can favor continuous depleted water vapor input into the atmosphere through evaporation. If the contribution of lake evaporative flux to local budget of atmospheric moisture is significant, the isotopic composition of atmospheric water above the lake will be modified from the regional value and the modification is as a factor of degree of turbulent mixing in the atmosphere (Mook, 2000).

The estimated environmental δ_A value has been used in calculating the limiting isotopic composition, δ^* for Ziway - Shalla basin. The limiting isotopic composition is the maximum enrichment an evaporating water attains under a given environmental condition. The limiting isotopic composition is given by:

$$\delta^* = \delta_A + \varepsilon / h$$

Where δ_A is isotopic composition of the atmospheric moisture and h is relative humidity normalized to kinetic temperature of the evaporating surface. The limiting isotopic composition for the study area is determined to be 12.5 ‰. This value is comparable to the most alkaline and enriched $\delta^{18}O$ of Crater Lake in the basin, Chitu, characterized by isotopic composition of 10.49 ‰ and reflect large evaporative loss relative to its total inflows (Craig *et al.*, 1977).

Using the assumptions made above and using equations 7.4 and 7.3 a mathematically more manageable simple equation can be derived (equation 7.5). This is similar to the equation derived by Gat and Levy (1978) for a study of lakes isotope budget.

$$\frac{I}{E} = \frac{h}{1-h}\left(\frac{\delta^* - \delta_L}{\delta_L - \delta_{in}}\right) \qquad \text{Equation 7.5}$$

Where $I = P + R_{in} + G_{in}$,

δ_{in} is the weighted average isotopic composition of all inflows to the given lake.

h is relative humidity normalized to kinetic temperature of the evaporating surface.

δ_L is mean isotopic composition of the well-mixed lakes

δ^* Is the limiting isotopic composition, which is the isotopic enrichment value approached by residual waters of shrinking water and determined to be 12.5 ‰.

By inserting all the necessary parameters into the above equations the water budget of the lakes are determined (**table 6**). The result shows that the lakes are influenced by different degree of groundwater flux **(table 7)**.

9.2.1. Lake Abiyata

As Abiyata is a terminal lake water balance is solved by substituting $G_0 = 0$. The main input to Abiyata Lake is inflow through Horakello and Bulbula Rivers and direct precipitation on the lake both account for more than 90% of the total input. The only output from the lake, evaporation is estimated to be 290.97mcm annually. The groundwater input to the lake is determined to be about 14 mcm annually that accounts 4.78 % of the total inputs to the lake. The groundwater flux that enters into lake Abiyata should come from lake Ziway through the lacustrine deposit and through the faults as it can be seen from enriched isotopic results from the wells, which are located between them.

9.2.2. Lake Ziway

As it is located at the highest altitude in the basin, 60% of its input comes from the rivers that drain the highland from either side of the rift and 31.4 % of the inputs for Ziway comes from direct precipitation on the lake. Annual groundwater inflow into the lake is computed to be 83.92 mcm that accounts 7.28% of the total inputs. Lake Ziway flows out into lake Abiyata through Bulbula River and it accounts for 10.8 % of the total water loss from the lake and the same amount of water is lost from the lake through groundwater outflow, which is 121.04 mcm.

	INFLOW				*OUTFLOW*			
Lakes	**P**	**Ri+Sr**	**Gin**	**I**	**E**	**Ro**	**Go**	**O**
Abiyata	97.18	179.87	13.92	291.0	290.97	0	0	290.97
Ziway	361.88	707.19	83.92	1153.0	906.95	125.47	121	1153.46
Langano	152.96	212.00	107.72	472.7	420.36	48.95	3.376	472.68
Shalla	219.42	224.96	140.75	585.1	585.12	0.00	0	585.12

Table 6. Water Budget of the lakes in mcm , where O is the total outflow from the lake

9.2.3. Lake Langano

The direct precipitation on the lake estimated to be 152.96 mcm as there is no discharge data for Feeder Rivers into the lake total annual inflow from rivers and remaining Small Rivers is estimated to be 212 mcm (Tenalem Ayenew, 1998). The groundwater input to the lake is calculated to be 107.72 mcm that accounts 22.8 % of the total input to the lake. There is significant groundwater input to the lake and this could be the reason for more or less stable nature of water level of lake Langano relative to the other two lakes mentioned above. Surface outflow from lake Langano through Horakello River is 10.36 % of the total output but the groundwater output from the lake is only 0.71 % of the total output.

9.2.4. Lake Shalla

Lake Shalla is the deepest lake in Ethiopia and characterized by high scarcity of data, as there is no meteorological and lake level measurement over the lake. Most of the samples, which are used in this study, are surfacial by assuming that there is no stratification as the samples from different depth of the lake Shalla are essentially uniform (Craig *et al.*, 1977). The shortage of all relevant data for the lake and its depth pose a limitation on the accuracy of the water budget.

Direct precipitation and surface inflows count for 75.95 % of the total input to lake Shalla while the remaining 24.05 % is contributed from the groundwater input which is calculated to be 140.75 mcm annually and the role of groundwater is significant for Lake Shalla.

Lakes	Gin %	Go %
Abiyata	**4.78**	**0**
Ziway	**7.28**	**10.49**
Langano	**22.79**	**0.71**
Shalla	**24.05**	**0**

Table 7. Percentage of groundwater inflows and outflows of the lakes

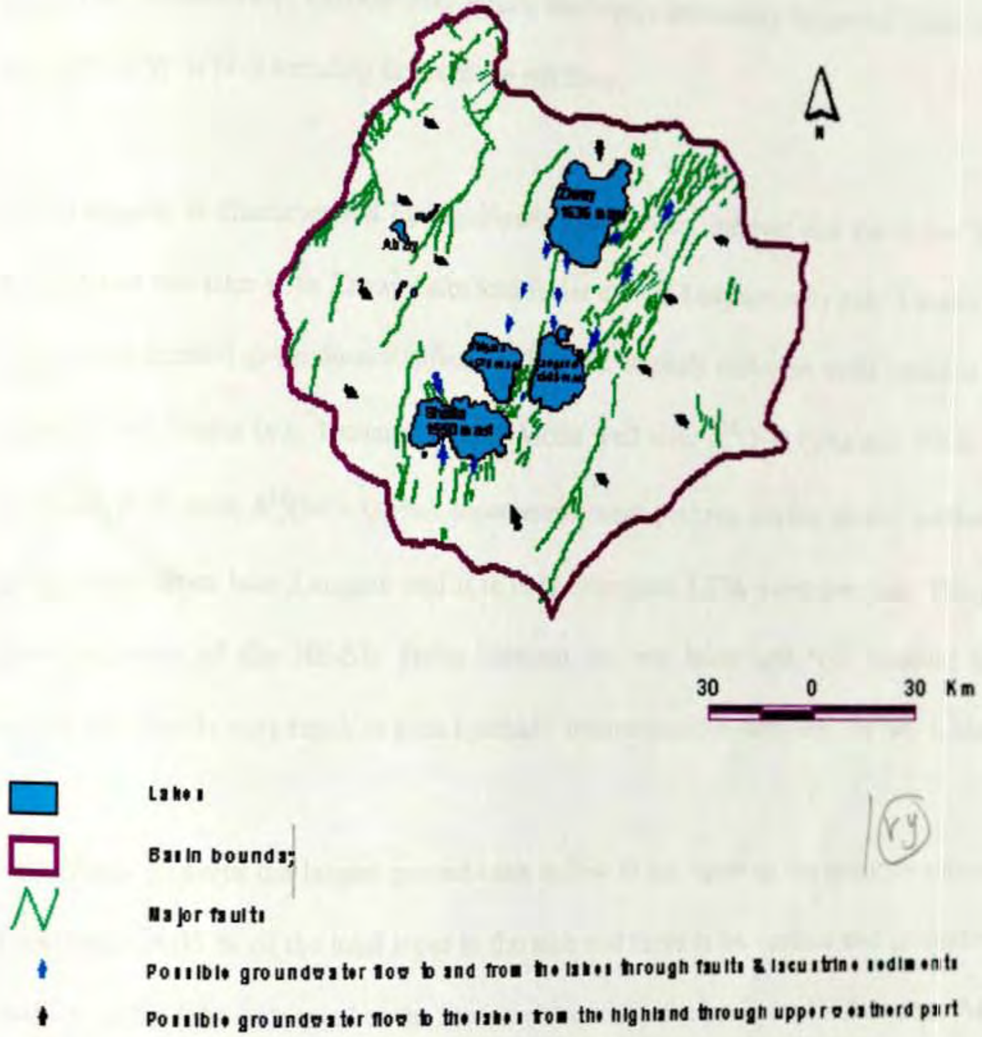


Figure 33. Possible groundwater flow to the lakes

Among the four permanent lakes in the basin Lake Ziway is characterized by significant groundwater outflow. This may be due to its higher elevation in the basin i.e. 1636 m.a.s.l and the outflow from the lake contribute to groundwater inflows into the two downstream lakes. This groundwater outflow may follow the highly permeable lacustrine deposit and recent NE-SW or N-S trending faults in the rift floor.

Lake Langano is characterized by significant groundwater inflows and the major faults that connect the lake with Ziway Lake and faults east of Langano may play a major role in fractured control groundwater inflow to the lake. Slightly enriched wells between lake Langano and Shalla (e.g. Langano Bekele Molla well with $\delta^{18}O=0.02‰$ and Wilde Life Langano Well with $\delta^{18}O= - 0.5‰$) show enrichment perhaps owing to the outflow of groundwater from lake Langano and it is only estimated 3.376 mcm per year. The poor interconnection of the NE-SW faults between the two lakes and N-S trending faults around lake Shalla may result in poor hydraulic interconnection between the two lakes.

Lake Shalla receives the largest groundwater inflow in the basin as the groundwater input contributes 24.05 % of the total input to the lake and there is no surface and groundwater outflow as the lake is located at the lowest elevation in the basin i.e.1550 m.a.s.l. As the groundwater outflow from Lake Langano is small and there is no groundwater outflow from Lake Abiyata, the large groundwater inflow most probably comes from other adjacent basins (e.g. Lake Awassa basin) through the faults that are located south of the lake.

CHAPTER TEN

Discussion and Conclusion

The study area is topographically differentiated into rift valley containing the lakes bordered by escarpments and two highlands as a consequence of the volcano-tectonic process. In the basin rainfall and temperature show strong altitudinal variation. Annual mean rainfall varies from about 1150 mm in the highlands to about 650 mm in the rift and temperature varies from 15 C^0 of the highlands to $20C^0$ is the rift. The seasonal drifting of the Inter Tropical Convergence Zone mainly controls the seasonal variation in rainfall. The rift floor of the basin contains four residual lakes, lake Ziway, Abiyata, Langano and Shalla and their open water evaporation estimated to be 1875.8, 1829.8, 1856.2, and 1834.4 mm respectively.

The major rivers rise from the plateau on either side of the rift valley and tend to follow generally southern direction into permanent and terminal lakes. Bicarbonate is dominant anion while the dominant cation of the rivers is as a factor of the geology of the reservoir. Most of the rivers plot above LMWL may be related to the importance of isotopically depleted summer rain or highland waters in feeding the rivers. In small rivers local precipitation event is very important in determining their isotopic composition as they are close to LMWL. For larger rivers isotopic composition of local precipitation is reflected near the head of the streams but near their downstream, modification of $\delta^{18}O$ can be observed due to the input of different isotopic composition. The chemical and isotopic compositions of the rivers are similar to the lakes if they are spill from the lakes.

Although all the lakes are dominated by Sodium and Bicarbonate, their salinity and pH are significantly different. This phenomenon is observed despite their proximity. This is most likely related to their hydrological setting. Since the salinity and pH of the lakes increase as the tightness of the lakes increases. Tightness determines the residence time of the system. The isotopic composition of the lakes show that they are enriched which respect to local meteoric line and they are in the state of evaporation with respect to the present day precipitation. The lakes plot on a local evaporation line defined by $\mathbf{\delta D = 5.75\delta^{18}O + 8.63}$.

The groundwater chemistry of the basin shows variation from the highland and escarpment toward rift floor. The alkalinity and salinity of the groundwater tend to increase toward the rift, which can be due to the groundwater chemical evolution as it moves from the recharge area in the highland to the discharge area in the rift or due to the influence of the alkaline lakes. Groundwater between the lakes is characterized by a salinity similar to the lakes.

All cold springs and some well samples plot above the Local Meteoric Water Line, which may be due to the fact that isotopically depleted summer rain is important in recharging the aquifer or the recharge takes place in higher altitude. Wells that are found between the lakes in the rift floor are enriched with respect to their inputs and plot on groundwater-lake mixing line. The fact that the groundwater between the lakes is characterized by higher salinity and isotopic composition similar to the lakes and their plot along the mixing line indicate the hydraulic link among the lakes and between the lakes and surrounding aquifer.

The existence of a terminal lake (Lake Abiyata) in the basin gives an opportunity to estimate the environmental parameters of isotope balance.

The unknown δ_A, isotopic composition of the atmospheric moisture is estimated to be -16.8‰ which is comparable to δ_A values of previous works. The limiting isotopic composition (δ^*) for Ziway - Shalla basin determined to be 12.5 ‰, which is comparable to isotopic composition of the most alkaline Crater Lake in the basin, Chitu.

From the stable isotope water budget of the lakes, lake Langano and Lake Shalla are characterized by significant groundwater inflow while lake Abiyata is typified by the smallest groundwater inflow. Lake Ziway is characterized by considerable groundwater outflow while lake Langano is affected only by small groundwater outflow.

The result of stable isotope water balance shows that the lakes are influenced by different degree of groundwater flux .The groundwater inflow to lake Ziway can be attributed to the groundwater inflow from the eastern highland and through the fractured zone that are concentrated east of the lake. The considerable groundwater outflows from lake Ziway become the groundwater inflow to lake Abiyata, which can be either through the lacustrine sediments between them or through the buried paleovalley, which is 15 km long, 2km wide and 3m deep narrow trough.

The groundwater inflow into lake Langano from lake Ziway may take place through the NNE-SSW trending faults between the two lakes. Lake Langano can also get groundwater through the Wonji fault belt, which is found east of the lake or through the groundwater flow from the eastern highland. The low groundwater inputs to lake Abiyata can be due to absence of well-interconnected fractures around the lake and the groundwater flow is forced to flow through lacustrine sediments in diffuse flow manner.

There is significant elevation difference between lake Langano and Shalla but according to the stable isotopic evidence there is only modest groundwater outflow from lake Langano. This can be due to the poor interconnection of the fractures between the two lakes or impermeable nature of the Shalla caldera.

Lake Shalla is characterized by the highest groundwater inflow into it as it is found at the lowest elevation. The groundwater inflow to lake Shalla is most likely through the faults around the lake and through the trans-basin groundwater inflow from Awassa basin. The presence of N-S trending negative bouger anomaly from the southeastern rim of Corbetti caldera to the shore of lake Shalla ((Jihad, 1980) as cited in Tenalem Ayenew 1998) may indicate the existence of thick lacustrine sediments, which may act as groundwater conduit from lake Awassa to lake Shalla.

Perspectives

The isotopic data, which have been used in this study, are collected by different researchers at different time in non-systematic manner. Systematic way of data collection for determination of the isotopic composition of all waters type in the basin should be done in the future for a better understanding of the lakes isotope budget. New rainfall sampling stations may be required in order to calibrate a more realistic LWMW. Comparison of the results obtained in this work with other regions such as Afar and the Northwestern Ethiopian Plateau may help to test the validity of the environmental parameter estimated in this work in a regional context.

The shortage of data on ungauged rivers and lack of lake level data for lake Shalla should be solved in future. The groundwater flow system of the basin needs further detail work, as it is complex to understand thoroughly due to the complexity of the geological setting of the basin.

Some previous works indicate the influence of a regional groundwater outflow from the Ziway-Shalla basin to the Awash Basin. To test this hypothesis isotope hydrological tracing around the upper Awash basin may be useful. This may have an implication in groundwater and geothermal waters recharge in the lower Awash basin. Detailed monitoring sampling and isotopic study between lakes Shalla and Awassa may be useful to test the basin scale hydraulic link between them.

REFERENCES

1. Baumann, A., Forestner, U., and Rohde, R. (1975). Lake Shalla: water chemistry, mineralogy and geochemistry of sediments in an Ethiopian Rift lake. Geologische Rundschau. **64**: 593-609.

2. Benvenuti, M., Carnicelli, S., Belluomini, G., Daninelli, N., Grazia, S.D., Ferrari, G.A., Iasio, C., Sagri, M., Ventra, D., Balemwal Atnafu and Seifu Kebede (2002). The Ziway-Shalla lake basin (Main Ethiopian Rift, Ethiopia): a revision of basin evolution with special reference to Late Quaternary. Journal of African Earth Science. **35**: 247-269.

3. Birhanu Gizaw (1996). The origin of high bicarbonate and fluoride in the Main Ethiopian Rift Valley, East African Rift system. J. African Earth Sci. **22**: 392-402.

4. Boccaletti, M., Bonini, M., Mazzuoli, R., Bekele Abebe, Piccardi, L., Tortorici, L. (1998). Quaternary oblique extensional tectonics in the Ethiopian Rift. Tectonophysics.**287**: 97-116.

5. Clark, I. & Fritz, P. (1997). Environmental Isotopes in Hydrogeology. Lewis Publishers, New York, USA. 327pp.

6. Craig, H., Lupton, J.E. and Horowiff, R.M. (1977). Isotope Geochemistry and Hydrology of geothermal waters in Ethiopian Rift Valley. Scripps Inst of Oceanography. Univ. of California report, 160pp.

7. Dagnachew Legesse (2002). Analyse De La Reponse Hydrologique du bassin lacustre De Ziway-Shalla (Rift Ethiopien) Aux Changements du Climat Et Des Activites Humaines. PhD thesis. Universite de De Deroit, D' Aix- Marseille.

8. Daniel Gemechu (1977). Aspects of climate and water budget in Ethiopia. Addis Ababa University Press. Addis Ababa. 71pp.

9. Dansgaard, W. (1964). Stable Isotopes in Precipitation. Tellus. **164** : 436-468.

10. Darling, W.G. (1996). The geochemistry of fluid processes in Eastern Branch of the East African Rift System. PhD thesis. British geological Survey.

11. Dincer, T. (1968). The use of oxygen 18 and deuterium concentrations in the water balance of lakes. Water Resource Res. **4**: 1289-1306.

12. Dingman, S.L. (1994). Physical Hydrology. Printice Hall Inc, New Jersey, USA.575pp.

13. Di Paola, G.M. (1972). The Ethiopian Rift valley (between 7°00'- 8°40' Lat North). Bull. Volcanology. **36** : 517-560.

14. Dunne, T. & Leopold, L. B. (1978). Water in environmental planning. Freeman and Co., San Francisco, USA. 818 pp.

15. Freeze, R. A. & Cherry, J. A. (1979). Groundwater. Prentice - Hall, Englewood cliffs, N.J., USA. 604pp.

16. Gat, J.R. & Levy, Y. (1978). Isotope hydrology of inland Sabkhas in Bardawil area, Sinai. Limnol. Oceanogr. **23**: 841-850.

17. Gezahegne Yirgu, Dereje Ayalew, Peccerillo, A.., Barberio, M.R., Donato, P. (1999). Fluorine and chlorine distribution in the volcanics rocks from the Gedemsa volcano, Ethiopian Rift Valley Acta.. Vulcanologia **11**: 169-179.

18. Gidaye Woldegabriel, Aronson, J.L. and Walter, R.C. (1990). Geology, geochronology and rift basin development in central sector of the Main Ethiopian Rift. Geological society of America Bulletin. **102**: 439-458.

19. Gilbert, E., Travi Y., Massault, M., Tesfaye Chernet, Barbecot, F. and Defarge, F.L. (1999). Comparing carbonate and organic AMS ^{14}C ages in lake Abiyata sediments (Ethiopia). Hydrochemistry and paleoenvironmental implications. Radiocarbon. **48**: 271-286.

20. Gonfiantini, R., Borsi, S., Ferrara, G. and Panichi, C. (1973). Isotopic composition of waters from the Danakil depression (Ethiopia). Earth Planet. Sci.Let. **18**: 13-21.

21. Grove, A.T., Goudine, A.S. (1971). Late quaternary lake levels in the rift valley of southern Ethiopia and elsewhere in tropical Africa. Nature. **234**: 433-405.

22. HALCROW. (1989). Rift valley lakes integrated natural resource development master plan. Ethiopian valley development studies, unpublished report.

23. Hem, J.D. (1992). Study and interpretation of the chemical characteristics of natural water. Third edition, US Geological Survey water supply paper 2254, Washington, 264pp.

24. Krabbenhoft, D.P., Bowser, C.J., Kendall, C. and Gat, J. (1994). Use of oxygen-18 and deuterium to asses the hydrology of groundwater - lake system. Environmental chemistry of lakes and reservoirs, American chemical society, USA.

25. Makin, M. J., Kingham, T. J., et al. (1975). Development prospects in the southern rift valley Ethiopia. Tolworth, Land resource Division, U.K. Min. Overseas Development. 270pp.

26. Mazor, E. (1997). Chemical and isotopic groundwater hydrology. Marcel Dekker, Inc., New York, USA. 409pp.

27. McKenzie, J.M., Siegel, D.I., Patterson, W. and McKenzie, D.J. (2001). A geochemical Survey of spring water from the Main Ethiopian Rift valley, Southern Ethiopia: implication for wellhead protection. Hydrogeology journal. **9**: 265-272.

28. Mhor, P.A. (1962). The Ethiopian rift System. Bulletin of the Geophysics. Obs. Addis Ababa University. **3**: N.1, 33-62.

29. Morbidelli, S.L. & Piccirillo, E.M. (1972). Tectonics and Volcanism in the Main Ethiopian Rift (preliminary report). Boll.Soc. Geol. It. **92**: 273-286.

30. Mohr, P. (1970). The Geology of Ethiopia. Addis Ababa University press. 1-268.

31. Mook, W.G. (2000). Environmental isotopes in the hydrological cycle. Principles and applications, Technical documents in hydrology. **Vol 1** UNESCO, Paris. 280pp.

32. Mook, W.G., Rozanski, K. and Froehlich, K. (2000). Environmental isotopes in the hydrological cycle. Principles and applications, Technical documents in hydrology. **Vol III** UNESCO, Paris. 117pp.

33. Rozanski, K., Araguas-Arguas, L. and Gonfiantini, R. (1996). Isotope pattern of precipitation in East Africa. *In* the Limnology, Climatology and Paleoclimatology of East African Lakes.

34. (Johnson, T.C. and Odada, E.o eds), Gordon and Beach pub. Canada. pp664.

35. Seifu Kebede (1999). The hydrology and hydrochemistry of the Bishoftu Crater lakes (Ethiopia), Hydrological and Isotope water balance modeling. Unpublished Msc. thesis, Addis Ababa University.

36. Seifu Kebede, Tenalem Ayenew and Mohammed Umer (2001). Application of Isotope and water balance approaches for the study of hydrological regime of the Bishoftu Crater lakes, Ethiopia. SINET Ethiop. J. Sci. **24**(12): 151-166.

37. Seifu Kebede, Lamb, H., Telford, R., Leng, M. and Mohammed Umer (2002). Lake – groundwater relationships, Oxygen isotope balance and climate sensitivity of the Bishoftu crater lakes, Ethiopia. The East African great lakes: Limnology, Paleolimnology and Biodiversity. 261-275.

38. Seifu Kebede, Travi, Y. (2003). Comment on article entitled 'a geochemical Survey of spring water from the Main Ethiopian Rift valley, Southern Ethiopia: implication for wellhead protection'. Hydrogeology journal, DOI 10.1007/s10040-003-0251-y.

39. Schoell, M. and Faber, E. (1976). Survey on the isotopic composition of waters from NE Africa. Geol. Jahrb. D17: 197-213.

40. Shaw, E.M. (1994). Hydrology in Practice. Third edition, Chapman and Hall, New York, 569pp.

41. Street - Perrott, F.A. (1982). Twentieth century fluctuation in lake level in the Ziway-Shalla, Ethiopia. Paleoecology of Africa.15: 99-110.

42. Tamiru Alemayehu (2000). Water pollution by natural inorganic chemicals in the central part of the Main Ethiopian Rift. SINET Ethiop. J. Sci. **23**(2): 197-214.

43. Tenalem Ayenew (1998). The Hydrological system of Lake District basin, Ethiopia. Ph.D. Thesis, ITC, Enschede, The Netherlands. 259pp.

44. Tenalem Ayenew & Tamiru Alemayehu (2001). Principle of Hydrogeology. Department of Geology & Geophysics, Addis Ababa University. 125pp.

45. Tesfaye Chernet (1982). Hydrogeology of lakes region, Ethiopia (Lake Ziway, Langano, Abiyata, Shalla and Awassa). Unpublished report, Ethiopian Institute of Geological Survey. 97pp.

46. Tesfaye Chernet (1988). Hydrogeological map of Ethiopia. Ethiopian Institute of Geological Surveys. Ministry of Mines and Energy, Printed by Eth. Mapping Auth., Addis Ababa.

47. Tesfaye Chernet (1998). Etude des mechanisms de mineralization en fluorure et elements associes de la region des lacs du rift Ethiopie. PhD thesis. University of Avignon.

48. Tesfaye Chernet (2002). Mechanism of degradation of quality of natural water in the lake region of the Ethiopian Rift Valley. Wat. Res. Vol. 35. No. 12: 2819-2832.

49. Tsegaye Abebe (2002). Geological limitation of a geothermal system in a continental rift zone: Example the Ethiopian Rift Valley. Proceedings World Geothermal Congress, Kyushu-Tohoku, Japan.

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

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

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

53. Yin, X. and Nicholson, S. E. (1999). The water balance of Lake Victoria. Hydrological Science. **43**(5): 789-809.

Annex 1 Meteorological data of the Ziway-Shalla basin

Rainfall mm

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Arsi	9.3	46.3	69.3	64.2	86.7	91.5	127.9	102.3	121.1	56.1	3.9	13.1
Bulbula	15.9	40.2	51.0	69.2	66.5	69.0	134.7	98.8	68.8	33.2	6.7	2.7
Koffele	35.2	58.4	124.0	152.6	113.5	111.4	142.3	156.4	153.2	95.8	46.9	27.3
Ke-Abure	4.5	24.8	45.1	74.9	93.2	101.7	132.2	128.9	106.0	43.2	3.6	4.7
Sagure	13.4	29.3	58.8	70.2	81.4	96.5	157.7	152.4	75.3	39.6	14.1	3.7
Munessa	27.8	77.0	114.6	146.2	123.3	121.7	194.1	170.6	182.7	81.1	28.7	18.0
Ziway	15.2	33.2	54.2	72.5	75.1	85.9	146.3	115.9	95.0	46.6	2.6	3.6
Kyera mi	20.6	44.6	70.2	102.4	88.9	101.1	123.5	109.6	131.6	72.3	28.1	11.6
Kyera	20.6	44.6	70.2	108.1	88.9	97.7	124.2	107.7	136.4	77.5	26.1	10.7
Kosh	20.3	62.4	73.6	102.5	101.5	96.5	178.7	182.3	116.4	47.3	4.3	5.1
Bekoji	27.3	51.2	74.9	104.8	99.4	114.2	184.5	193.7	88.2	55.3	16.5	13.6
HaroKell	13.0	14.5	65.4	182.9	128.1	25.1	10.7	4.5	43.6	134.1	45.1	7.6
Assela-s	11.5	39.9	88.1	124.0	106.7	142.2	178.1	171.2	143.5	69.4	19.3	14.5
Kulumsa	18.9	43.6	87.3	78.4	91.6	90.4	127.9	127.0	101.6	39.2	13.5	9.2
Mararo	36.3	47.7	71.0	105.6	93.8	91.1	190.8	191.2	91.3	48.4	22.0	15.1
Shasheme	24.6	41.2	79.7	108.8	112.8	81.6	99.1	122.9	133.8	84.5	22.3	16.9
Abiyata	11.9	45.3	47.4	66.7	77.0	82.3	105.5	71.8	71.4	24.3	1.9	5.5
Adamitul	24.6	40.1	50.3	61.2	65.7	84.0	127.7	157.3	70.2	28.1	5.1	4.2
Langano	18.8	20.7	35.2	58.8	73.1	94.6	129.4	106.9	82.0	40.8	8.4	8.3
Shasheme	25.3	38.7	78.7	120.6	118.1	77.4	109.4	118.5	132.1	88.3	23.2	16.7
Wulberg	22.7	63.0	82.9	130.2	155.8	150.5	225.7	201.7	157.8	57.7	11.9	7.2
Silte	59.2	110.3	195.3	80.2	97.9	114.3	177.9	255.2	151.9	57.2	6.5	12.5
Meki	12.9	50.3	54.9	58.1	63.6	76.4	169.1	152.0	87.6	38.0	7.1	1.2
Mitto	10.7	61.4	83.1	121.1	83.3	70.8	112.7	115.3	125.2	48.8	13.3	20.0
Butajira	36.3	70.1	128.2	126.0	113.5	115.5	169.4	159.6	113.0	47.0	11.1	10.9
Teji	16.5	38.3	54.5	72.4	63.4	110.8	219.6	215.5	104.2	26.8	7.4	6.6
Kersa	25.2	49.1	83.4	111.2	96.5	76.9	107.1	115.9	111.3	50.3	21.8	12.0

Humidty

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Mean
Sagure	78.9	81.6	81.9	86.9	89.1	89.5	91.9	93.4	90.7	88.4	89.5	80.1
Adamitul	53.9	57.5	53.8	66.8	70.5	66.0	67.8	70.8	73.6	55.3	52.5	57.4
Mitto	32.1	43.0	45.0	62.8	63.3	63.5	67.8	74.3	73.5	57.8	61.3	53.7
Kulumsa	56.9	56.3	68.2	61.5	62.9	68.1	77.9	80.8	78.3	61.6	56.4	60.8
Bekoji	63.2	64.6	66.3	72.7	71.4	78.4	87.4	88.1	83.4	76.1	66.0	68.1
Kore	77.7	81.5	81.7	77.9	75.5	77.2	90.4	90.8	89.5	86.0	82.3	75.9
Meraro	61.7	65.1	56.6	66.4	68.0	71.6	81.3	83.1	78.8	75.6	67.6	64.6
Koffle	64.0	60.7	72.0	68.3	51.7	54.0	87.8	86.3	84.7	83.8	71.8	65.4
Ziway	71.8	68.9	70.5	72.4	74.0	74.7	79.9	80.8	80.3	73.0	69.7	68.0
C Amba	40.2	45.1	40.9	48.8	48.1	51.9	62.3	60.1	56.2	45.6	34.8	44.5
Abiyata	55.2	57.8	57.2	58.8	57.0	60.1	70.6	69.6	68.5	50.4	43.5	54.1
Langano	67.8	69.1	70.1	70.9	65.1	67.6	86.5	86.8	84.3	81.8	73.9	68.7
Shalla	61.5	63.5	63.6	64.9	61.0	63.9	78.5	78.2	76.4	66.1	58.7	61.4

Wind Speed m/s at 2m

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Langano	1.3	1.6	1.3	1.2	1.1	1.4	1.4	1.2	1.0	1.0	1.2	1.1
AdamiTul	2.5	2.5	2.2	2.1	2.5	2.7	2.8	2.2	1.7	1.9	2.2	2.7
Mitto	2.6	2.9	2.6	2.2	2.0	2.1	2.0	1.7	1.5	2.1	2.6	3.0
Abiyata	4.3	3.2	2.9	2.5	1.9	2.6	2.4	2.2	1.8	2.8	4.1	4.7
Kulumsa	2.6	2.5	2.3	2.2	2.2	2.0	2.3	1.8	1.4	2.8	3.0	2.8
Sagure	1.2	1.2	1.3	1.2	1.3	1.0	0.9	0.8	0.9	1.1	1.1	1.2
Meraro	2.7	2.9	3.1	3.3	3.0	2.0	1.8	1.7	2.1	2.7	2.9	2.8
Bekoji	2.5	2.3	3.3	3.1	2.7	1.7	1.4	1.3	1.5	2.0	2.6	2.4
Kore	1.6	1.5	1.7	1.6	1.4	1.2	1.2	1.0	1.0	1.3	1.4	1.5
C.Amba	1.9	1.9	1.6	1.6	1.4	1.7	1.6	1.3	1.2	1.6	1.9	2.2
Ziway	1.4	1.4	1.3	1.2	1.5	2.0	1.9	1.6	1.1	1.2	1.4	1.4

Sunshine hours

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Kulumsa	7.2	7.1	7.8	7.8	6.6	7.3	4.8	5.2	5.9	6.2	7.1	8.3
Bekoji	8.2	7.6	7.1	5.8	6.6	5.2	3.1	3.4	4.6	6.1	11.1	8.5
Meraro	8.5	7.4	8.0	6.8	7.5	6.3	4.7	5.0	5.8	7.6	8.5	9.1
Sagure	8.7	7.4	7.1	6.2	6.2	4.3	4.0	3.9	5.2	6.8	8.5	8.6
Kersa	7.9	7.3	7.4	6.6	6.8	6.2	4.1	5.0	5.3	5.4	9.2	9.6
Kore	8.4	6.9	6.7	4.9	5.8	5.4	2.9	3.4	4.0	5.4	7.5	8.7
C Amba	8.6	7.3	7.6	6.7	8.1	4.4	3.7	4.6	6.7	6.5	9.3	7.0
Abiyata	9.3	8.1	8.2	7.5	8.1	7.7	6.3	5.9	6.9	8.6	9.8	9.0
Ziway	9.5	9.2	8.0	7.8	8.5	7.7	6.0	6.1	7.3	9.2	9.7	9.6

Temperature

Station	Jan	Feb	Mar	April	May	June	July	August	Sept	Oct	Nov	Dec
Ziway	19.2	20.2	21.2	21.3	21.6	20.8	19.6	19.6	19.7	19.3	19.0	18.6
Kuyera	16.7	17.9	18.3	18.9	18.7	17.4	17.0	17.2	17.2	17.2	16.2	15.9
C.Amba	20.8	21.6	22.4	22.3	22.2	21.3	20.1	19.9	20.7	20.5	20.1	20.0
Butajira	18.2	18.6	19.2	19.1	19.0	18.4	17.6	17.7	18.4	18.5	17.6	17.9
AdamiTul	19.3	20.5	21.5	20.7	21.7	20.9	19.5	19.5	19.6	19.3	18.8	19.0
Langano	19.9	20.4	21.5	21.8	21.6	21.1	20.0	20.0	20.0	20.5	19.8	19.0
Kore	10.5	11.4	11.8	11.7	11.3	10.7	10.3	10.6	10.8	10.8	10.2	10.3
Munessa	12.2	13.4	14.1	14.2	13.3	12.5	12.0	11.9	12.3	12.2	11.9	10.0
Kofele	13.5	14.2	14.6	14.4	14.2	14.0	13.2	13.2	13.4	13.3	12.8	12.8
Sagure	12.9	13.8	14.4	14.3	13.8	13.2	12.6	12.6	12.9	12.8	12.3	11.4
Meraro	11.4	12.1	12.7	12.7	12.7	12.0	11.4	11.6	11.4	10.1	11.0	11.2
Kulumsa	15.7	16.8	17.9	18.4	18.2	17.3	16.2	16.0	16.0	16.7	15.9	15.4
Asela	13.9	15.1	15.9	16.3	16.4	15.7	14.8	14.6	14.5	14.8	13.7	13.5
Abiyata	21.1	20.7	22.1	22.1	21.2	20.7	19.6	19.6	19.8	20.4	20.8	19.9
Abure	19.5	19.9	21.1	21.4	21.7	20.8	19.8	18.8	19.4	20.0	19.3	19.1
Aje	19.5	20.3	20.9	20.8	20.6	20.4	19.6	19.5	19.4	19.4	19.7	19.6
Bekoji	13.9	14.5	14.9	14.5	14.3	13.2	12.1	12.2	12.6	12.7	13.1	13.5
Kersa	12.9	13.7	14.5	14.6	14.3	13.2	12.7	12.6	12.8	13.1	12.5	16.9
Shasheme	16.3	16.4	18.0	18.4	18.3	17.5	16.8	16.8	17.1	17.1	16.4	16.2
Silte	17.7	18.8	20.5	19.9	20.0	17.9	17.2	17.2	17.4	17.9	16.8	18.2
Wulberge	18.9	19.3	19.5	19.7	19.4	19.1	19.0	19.1	19.2	18.7	18.8	18.8

Annex 2 Chemical data of the Ziway-Shalla basin

in meq/l

LAKES

No	LAKES	Na	K	Ca	Mg	HCo3	Cl	SO4	F
1	Ziway	2.39	0.46	1.00	0.62	3.26	0.34	0.05	0.07
2	Ziway	3.96	0.41	1.00	0.64	4.72	0.35	0.06	0.07
3	Ziway	3.05	0.34	0.85	0.69	4.38	0.37	0.27	0.10
4	Abiyata	345.83	9.98	0.02	0.02	260.40	84.07	26.03	10.00
5	Abiyata	246.99	13.28	0.05	0.02	193.39	103.25	8.18	17.58
6	Abiyata	215.19	8.29	0.05	0.00	195.18	71.85	5.29	11.90
7	Abiyata	253.04	13.28	0.50	3.60	251.79	74.87	0.00	0.02
8	Abiyata	261.83	13.28	0.02	0.15	243.05	74.87	5.04	12.79
9	Abiyata	265.05	13.28	0.02	0.09	239.81	79.58	5.52	14.32
10	Abiyata	265.05	13.28	0.02	0.08	239.83	79.02	5.39	14.90
11	Langano	18.71	0.68	0.04	0.08	14.36	5.36	0.62	0.75
12	Langano	16.14	0.72	0.22	0.07	11.22	4.93	0.37	0.72
13	Langano	16.79	0.72	0.22	0.07	12.59	6.04	0.38	0.00
14	Langano	16.66	0.72	0.22	0.07	12.74	5.00	0.36	0.76
15	Langano	15.70	0.87	0.23	0.53	13.02	4.25	0.23	0.74
16	Langano	17.18	0.74	0.24	0.55	14.23	4.38	0.24	0.76
17	Langano	16.31	0.72	0.22	0.53	13.30	4.40	0.26	0.78
18	Langano	17.31	0.72	0.23	0.52	14.46	4.29	0.25	0.75
19	Langano	17.05	0.72	0.24	0.53	14.20	4.27	0.24	0.77
20	Langano	18.53	0.72	0.22	0.53	15.68	4.25	0.24	0.76
21	Langano	16.79	0.72	0.28	0.56	13.94	4.27	0.25	0.77
22	Shalla lac	159.91	7.49	0.05	0.01	173.86	83.70	2.85	14.11
23	Shalla lac	295.80	7.16	0.05	0.01	273.25	78.71	2.64	15.48
24	Shalla lac	289.80	7.49	0.02	0.13	255.07	80.57	3.16	16.95
25	Shalla lac	284.84	7.49	0.03	0.11	274.20	69.45	2.18	13.48
26	Shalla lac	310.11	7.49	0.02	0.12	285.58	79.95	2.69	16.58
27	Shalla lac	289.28	7.03	0.02	0.04	205.69	75.60	13.53	10.00
28	Chitu	859.13	48.35	0.01	0.01	676.98	179.13	86.40	13.16

RIVERS

No	RIVERS	Na	K	Ca	Mg	HCo3	Cl	SO4	F
1	Gonde	0.20	0.07	0.29	0.19		0.2003	0.00	0.00
2	Simba	0.27	0.05	0.24	0.04		0.2003	0.00	0.00
3	Wolchesa	0.30	0.09	0.28	0.12		0.299	0.00	0.00
4	Anko	0.22	0.03	0.12	0.10		0.2003	0.00	0.00
5	Kompolcha	0.20	0.03	0.16	0.07		0.1608	0.00	0.00
6	Dusha	0.15	0.06	0.41	0.01		0.299	0.00	0.00
7	Eliena	0.20	0.03	0.16	0.05		0.2003	0.00	0.00
8	Bilatu	0.19	0.05	0.20	0.07		0.2003	0.00	0.00
9	Alaltu	0.22	0.05	0.16	0.01		0.4006	0.00	0.00
10	Katijama	0.22	0.04	0.24	0.08		0.299	0.00	0.00
11	Sagure Aleltu	0.30	0.04	0.28	0.12		0.299	0.00	0.00
12	Ashebeka	0.24	0.03	0.28	0.07		0.1608	0.00	0.00
13	Temala	0.26	0.04	0.26	0.10		0.299	0.00	0.00
14	Gusha	0.30	0.05	0.36	0.12		0.2398	0.00	0.00

RIVERS

NO	SOURCE-CODE	Na	K	Ca	Mg	HCO3	Cl	SO4	F
15	Woshe	0.33	0.06	0.32	0.18				
16	Sida	0.24	0.04	0.28	0.15		0.2003	0.00	0.00
17	Sirba	0.28	0.04	0.39	0.08		0.299	0.00	0.00
18	Upper Ketar	0.26	0.06	0.28	0.12		0.299	0.00	0.00
19	Kersa	0.21	0.04	0.24	0.04		0.299	0.00	0.00
20	Teji	0.23	0.04	0.24	0.04	0.40	0.1495	0.00	0.00
21	Matana	0.24	0.04	0.20	0.07	0.35	0.2003	0.00	0.00
22	Delali	0.19	0.03	0.08	0.04	0.45	0.1495	0.00	0.00
23	Mekanesa	0.23	0.04	0.22	0.04	0.45	0.1495	0.00	0.00
24	Guna	0.21	0.03	0.21	0.06	0.25	0.1495	0.00	0.00
25	Rajebo	0.28	0.05	0.24	0.16	0.35	0.1495	0.00	0.00
26	Gedemso	0.23	0.04	0.17	0.03	0.50	0.1495	0.00	0.00
27	Gedemso close langa	0.25	0.08	0.38	0.16	0.35	0.1495	0.00	0.00
28	Ajioftu	0.26	0.05	0.15	0.05	0.69	0.048	0.04	0.00
29	Lepis close to lang	0.31	0.06	0.17	0.05	0.35	0.1495	0.00	0.00
30	Hulka close to lepi	0.33	0.12	0.91	0.20	0.40	0.2003	0.00	0.00
31	Enkululu	0.22	0.06	0.85	0.09	1.51	0.0451	0.04	0.01
32	Tilku Debaba at ran	0.21	0.08	0.68	0.15	0.34	0.0705	0.04	0.00
33	Tinshu Debaba at ra	0.23	0.08	0.52	0.11	1.18	0.0282	0.06	0.00
34	Debaba at Adventist	0.29	0.09	0.10	0.12	0.93	0.0226	0.06	0.01
35	Tilku Debaba close	0.28	0.09	0.11	0.12	0.49	0.0423	0.06	0.00
36	Meki at Meki bridge	0.33	0.12	0.08	0.10	0.51	0.048	0.07	0.00
37	Ajemsa	0.45	0.20	0.11	0.14	0.56	0.0536	0.06	0.00
38	imzaf	0.13	0.03	0.35	0.16	0.70	0.11	0.12	0.00
44	Kulumsa	0.19	0.09	0.32	0.14	0.70	0.1128	0.00	0.01
45	Aleltu	0.43	0.06	0.20	0.16	0.58	0.06	0.04	0.00
46	Kechema	0.12	0.04	0.26	0.14	0.20	0.42	0.22	0.00
47	Kelechaa	0.25	0.06	0.66	0.26	0.27	0.06	0.02	0.00
48	Ashebeka	0.19	0.05	0.40	0.20	1.00	0.05	0.02	0.00
49	Ketar Up	0.15	0.10	0.30	0.14	0.56	0.03	0.02	0.00
50	Ketar Ogolcho	0.31	0.09	0.52	0.21	0.51	0.06	0.04	0.00
51	Choba	0.14	0.05	0.26	0.12	1.08	0.06	0.06	0.00
52	Sotira	0.13	0.05	0.26	0.14	0.30	0.08	0.02	0.00
53	Damo	0.13	0.05	0.24	0.12	0.32	0.08	0.02	0.00
54	Huluka	0.44	0.13	0.34	0.14	0.33	0.06	0.02	0.00
55	Lepis	0.34	0.10	0.28	0.14	0.51	0.17	0.04	0.00
56	Gedemso	0.24	0.07	0.24	0.12	0.46	0.11	0.02	0.00
57	Guracho	0.23	0.08	0.22	0.12	0.46	0.08	0.02	0.00
58	Mekonisa	0.19	0.06	0.22	0.12	0.35	0.08	0.02	0.00
59	Dalele	0.13	0.04	0.20	0.10	0.34	0.08	0.02	0.00
60	Iresho	0.39	0.09	0.48	0.28	0.23	0.06	0.02	0.00
61	Akemoja	0.45	0.12	0.50	0.30	1.02	0.06	0.04	0.00
62	Meki_Kela	0.50	0.12	0.84	0.32	1.19	0.06	0.02	0.00
						1.37	0.08	0.24	0.00

Hand Dug well

No	SOURCE-CODE	Na	K	Ca	Mg	HCO3	Cl	SO4	F
1	1(Tenalem,1998)	1.48	0.56	0.55	0.49	2.98	0.11	0.00	0.03
2	2(Tenalem,1998)	0.78	0.38	0.50	0.49	1.79	0.17	0.00	0.03
3	3(Tenalem,1998)	0.52	0.15	1.55	0.99	3.10	0.23	0.12	0.02

Hand Dug well

No	source-code	Na	K	Ca	Mg	HCO3	Cl	SO4	F
4	4(Tenalem,1998)	1.65	0.31	3.04	1.15	5.47	0.65	0.15	0.00
5	5(Tenalem,1998)	1.87	0.36	2.79	1.48	6.00	0.20	0.37	0.01
6	6(Tenalem,1998)	1.04	0.18	2.69	2.37	5.98	0.17	0.05	0.04
7	7(Tenalem,1998)	2.74	0.30	0.73	1.77	5.24	0.20	0.29	0.07
8	8(Tenalem,1998)	1.96	0.26	1.80	1.23	5.00	0.23	0.27	0.01
9	9(Tenalem,1998)	9.79	0.26	2.30	3.95	13.01	1.35	0.96	0.15
10	10(Tenalem,1998)	6.31	0.43	2.30	0.74	9.06	0.39	0.21	0.14
11	11(Tenalem,1998)	5.66	0.31	1.45	0.49	7.54	0.65	0.15	0.24
12	12(Tenalem,1998)	0.44	0.51	0.50	0.33	1.02	0.51	0.15	0.01
13	13(Tenalem,1998)	0.22	0.03	0.50	0.25	0.56	0.45	0.00	0.00
14	14(Tenalem,1998)	5.44	0.42	0.53	0.71	5.90	0.79	0.48	0.17
15	16(Tenalem,1998)	33.06	0.51	0.10	0.08	25.13	4.51	4.58	1.95
16	18(Tenalem,1998)	19.84	0.51	1.05	0.66	16.32	3.64	1.54	0.11
17	19(Tenalem,1998)	7.18	0.51	2.15	0.66	8.51	0.45	0.48	0.10
18	20(Tenalem,1998)	1.61	0.18	1.95	0.41	3.65	0.31	0.42	0.05
19	22(Tenalem,1998)	7.83	0.46	2.25	0.82	10.26	1.35	0.37	0.26
20	23(Tenalem,1998)	6.96	0.36	1.15	0.41	8.51	0.82	0.00	0.08
21	24(Tenalem,1998)	1.22	0.13	3.44	0.25	4.92	0.23	0.04	0.04
22	25(Tenalem,1998)	2.18	0.15	1.15	0.33	3.88	0.11	0.06	0.14
23	26(Tenalem,1998)	15.01	0.84	1.80	1.15	16.50	1.35	0.69	0.53
24	27(Tenalem,1998)	1.93	0.08	1.93	1.14	1.35	0.49	0.00	0.00
25	Bulbula P,/93	6.13	0.41	1.44	0.64	7.05	0.41	0.02	0.12
26	Meki Sidamo ber bar	2.87	0.28	1.27	11.66	8.78	0.95	0.10	0.28
27	Bulbula Tesfaye Hag	2.87	0.31	2.05	10.98	9.32	0.54	0.06	0.10
28	Michaelo S Butajira	0.13	0.41	3.09	11.58	7.75	0.03	0.06	0.02
29	Cht.1,Kofele Husen	0.57	0.38	4.15	0.44	2.20	0.98	0.10	0.01
31	Cht6,ZiwaySaid P	3.00	0.46	2.79	1.98	5.31	0.38	0.04	0.08
32	Cht.15 Ziway Debrit	7.05	0.36	0.85	0.46	7.10	0.85	0.04	0.12
33	Cht.19 Ziway Bal As	7.87	0.59	1.33	2.87	8.05	1.91	0.73	0.16

Borehole

No	source-code	Na	K	Ca	Mg	HCO3	Cl	SO4	F
1	1(Tenalem,1998)	2.91	0.33	0.39	0.29	3.69	0.03	0.04	0.18
2	4(Tenalem,1998)	0.70	0.18	0.35	0.16	1.20	0.06	0.21	0.00
3	8(Tenalem,1998)	0.96	0.09	1.68	0.84	3.32	0.10	0.00	0.01
4	9(Tenalem,1998)	0.65	0.11	1.08	0.72	2.20	0.15	0.00	0.06
5	10(Tenalem,1998)	1.04	0.13	2.24	0.98	4.16	0.20	0.00	0.08
6	11(Tenalem,1998)	0.85	0.16	2.21	1.72	4.11	0.20	0.52	0.08
7	12(Tenalem,1998)	1.09	0.10	0.65	0.33	2.28	0.11	0.02	0.03
8	14(Tenalem,1998)	0.78	0.05	0.64	0.20	1.50	0.20	0.00	0.02
9	15(Tenalem,1998)	0.47	0.05	0.81	0.18	1.30	0.20	0.00	0.01
10	20(Tenalem,1998)	0.94	0.15	2.30	0.72	3.80	0.20	0.00	0.06
11	23(Tenalem,1998)	0.94	0.15	2.30	0.72	3.80	0.20	0.00	0.00
12	24(Tenalem,1998)	0.61	0.13	0.50	0.16	0.89	0.20	0.08	0.04
13	25(Tenalem,1998)	8.48	0.46	0.80	0.66	9.60	0.42	0.15	0.17
14	27(Tenalem,1998)	8.70	0.31	0.30	0.16	6.90	1.21	0.96	0.58

Borehole

No	source-code	Na	K	Ca	Mg	HCO3	Cl	SO4	F
15	28(Tenalem,1998)	45.68	1.94	0.17	0.04	32.39	11.23	0.96	2.37
16	29(Tenalem,1998)	3.48	0.31	2.00	0.66	6.40	0.31	0.02	0.16
17	30(Tenalem,1998)	4.35	0.00	0.85	0.21	5.74	0.10	0.15	0.21
18	31(Tenalem,1998)	11.75	0.41	0.10	0.08	10.98	0.24	0.21	0.63
19	32(Tenalem,1998)	1.91	0.23	1.10	0.99	4.13	0.11	0.04	0.07
20	33(Tenalem,1998)	15.44	2.56	0.05	0.08	13.89	0.96	0.25	3.95
21	34(Tenalem,1998)	9.14	0.38	0.30	0.16	8.67	1.02	0.60	0.44
22	35(Tenalem,1998)	6.96	0.43	2.54	0.74	9.34	0.82	0.54	0.15
23	37(Tenalem,1998)	6.09	0.41	0.95	0.41	6.85	0.45	0.12	0.14
24	38(Tenalem,1998)	0.87	0.10	0.70	0.33	1.64	0.06	0.48	0.05
25	39(Tenalem,1998)	1.09	0.08	0.70	0.33	2.29	0.07	0.17	0.05
26	40(Tenalem,1998)	0.65	0.10	0.85	0.25	1.48	0.16	0.23	0.03
27	42(Tenalem,1998)	0.52	0.10	0.55	0.25	1.34	0.00	0.17	0.02
28	44(Tenalem,1998)	11.53	0.00	0.10		10.24	0.28	0.25	0.79
29	45(Tenalem,1998)	17.18	0.29	0.04	0.03	13.44	1.50	1.87	0.77
30	46(Tenalem,1998)	8.70	0.38	0.70	0.74	8.15	0.51	0.10	0.17
31	47(Tenalem,1998)	8.70	0.38	0.70	0.74	9.79	0.51	0.10	0.17
32	48(Tenalem,1998)	1.48	0.08	2.74	0.58	4.65	0.17	0.17	0.00
33	49(Tenalem,1998)	3.18	0.10	2.30	0.49	5.82	0.39	0.06	0.07
34	50(Tenalem,1998)	13.57	0.51	3.09	0.16	16.60	0.37	0.00	0.00
35	51(Tenalem,1998)	1.53	0.21	0.84	0.32	3.50	0.19	0.00	0.00
36	52(Tenalem,1998)	2.71	0.31	0.76	0.28	3.70	0.19	0.00	0.00
37	53(Tenalem,1998)	2.04	0.24	1.15	0.91	4.00	0.20	0.00	0.00
38	55(Tenalem,1998)	1.57	0.16	0.74	0.50	2.70	0.19	0.00	0.00
39	57(Tenalem,1998)	3.05	0.13	1.40	0.80	4.80	0.39	0.00	0.00
40	64(Tenalem,1998)	9.57	0.00	0.70	0.41	9.83	0.59	0.17	0.32
41	67(Tenalem,1998)	87.00	1.05	0.15	0.08	60.38	27.05	2.21	3.37
42	68(Tenalem,1998)	23.93	1.00	0.01	0.01	14.97	9.03	0.46	0.78
43	69(Tenalem,1998)	13.62	0.64	0.15	0.04	8.40	6.01	0.06	0.40
44	Meki forage	9.92	0.51	0.70	0.16	9.11	1.27	0.28	0.34
45	Negelle Arsi forage	1.44	0.05	0.70	0.28	1.72	0.14	0.06	0.09
46	Butajira S,F	2.78	0.41	0.40	1.12	3.54	0.26	0.09	0.02
47	Koshe F	5.74	0.49	0.95	0.31	6.26	0.36	0.14	0.14
48	Jido combol F	15.18	0.33	0.05	0.00	12.98	1.29	0.37	1.85
49	Soda ash F	45.33	0.28	0.16	0.07	32.16	9.20	4.14	2.72
50	Langano Bekele Mola	19.10	0.87	0.02	0.00	12.82	7.43	0.08	0.75
51	Arsi Negelle F	0.91	0.13	0.50	0.31	1.25	0.09	0.04	0.05
52	Butajira F	0.17	0.41	1.95	11.58	7.24	0.06	0.03	0.03
53	Ziway Bekele M F	4.79	0.38	0.63	13.82	12.00	0.38	0.01	0.18
54	Langano Bek.Molla,	20.53	0.74	0.02	0.00	15.18	6.43	0.06	0.76
55	Bulbula F	12.92	0.41	0.61	7.49	15.83	0.50	0.17	0.96
56	Arsi Negelle F	0.39	0.10	0.73	5.12	3.20	0.07	0.03	0.04
57	Cherent 2,Butajira	0.13	0.31	7.93	1.57	5.02	0.07	0.09	0.02
58	Cherent3,Kela F	0.44	0.15	15.01	2.22	6.33	0.36	4.39	0.02

Cold Spring

No	source-code	Na	K	Ca	Mg	Hco3	Cl	SO4	F
1	1(Tenalem,1998)	2.35	0.34	0.30	1.18	4.59	0.08	0.04	0.16
2	2(Tenalem,1998)	3.18	0.26	1.05	1.40	5.21	0.25	0.44	0.14
3	3(Tenalem,1998)	2.26	0.21	0.36	0.19	3.03	0.03	0.44	0.14
4	4(Tenalem,1998)	1.04	0.13	0.65	0.58	2.43	0.03	0.04	0.13
5	5(Tenalem,1998)	0.44	0.13	1.45	0.74	2.51	0.23	0.12	0.03
6	6(Tenalem,1998)	0.87	0.23	0.90	0.41	2.39	0.14	0.12	0.00
7	7(Tenalem,1998)	0.09	0.03	0.40	0.25	0.93	0.06	0.06	0.02
8	8(Tenalem,1998)	1.00	0.31	2.05	1.07	4.00	0.03	0.06	0.01
9	9(Tenalem,1998)	0.17	0.13	0.90	0.91	2.21	0.20	0.19	0.03
10	10(Tenalem,1998)	0.39	0.13	0.50	0.29	1.39	0.08	0.10	0.02
11	11(Tenalem,1998)	0.65	0.15	0.90	0.58	2.39	0.20	0.06	0.01
12	12(Tenalem,1998)	0.13	0.03	0.27	0.16	0.51	0.14	0.06	0.02
13	13(Tenalem,1998)	0.44	0.18	0.45	0.16	1.00	0.17	0.06	0.01
14	14(Tenalem,1998)	0.48	0.10	0.30	0.25	0.70	0.08	0.19	0.01
15	15(Tenalem,1998)	0.35	0.08	0.70	0.41	1.46	0.51	0.04	0.11
16	16(Tenalem,1998)	0.26	0.08	0.50	0.29	0.92	0.08	0.12	0.02

Hot spring

No	source code	Na	K	Ca	Mg	HCO3	Cl	SO4	F
1	1(Tenalem,1998)	2.39	0.20	0.80	0.25	6.58	0.17		0.09
2	4(Tenalem,1998)	9.79	0.59	0.40	0.16	9.83	0.62	0.04	0.27
3	5(Tenalem,1998)	44.81	2.02	0.06	1.18	29.94	11.28	1.87	1.04
4	7(Tenalem,1998)	54.98	1.79	0.08	0.08	40.18	14.39	0.94	1.16
5	8(Tenalem,1998)	50.03	2.30	0.00	0.25	38.85	11.68	1.27	1.05
6	9(Tenalem,1998)	42.20	2.12	0.20	1.23	33.04	10.16	1.62	1.05
7	11(Tenalem,1998)	56.55	2.05	0.00		38.99	13.71	1.33	1.53
8	12(Tenalem,1998)	58.46	1.79	0.06	0.04	51.20	14.36	1.00	1.11
9	13(Tenalem,1998)	180.83	2.81	0.12	0.08	114.70	55.24	0.46	7.90
10	14(Tenalem,1998)	113.10	2.05	0.20	0.25	76.79	35.23	0.50	5.00
11	15(Tenalem,1998)	54.81	2.46		0.25	34.86	20.37	0.69	2.11
12	16(Tenalem,1998)	47.85	1.59		0.41	30.41	17.10		1.58
13	17(Tenalem,1998)	50.03	2.17			34.44	15.01	0.77	1.84
14	18(Tenalem,1998)	16.53	1.05			10.86	6.38		0.53
15	21(Tenalem,1998)	38.06	1.18	0.15		25.99	9.65	0.40	2.68
16	22(Tenalem,1998)	23.06	1.15	0.60	0.49	14.96	8.97	0.50	2.00
17	23(Tenalem,1998)	37.32	1.15	0.45	0.02	27.48	9.56	0.31	0.74
18	24(Tenalem,1998)	73.95	3.33	0.36	0.88	42.56	19.18	8.12	1.02
19	25(Tenalem,1998)	32.63	1.43	0.15		14.74	12.98	5.45	0.74
20	26(Tenalem,1998)	24.36	0.82			11.26	7.73	6.37	0.11
21	27(Tenalem,1998)	38.28	2.05	0.03	0.12	21.97	14.67	1.00	1.63
22	28(Tenalem,1998)	25.67	0.61	0.01	0.00	8.97	8.60	7.08	0.72

Annex 3 Isotopic data of the Ziway-Shalla basin

LAKES

No	CODE	Year	Lakes	18-O	D
1	LK4	1998*	Ziway	6.70	49.00
2	LLW1	1992	Ziway	5.89	43.2
3	GIZ3	1988	ziway	6.7	49
4	LLW2	1992	Ziway	6.94	48.2
5	CRA 15	1977	Ziway	5.29	39
6	ET3/92	1998	Ziway	4.067	
7	TAM 1	2002	Ziway surface	5.40	41.00
8	LK1	1998*	Abiyata	7.09	46.85
9	ET19	1977	Lake Abiyata	10.00	64.20
10	ET6/92	1998	Abiyata Marginal NE	8.36	
11	ET48A/94	1998	Abiyate midlake surface	7.52	
12	ET48B/94	1998	Abiyata midlake, 1m	7.56	
13	ET47/94	1998	Abiyata 1.5 km	7.46	
14	LAH95/4	1998	Abiyata sud	8.946	
15	TAM 4	2002	Abiyata, near Horkell	8.60	56.00
16	E17	1996	Lake Langano	7.50	50.00
17	LK2	1998*	Langano	7.10	46.28
18	ET28	1977	Lake Langano, SW	6.73	45.00
19	ET15	1977	Langano	6.85	45.8
20	Lan	1988	langano	6.9	49
21	ET 12/92	1988	Langano	6.285	
22	ET41/94	1998	Langano lac 40-45m	6.074	
23	ET40/94	1998	Langano meme 10m	5.995	
24	ET39/40	1998	Langano meme 25m	6.276	
25	ET38/94	1998	Langano ligne faille su	6.341	
26	TAM 5	2002	Langano, B Molla	7.50	52.00
27	LK3	1998*	Shalla, surface	7.52	48.40
28	ET44	1977	Lake shalla, surface	8.49	54.50
29	ET43	1977	Lake Shalla, 120m	8.30	54.40
30	ET42	1977	Lake shalla, 195m	8.28	54.30
31	ET11/92	1998	Shalla Marginal NE	7.23	
32	ET16/93	1998	Shalla marginal NE	6.96	
33	ET52/94	1998	Shala, Marginal NE,S	5.36	
34	LAH95/11	1998	Shala, Marginal NE, S	7.73	
35	LAH95/12	1998	Shala, surface	7.82	
36	LAH95/13	1998	Shala, 12,2m	7.66	
37	LAH95/14	1998	Shala, 45m	7.49	
38	LAH95/16	1998	Shala, Marginal NE, S	7.77	
39	ET29	1977	NE Shalla (surface)	8	54.5
40	ET51/94	1998	shalla hydrologic stati	7.349	
41	TAM 6	2002	Shalla, east side	8.70	56.00

RIVERS

	Code	Year	River	18-O	D
	ET.D93	1998	Eresha riv	-3.057	
	ET.20/94	1998	Iresha R Butajira	-2.548	
	ET.1/92	1998	Meki R	-0.881	
	ET10	1977	Meki river	0.7	7.5
	RV3	1998*	Meki at Meki town	-1.05	1.6
	ET3/94	1998	Aleltu Sagure R	-4.928	
	ET3/94	1998	Aleltu Sagure R	-1.545	2
	ET.J93	1998	Ketar R	-2.37	
	ET4/92	1998	Bulbula R	4.4	
0	ET6	1977	Bulbula river/lake Ziwa	5.29	39
1	TAM 2	2002	Bulbula river	5.00	37.00
2	ET5/92	1998	Horakelo R	6.5	
3	ET15	1977	Horkalo river/L.Langano	6.85	45.8
4	TAM 3	2002	Horkalo river	7.5	49
5	ET.E93	1998	Huluka Oda riv	-1.51	
6	ET.G93	1998	Huluka R 6km	-1.616	
7	ET.H93	1998	Dalele R	-2.04	
8	ET.I 93	1998	Entreee Kersa	-1.887	
9	ET23/94	1998	Huluka kersa route	-1.586	
0	ET24/94	1998	Lepize kersa route	-1.468	
1	RV2	1998*	Lepis at Langano	-0.87	7.25
2	ET25/94	1998	Gedmso kersa route	-1.346	
3	ET26/94	1998	Guracho kersa route	-1.871	
4	ET27/94	1998	Mokonissa kersa route	-1.234	
5	ET28/94	1998	Latellelle kersa route	-2.111	
6	ET29/94	1998	Metana R	-1.869	
7	ET30/94	1998	Tedji R	-2.423	
8	ET34	1977	Tej	-0.73	5.7
9	ET35	1977	Gedamso	-0.59	6.4
0	ET37	1977	Stream NEof Langano	-2.93	-8.2
1	ETH40	1992	Langano4092	-1.66	-3.6
2	Kulmusa-As	1993	Langano93	-2.03	0.1
3	Huluka	1988	Huluka near Langano	-1.9	
4	ET18	1977	Jido river	0.53	5.2
5	ET46/94	1998	Debaba, Arisi Negele	-2	2.6
6	ET47	1977	Melka Oda Stream	-0.65	6.3
7	ET46/94	1998	Tilku Debaba R	-1.996	
8	ET45/94	1998	Debaba R	-1.246	
9	ET.F93	1998	Delaba (Debaba) R	-1.654	

RAIN

No	Source	Year	Elevation-Station	18-O	H
1	Tesfay C.	1998	2250-Asella	3.64	16.9
2	Tesfay C.	1998	2250-Asella	0.65	20.6
3	Tesfay C.	1998	2250-Asella	0.44	12.2
4	Tesfay C.	1998	2250-Asella	-2.56	-1.6
5	Tesfay C.	1998	2250-Asella	2	20.5
6	Tesfay C.	1998	2250-Asella	-4.65	-24.3
7	Tesfay C.	1998	2250-Asella	-3.54	-11.7
8	Tesfay C.	1998	2250-Asella	1.1	14.3
9	Tesfay C.	1998	2250-Asella	0.93	13.6
10	Tesfay C.	1998	2250-Asella	-2.14	-5.4
11	Tesfay C.	1998	2250-Asella	3.49	26.9
12	Tesfay C.	1998	2250-Asella	-1.25	1.4
13	Tesfay C.	1998	2250-Asella	3.37	32.4
14	Tesfay C.	1998	2250-Asella	-3.93	-19.8
15	Tesfay C.	1998	2250-Asella	-4.25	-18.3
16	Tesfay C.	1998	2250-Asella	-3.9	-18.1
17	Tesfay C.	1998	2250-Asella	-0.79	-1.8
18	Tesfay C.	1998	2250-Asella	-0.92	4.2
19	Tesfay C.	1998	2250-Asella	-3.90	-19.80
20	Tesfay C.	1998	2250-Asella	-1.80	-11.30
21	GNIP	1995	2250-Asella	-0.90	5.70
22	GNIP	1995	2250-Asella	1.20	20.00
23	GNIP	1995	2250-Asella	-1.10	2.80
24	GNIP	1995	2250-Asella	0.10	4.70
25	GNIP	1995	2250-Asella	0.20	11.00
26	GNIP	1995	2250-Asella	-0.3	11.9
27	GNIP	1995	2250-Asella	0.26	11.9
28	Tesfay C.	1998	1638-Ziway	-0.7	11.8
29	Tesfay C.	1998	1638-Ziway	-2.56	-4.1
30	Tesfay C.	1998	1638-Ziway	-3.91	-16.9
31	Tesfay C.	1998	1638-Ziway	-4.68	-29.7
32	Tesfay C.	1998	1638-Ziway	-0.86	5.1
33	Tesfay C.	1998	1638-Ziway	0.04	12
34	Tesfay C.	1998	1638-Ziway	-2.33	-3.9
5	Tesfay C.	1998	1638-Ziway	-0.71	7.6
6	Tesfay C.	1998	1638-Ziway	-2.03	2
7	Tesfay C.	1998	1638-Ziway	1.45	27.1
8	Tesfay C.	1998	1638-Ziway	2.86	31
9	GNIP	1995	1638-Ziway	-2.4	-3.1
0	GNIP	1995	1638-Ziway	-2.8	-10.9
1	GNIP	1995	1638-Ziway	-0.6	9.1
2	Tenalem A.	1996	1638-Ziway	0.5	8.1
3	Tenalem A.	1998*	1638-Ziway	-0.7	12.85
4	Seifu K	1999	1638-Ziway	-4.28	-16.6
5	Tesfay C.	1998	2000-Silte	-2.68	-3.1

RAIN

46	Tesfay C.	1998	2000-Silte	-5.71	-27.4
47	Tesfay C.	1998	2000-Silte	-1.16	12
48	Tesfay C.	1998	2000-Silte	-1.55	0.9
49	Tesfay C.	1998	2000-Silte	1.99	18.4
50	Tesfay C.	1998	2000-Silte	-3.37	-12.7
51	GNIP	1995	2000-Silte	-2.7	-3.1
52	GNIP	1995	2000-Silte	-2	2
53	Tesfay C.	1998	2040-Butajira	-2.43	-6.8
54	Tesfay C.	1998	2040-Butajira	-0.75	-6.4
55	Tesfay C.	1998	2040-Butajira	4.35	22.5
56	Tesfay C.	1998	2040-Butajira	-2.05	-9.5
57	Tesfay C.	1998	2040-Butajira	-1.09	2.1
58	Tesfay C.	1998	2040-Butajira	-3.56	-17.1
59	Tesfay C.	1998	2040-Butajira	-0.75	3.9
60	Tesfay C.	1998	2040-Butajira	-0.9	-3.5
61	GNIP	1995	2040-Butajira	-1.9	-4.4
62	GNIP	1995	2040-Butajira	0.5	8.1
63	GNIP	1995	2040-Butajira	0.49	8.05
64	Panichi,	1995*	1600-Langano	-2.9	-3.7
65	Seifu K	1999	1600-Langano	-2.22	2.65
66	EIGS	1992	1600-NW of Langano	-2.85	-3.7
67	Seifu K	1999	2250-Chilalo	1.34	21.6
68	Seifu K	1999	2200-Kersa	1.26	23.45

WELLS

No	Well	Year	Location	O	H
1	ET5	1977	Adamitulu	4.28	32.6
2	ET7	1977	Ziway south Town	5.04	35.2
3	ET9	1977	Meki	-2.73	-8.1
4	ET16	1977	Wild life Langano	-0.5	5.3
5	ET33	1977	Bekel Mola well Langno	0.39	10
6	BH3	1998*	Adami Tulu	4.45	32.39
7	BH2	1998*	Meki Bush Hotel	-1.95	-3.93
8	ET14	1977	Koshe	-3.53	-15
9	ET18	1977	Bekele Molla	0.39	10
10	DW1	1996	Abura Hand dug well	-3.37	-11.3
11	ET384/94	1998	Langano BM F	0.052	14.1
12	ET17	1977	Jido Combol	-4.12	-24.1
13	ET43/94	1998	Soda ash F	1.445	19.5
14	ET4/95	1998	Ziway Asefa yilma (Bal)	4.019	34.2
15	ET6/95	1998	Ziway Debritu P	5.087	41.4
16	ET7/95	1998	Ziway Said P	4.268	40.3
17	ET22/95	1998	Kofele Husen P	-2.092	9.3
8	ET5/93	1998	Koshe F	-3.852	
9	ET6/93	1998	Dalocha F	-3.852	
0	ET19/94	1998	Butajira P	-2.695	
1	ET18/94	1998	Michaelo P sud de Butaj	-2.872	
2	ET22/95	1998	Kofele Husen P	-2.092	
3	ET8	1977	Southern cross	-0.23	5
4	TAM 8	2002	Adami Tulu, EWWCA well	4.00	35.00
5	TAM 7	2002	Bulbula town 26m depth	- 0.5	7.00
6	TAM 9	2002	Meki Bush hotel-27m dep	- 2	-9.00

COLDSPRINGS

CODE	Year	Location	18-O	D
ET12	77	Silte Tebel	-2.44	-3.7
ET13	77	Butajira	-2.55	-3.1
ET36	77	Huluka near Lepis	-1.89	2.1
ET38	77	Sedi 1	-3.49	-12
ET39	77	Sedi 2	-3.33	-10.2
ET40	77	Sedi 3	-3.32	-10.2
ET41	77	Shala cold spring	-1.62	2.9
TCS1	98*	Dulati at Kela	-2.21	-4.5

HOTSPRINGS

CODE	Year	Location	18-O	D
ET11	1977	Imba Kolo		-15
ET20	1977	Langano 1	-1.33	-0.3
ET21	1977	Bole Fault 5	-0.87	-2.2
ET22	1977	Bole Falult 8		
ET23	1977	Bole Fault 6		
ET24	1977	Geyser island 10		
ET25	1977	Geyser island 11	0.39	3.6
ET26	1977	Geyser island 12	-0.44	2.5
ET27	1977	Oitu Springs	-3.48	-13
ET30	1977	Shala hot spring	2.5	24
ET33	1992	Langano1.92	-1.19	1.2
ET38	1992	Langano4.92	-3.08	-10.5
ET39	1992	Langano5.92(N Lang)	-2.46	-10.1
UN73.2	1973	Langano2.73(N Lang)	nd	nd
UN73.3	1973	Langano2.73(N Lang)	nd	nd
Spring 5	1988	Langano5.88(N Lang)	-0.8	nd
Spring 6	1988	Langano6.88(N Lang)	-1.2	nd
Spring10	1988	Langano10.88(N Lang)	-0.6	9
Spring84	1984	Langano84.88(N Lang)	-1.3	-1
Spring84	1988	Langano84.88(N Lang)	-0.2	17
UN73.10	1973	Langano10.73(N Lang)	nd	nd
UN73.12	1973	Langano12.73(N Lang)		
UN73.5	1973	Langano5.73(N Lang)	nd	nd
UN73.BA	1973	LanganoBA.73(N Lang)	nd	nd
UN73.16	1973	Langano16.73(N Lang)		
UN73.84	1973	Langano84.73(N Lang)		
SP 10	1992	Langano10.92	-0.53	1.4
SP 12	1992	Langano12.92	-0.3	2.2
SP 119	1992	Langano119.92(N Lang)	-0.35	1.2
SP 118	1988	Langano120.92(N Lang)	-0.51	2
HS1	1998*	Citu	-1.14	-0.68
HS2	1998*	Big Tuffa	-3.58	-14.58
HS3	1998*	Shala east	2.69	25.2
HS4	1998*	Chitu	1.57	16.6

UN		
Craig et al	1998	Tesfay Chernet
Gizaw et al	1998*	Tenalem Ayenew
EIGS	2002	This Issue
GNIP		
Panichi,		