HYDROLOGY AND HYDROCHEMISTRY OF BISHOFTU CRATER LAKES
(Ethiopia)

Hydrological, Hydrochemical and oxygen isotope modeling

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ABSTRACT

The Bishoftu Crater Lakes, located on the western shoulder of the main Ethiopian Rift can provide a sedimentary record, which has registered the changes in the balance between precipitation input and evaporative water loss. However, groundwater fluxes may reduce sensitivity of the lakes to a change climate.

In order to test the possibility to use the lakes as paleohydrometers, the modern balance between precipitation, evaporation and groundwater flux has been determined.

In the Bishoftu area where hardrock form the terrain geochemical and isotope mass balance has been found suitable to be used to constrain the water budget. Although stable isotopes of oxygen and deuterium as aid in quantifying water balance of the lakes have limitations due to the lack of measurement of environmental parameters such as h, ε, $\Delta\varepsilon$; the same approach has been found appropriate for this study.

The varying hydrology of the Bishoftu crater lakes has provided a suitable base for determining water budget using stable isotope method without reverting to the measurement of environmental parameters. Accordingly the lakes have been found suitable for quantitative isotope hydrology and quantitative reconstruction of paleoclimate from lake carbonate records.

Of the existing five crater lakes, lake Hora, lake Arenguade and lake Kilole are least affected by groundwater outflow while lake Babogaya and lake Bishoftu are more influenced by groundwater outflow. The hydrology of lake Kilole is recently influenced by the diversion of the Mojo river into the lake. Geochemical mass balance results show that lake Arenguade might be affected by geothermal water flux. Of all crater lakes, lake Hora is therefore selected as the most suitable for paleoclimate studies.

INTRODUCTION

1.1 Background to the problem

Crater lakes provide a unique opportunity to study the climate variability of the past at different degrees of resolution. They give such information if the chemical and isotopic compositional variability is responsive to the climatic variability. The potential to use such lakes to study ultra-high resolution climate variability, such as El Nino and ENSO variability from lake sediment records needs continuos monitoring of the lakes chemistry at a similar temporal resolution. Such a study helps to understand the relative importance of climate, hydrological and human controls on lake chemistry and the control of the lake chemistry on the sedimentary record.

Recent studies (Lamb *et al.,* 1997) have shown that the Bishoftu Crater Lakes (BCLs) provide a record of high-resolution environmental change because they contain laminated sediments. The water budget of the lakes which determines the water resources, chemistry and sensitivity of the lakes for environmental and climate change is not well known. There has not been a major continuous monitoring of the chemistry of the lakes and moreover previously collected data lack isotopic and trace element characterization. The impact of land use on the lakes' chemistry and hydrology is not well studied. The risk and vulnerability of the lakes to pollution which depends on the degree of surface-lake-ground water interaction, and the possible residence time of the chemical species in the lakes has not yet been assessed.

The goals of the research are:

- To characterize and determine lake-ground water interaction through water budget studies based on meteorological, hydrological, chemical and isotopic approaches;
- To test the sensitivity of the lakes to climate controlled parameters and select a suitable lake for paleoclimate studies; and
- To determine the suitability of lakes for water supply development and irrigation.

1.2 Previous work

The BCLs and the surrounding area have been the subject of previous geological (Mohr, 1961 and Gasparon *et al.*, 1993), chemical (Prosser *et al.*, 1968; Rippey and Wood, 1985; Wood and Talling, 1988), biological (Getachew Tefera, 1980), hydrogeological (Tamiru Alemayehu, 1992) investigations. However, these studies were mostly based on the inspection of the lakes for few months of the year or even a couple of weeks. Major monitoring works that were carried out for long periods in the BCLs include: Rippey and Wood (1985), Wood *et al.*, (1976, 1984). These long-term studies lack complete chemical characterization, as they miss some cation and anion species (trace elements in particular) and stable isotope analysis. These studies show that the difference in the chemistry of the BCLs, which have fairly similar geology, is due to the difference in the rates of groundwater in and outflow and rates of evaporative concentration, or biological activities. None of these investigations are supported by water budget determinations. The quantity of groundwater and solute inflow and outflow and their residence time has not been estimated. There is also no major work on the relation between the lakes chemical and hydrological characteristics and land use. Moreover, there is no continuity in the investigations since 1988, so data on possible recent changes have not been obtained.

1.3 Research Objectives

The specific objectives of this research are:

- to quantify the rate of interactions among different hydrologic elements (surface-groundwater) and calculate water and solute budgets for the lakes;
- to monitor the temporal (seasonal and monthly) variability and trend of the chemistry and isotopic composition of the lakes and to identify the possible controlling factors for the chemical variables and test sensitivity of the lakes isotopic composition to climate and hydrologic change;
- to identify long term trends in the chemistry of the lakes, i.e. to compare the present data with data prior to the 1980's;
- to characterize the physicochemical parameters and variability of the lakes in a given depth section;
- to characterize and test factors that control carbonate precipitation in the lakes and therefore the formation of laminated lake sediments;

- to identify the possible human impact on the chemistry of the lakes;

1.4 Methods and Approaches

To achieve the objectives of the research the following methods were applied.

1. Field observations and on site data measurements including

- Monthly, seasonal and spatial collection of water samples from lakes, selected ground water wells, surface and rain water for isotopic and chemical analysis.
- Seasonal collection of lake sediments at different depths and seasons using sediment traps installed in the depth section of the lakes.

2. Laboratory studies of water and lake sediment samples:

The water and sediment samples were collected and stored in the geochemistry lab of the Department of Geology and Geophysics, until they were sent to the University of Wales for trace and Major element analysis and to the British Geological Survey at Kentworth for stable isotope analysis. Na, K, Ca and Mg were analyzed using Perkin Elmer Atomic Absorption Spectrometer, major anions were analyzed using DIONEX chromatograph and trace element analysis were carried out with an Inductively coupled plasma mass spectrometer (ICP-MS). Alkalinity was calculated from the charge balance. Conductivity, temperature, and pH measurement were carried out on the field using Hanna instrument HI 9024.

A locally made sediment trap was installed in the lake and sediment have been collected on monthly and seasonal basis.

1.5. Relevance of the Research

The data that will be obtained from this research will have a great benefit from the water resources, scientific, environmental and, socioeconomic point of view.

For proper utilization of water resources a basic understanding of the hydrologic system and water budget is very important. This helps to properly manage available water resources; to understand effect of land use practice on hydrology, and to understand groundwater-surface water interactions.

Knowledge of climate patterns is indispensable for society and its activities. Prediction of climate changes is one of the most significant outcomes of systematic scientific studies based on multi-disciplinary research. The understanding of how climates changed in the past is of utmost importance to predict possible patterns in the future. Records of past climates are preserved in sediments deposited in the last thousands of years. The study will provide a modern reference for the various factors that control chemistry. This can be used to understand mechanisms that have controlled past environmental and climatic changes. Such an understanding will have a wider benefit from a global change point of view (El Nino, ENSO type variability and other types of climate changes) which are affecting the regions of Ethiopia and the Horn of Africa (e.g. droughts).

The study will help to assess the potential for use of the lakes as aquatic development (fisheries), recreational, irrigation, water supply and related environmental impacts. Understanding recent impact of human activity on the quality of the environment of the study area also relies on the understanding of hydrological interactions. Information on the vulnerability of the different lakes in the area to pollution by increased urbanization, industrialization, and agricultural practices will be obtained. This information helps planners or decision-makers to minimize environmental costs of human activities by planning future development in an appropriate manner.

CHAPTER TWO

SITE DESCRIPTION

2.1. Location of the study Area

The study area is located 45km SE of Addis Ababa at an altitude that range from 1800 to 2000m (fig. 1). The Bishoftu crater lakes have been mentioned under several names. The original Oromo name of the region is Bishoftu, one of the Crater Lake is also named Bishoftu. The region is also named as Debre Zeyt. The five permanent lakes are lake Hora (Betemengist, Hora Arsodi), Babogaya (Pawlo, Guda), Kilotle (Kilotes, Hora Kilole), and Arenguade (Arenguadi, Verde, Green lake). The name 'Bishoftu Crater Lakes' is adopted in this work for a group of the five crater lakes, because in most previous literature the lakes have been named by the same name. The name 'Debre Zeyit' stands for the region in which the lakes are located.

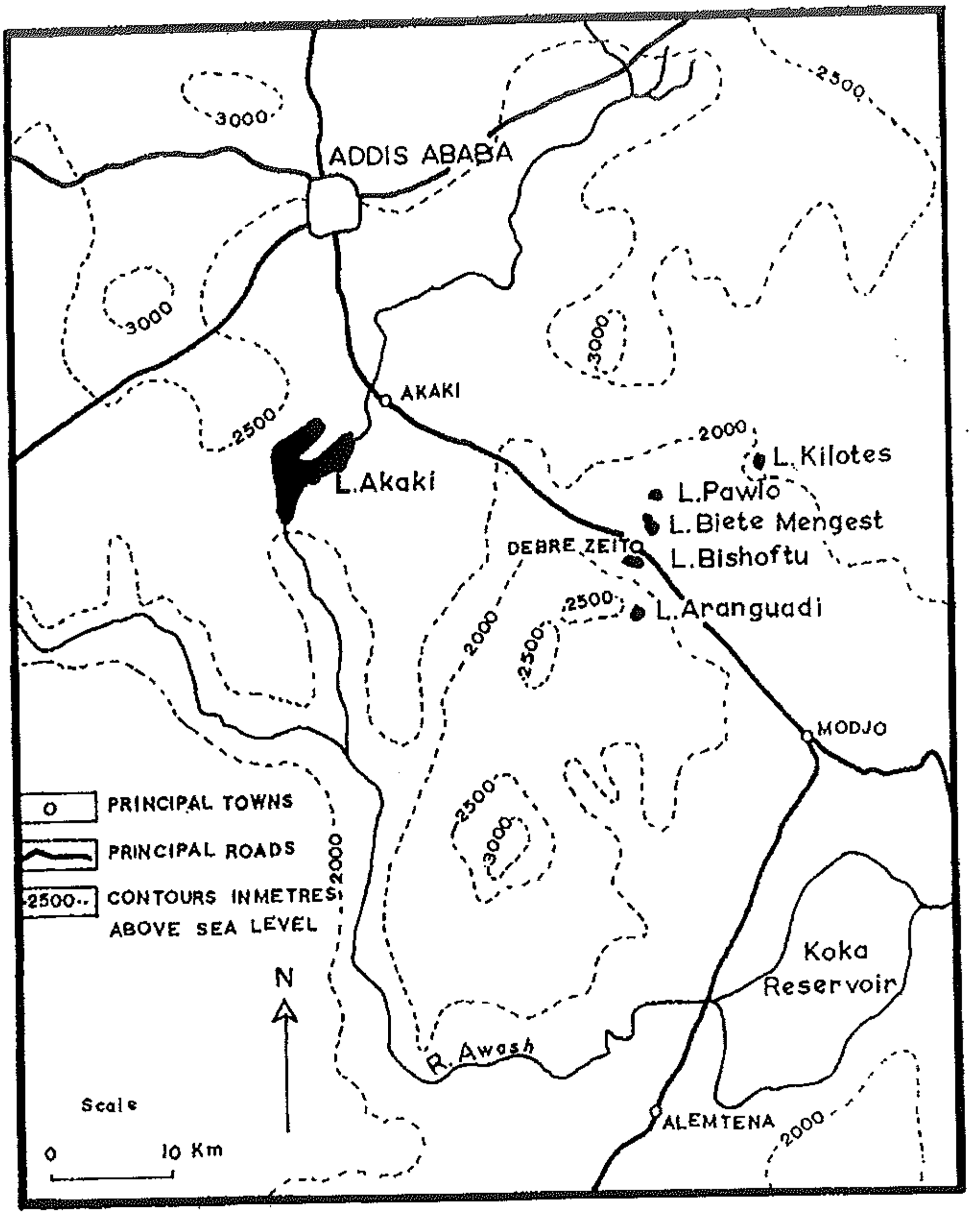


Figure 1. Map showing the location of the Bishoftu Crater Lakes and the Physiography of the region, after Prosser, *et al.;* 1968.

2.2 Physiography of the Study Area

The area is characterized by typical volcanic geomorphology. The topography of the area generally dips towards southeast and is dotted by various small scoria cones; splendid volcanoes such as Ziquala, Yerer and Bede Gebabe; rhyolitic lava domes, explosion craters which are filled by permanent or seasonal water. The explosion craters are roughly circular in shape, and the size ranges between 0.5 and 1 km^2 in area. The lakes vary in depth from 10m (Lake Kilole) to 87m (Lake Bishoftu). The only perennial stream in the area is the Wedecha that is the main tributary of the Mojo river (fig. 2). Most of the other streams are intermittent and seasonal in nature and drain volcanic domes and the major volcanoes. These intermittent streams enter the swamps of the area (such as Cheleleka) from which the water infiltrates or evaporates.

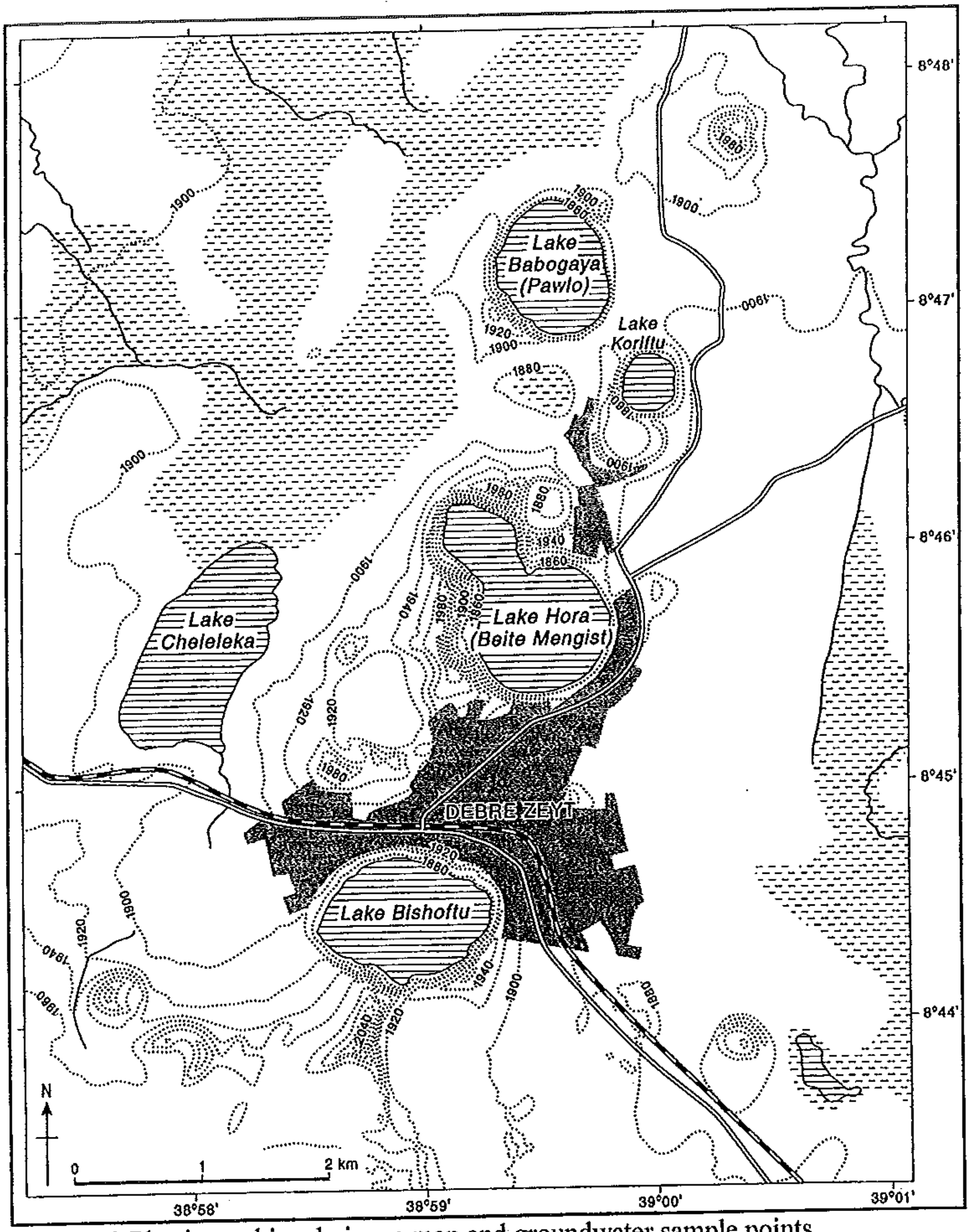


Figure 2 Physiographic, drainage map and groundwater sample points.

___ streams

----- contours

\+ groundwater well points

2.3.Bathymetry and Physiography of the Crater lakes

Prosser *et al.,* (1968) presented the morphometric characteristics of the lakes as indicated in table 1 and figure 3.

Lake	Altitude m	Area km^2	Max. depth m	Ave. depth M	Volume $m^3 \times 10^6$
Kilole	2000	0.771	6.4	2.6	2
Arenguade	1900	0.541	32	18.5	10
Babogaya	1870	0.579	65	38	22
Hora	1850	1.029	38	17.5	18
Bishoftu	1870	0.929	87	55	52

Table 1 Morphometric Characteristics of Bishoftu Crater Lakes, after Prosser *et al.,* (1968).

Most of the crater lakes are characterized by circular shape, steep rims with average slope of 60°, and fairly flat bottom. The rim of some of these craters are slumped and triangular notches are commonly observed. The lake sediments taken closer to the slumped rims is commonly disturbed and shows no lamination as compared to those from like the lakes' center. Most of these lakes have the steepest rim and the highest elevation on the western part of the crater (fig. 2). Mohr (1961) relates these features to the prevailing wind direction at the time of explosion of the craters. Unlike the other lakes the crater of lake Hora is made of a juxtaposition of two twin craters. At the junction between the two craters the lake has a depth of about 12m compared to the depth of 40m in the western and 26m in the eastern twins.

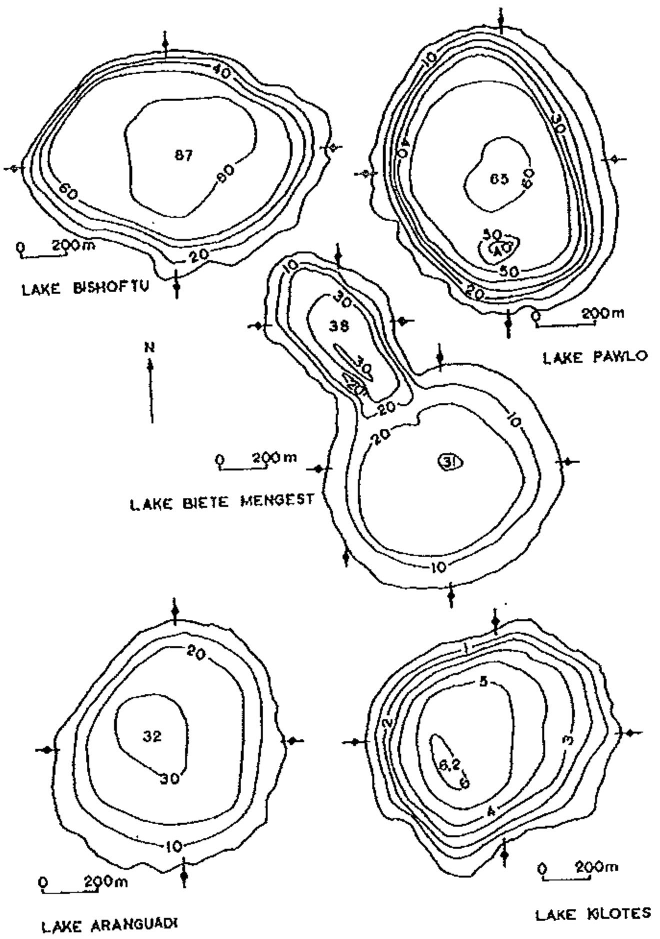


Figure 3.Bathymetric map of the Bishoftu Crater Lakes, after prosser *et al.,* (1968).

Unlike volcanic crater developed on the top of volcanoes, most of the BCLs depressions are found generally below the level of the surrounding plain. The depressions are surrounded by low rims of ejecta beds which accumulated on the surface which decrease in thickness outwards. Therefore the depressions are considered as explosion craters or maars in this work..

The crater lakes are closed to surface water inflow, except for runoff from the crater walls. Therefore the catchment of the lakes is defined by the rims of the craters. However the rims of two of the lakes: the artificial lake Kuriftu and lake Kilotes are artificially channalised to divert rivers from adjacent areas. The elevation of the lakes as measured by Prosser *et al.*, (1968) show that lake Hora is found at the lowest elevation, and lake Kilotes at the highest.

2.4. Land Use and Population

Bishoftu town with a population of more than 100, 000 (Tamiru Alemayehu, 1992) is founded around the crater lakes. Various small-scale industries such as grain milling, food processing, tanning, poultry, diary and swine farms are found. Most of the rural area, with a population over 300,000, is ploughed under both mechanized and non-mechanized agricultural technology. Fertilizers are also widely used in the area.

The hydrologic behavior of the lakes has been affected by human activities. Rivers have been diverted into the crater lakes to use the lakes as reservoirs (eg. lake Kilole and lake Kuriftu). Water has been withdrawn from some lakes to supply livestock.

The main water supply for the town of Bishoftu is extracted from a well field found in the northern part of the region stated as Genda Gorba or Shimbra Meda well field. Ground water is extensively used by the small-scale industries located in and around the town. The number of deep ground water wells in the area exceeds 50. There are also a number of shallow hand dug wells.

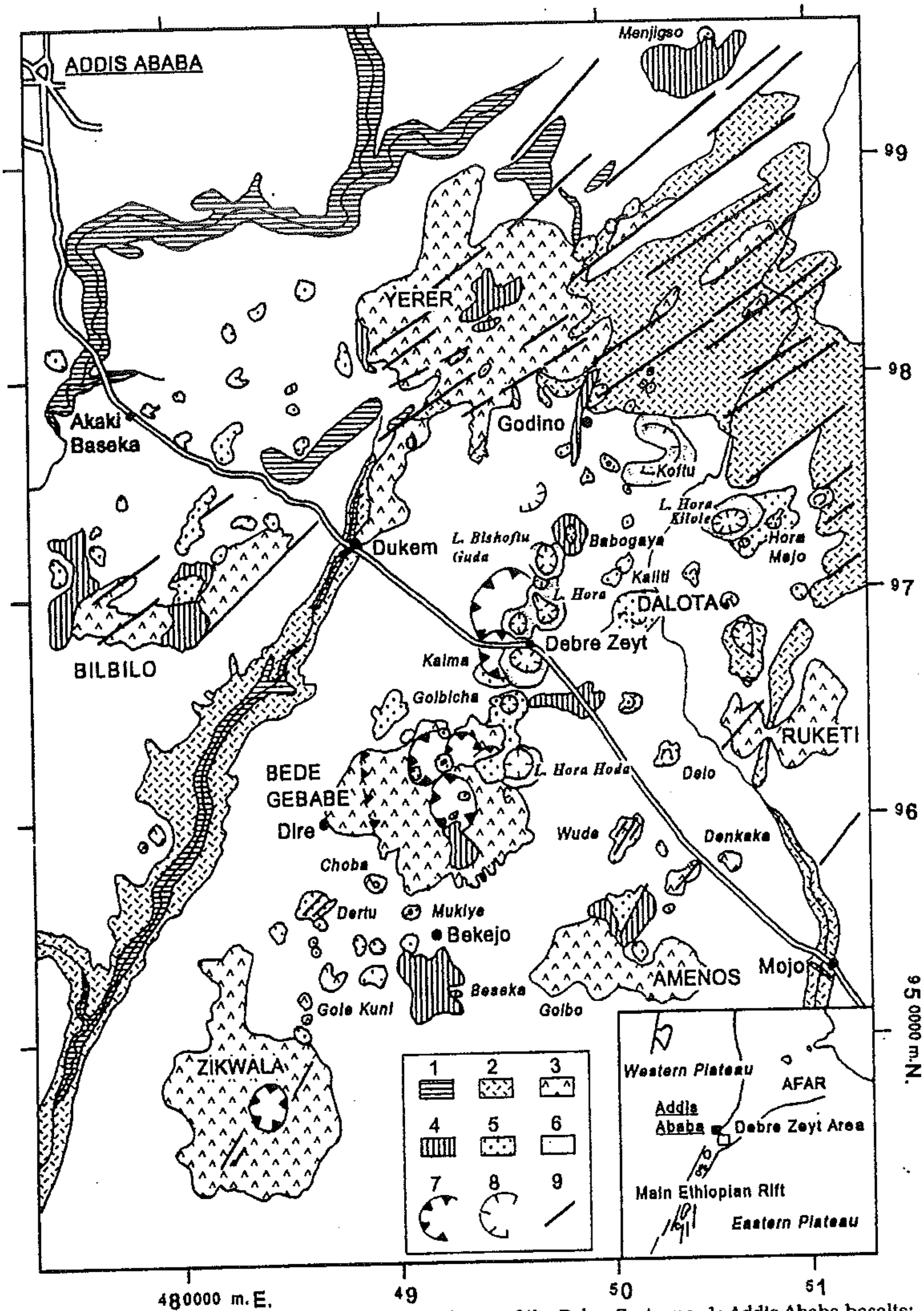
CHAPTER THREE

GEOLOGY, STRATIGRAPHY AND TECTONICS OF THE AREA

3.1 Geology and Stratigraphy

Gasparone *et al.,* (1993) recognized several volcanic unit in the area (fig. 4), these include from oldest to youngest:

- fissural basalts , probably equivalent to the Addis Ababa basalts which are found in small outcrops along some of the deepest river gorges.
- trachytic and rhyolitic ignimbrites, with minor intermediate acid lava flows and domes, form in extensive outcrops NE and E of Bishoftu where they make the base of Mt. Yerer and smaller outcrops occur west of Bishoftu. This unit is part of the upper Miocene-Pliocene Nazareth group volcanics.



[illegible] Schematic geological and volcanological map of the Debre Zeyt area. 1: Addis Ababa basalts; 2: Ignimbrites of the Upper Miocene-Pliocene Nazret Group; 3: Trachytes and rhyolites of central volcanoes 4: Younger basaltic lavas; 5: Younger basaltic cinder cones; 6: Younger hydromagmatic pyroclastic deposit

Figure 4. Geological map of the Debre Zeyit area. After Gasparone *et al.*, (1993)

- Yerer, Ziquala and Bede Gebabe volcanoes; Yerer is a partially eroded composite volcano mainly built up of acidic to intermediate pyroclastics and lava flows. Ziquala is a well-preserved cone made up of acidic lava flows with minor pyroclastics. The Bede Gebabe complex results from coalescence of several composite volcanoes, characterized by collapse calderas and post-caldera acidic domes and obsidian flows. The acid complexes of Amenos and Ruketti, respectively southeast and east of Bede Gebabe, as well as the small rhyolitic dome in the vicinity of Bishoftu, seem to belong to this phase of activity. The oldest age found for Ziquala by Zanetti *et al.,* (1979) is 5.2Ma and the youngest age reported for this group of rocks ranges from 1.3-0.9Ma.

- Basaltic lava flows, spatter and cinder cones and maars (younger volcanics): These are associated with sporadic intermediate and acidic volcanics. The formation of these rocks is estimated to be in the Holocene (Mohr , 1961).

The maars (volcanic craters) cut into pre eruption surfaces and pre eruption rocks, as evidenced by the presence of older basaltic and rhyolitic lavas at the base of the walls of the craters. Several ejecta beds of phereatomagmatic maars were observed forming up the maar walls. The pyroclastic material consists of a juvenile fraction of dominantly basaltic scoria and a minor fraction of acidic ash-pumice sized tephras and a large proportion of bomb/block sized clasts of country rocks. As can be observed from the geological map, some of the maar rims are later draped by scoria cones. As the model of maar formation by Lorenz (1986) in model figure (fig. 5) testifies, the scoria cones that commonly develop around the maar lakes are emplaced along concentric fractures that develop around the maars. During this event ground water is sealed off by the collapse dieatrems and eruptive style changes from phreatomagmatic style of maars to lava fountaining of scoria cones.

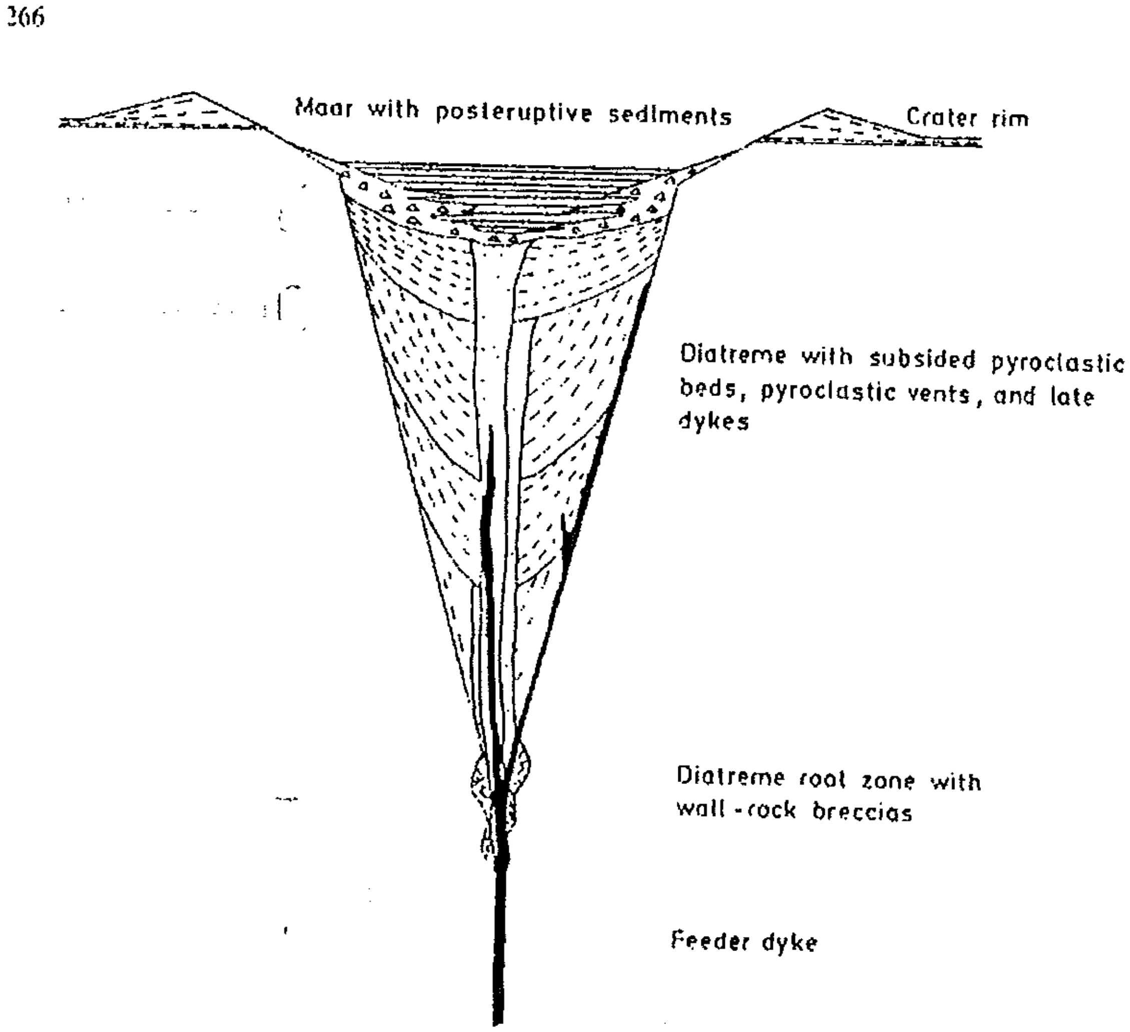


Figure 5. Internal structure of maar, after Lorenz (1986)

Gasparone *et al.*,(1993) suggest that the younger volcanics mostly fall in the field of basalt, with a few intermediate and evolved products. This basic unit is derived by mantle melting as rifting extends. The associated acids are the result of mixing of basaltic magma with acidic end members of possible crustal sources. The voluminous older acidic and intermediate products are derived by fractional crystallization of mantle-derived magma.

The work of Mohr (1961), on the other hand suggests, the possible presence of carbonatite magma at depth which gave rise to the hyper alkaline rocks and carbonated hot springs of the younger volcanics. In this study there are no hot springs observed in the area, except an indication of thermal activity infered from sinter on the northern part of lake Arenguade. According to Mohr (1961) the craters were formed 7000 years ago, on the basis of a simple archaeological material found within the pyroclastic rocks making up the crater walls.

There are no major differences in the geology of the catchment of the lakes, except minor variations in the proportion of the different lithologies. Lake Kilole and Lake Hora have some calcareous deposits in their catchment. Mohr (1961) suggests the presence of hydrothermal activity at the time of crater explosion to explain the calcareous deposits. But surficial chemical weathering of plagioclase feldspars, pyroxenes and calcic amphiboles from the basic volcanics can give rise to secondary carbonate. Therefore Mohr's suggestion of hydrothermal activity may not work.

3.2 Tectonics

The Bishoftu region is situated on the ill-defined western margin of the Main Ethiopian Rift (MER). The major faults in the region predate the explosion craters and are oriented parallel to the main Ethiopian rift in a NE-SW direction approximately with N45°E trend. The orientation of these major faults is indicated in figure 4. The second set of faults which is not very common appears to parallel the Wonji fault belt. One of the major gorges, (along which the old Basalt unit is exposed) located in the southeastern corner of the area (fig. 4) follow the orientation of the belt.

The second major tectonic features, discussed by Tesfaye Korme *et al.*, (1998), are extension fractures. These are observed from a LandSat Image. The fractures are either directly observed or are inferred from the orientation of volcanic vents and linear clusters of scoria cones and maars. The same work indicates that, the maars are rooted on these extension fractures and more than one maar can be observed on a fracture. The strike of lenticular extension fractures inferred from elongated volcanic vents and rectilinear clusters varies between N26° and N49°, with an average of N39° (fig. 6). According to the same work the linear clusters are situated in zones free from the influence of large faults, and they are certainly rooted on extension fractures.

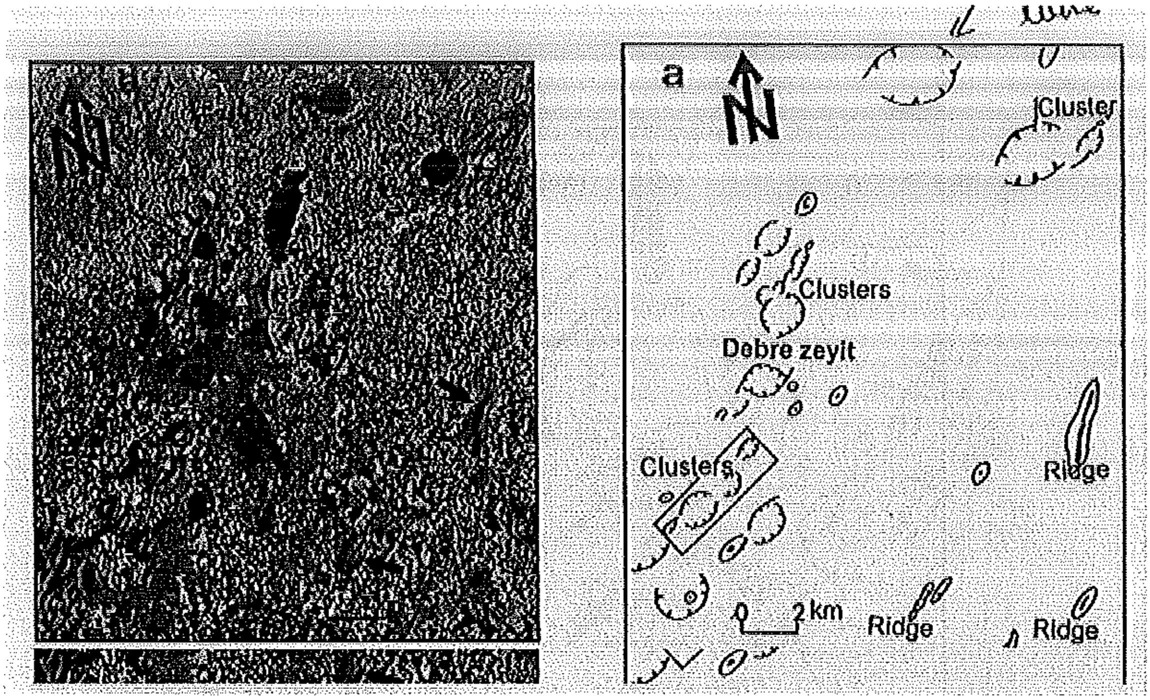


Figure 6 Orientation of extension fractures inferred from maars and volcanic clusters from Landsat satellite image, after Tesfaye *et al.,* (1998)

The younger faults and extension fractures may produce a secondary permeability and promote surface water-groundwater hydraulic connection.

CHAPTER FOUR

HYDROMETEOROLOGY AND HYDROLOGY

4.1. Climate over Ethiopia

The climate of Ethiopia has been described by Griffits (1972) and summarized by Gamachu (1977) as follows:

> Ethiopia is situated within the tropics and therefore is subject to comparatively small seasonal variations in temperature, but experiences considerable diurnal fluctuations in temperature. The area however shows great seasonal variation in rainfall and humidity. Most of the annual rainfall occurs between late June and mid September. During this period the prevailing southwesterly winds bring moist air across the Congo basin from the South Atlantic and Gulf of Guinea. The driest time of the year is usually the months of November to January, when the prevailing winds are the northeast trades, bringing dry air from central Asia. The lowest daily minimum temperatures usually occur during this period. In most years a shorter period of fairly heavy rainfall (the little rains) can be distinguished sometime between February and May. But in some years this scarcely occurs, and in other years there is no very obvious interruption between the rains of the main wet season and the period of the small rains. The weather throughout the Ethiopian highlands may vary considerably from one year to another. This is due, in part at least, to the passage of the Inter tropical Convergence Zone over Ethiopia.

4.2. Hydrologic Behavior of the Lakes

4.2.1 Crater Lakes

Unlike crater lakes that are formed over the top of volcanoes the hydrologic behavior of maar lakes are here believed to be significantly influenced by ground water. The net gain of water for such lake comes from precipitation on the lake, surface runoff from the crater walls and from ground water. The crater lakes of Hora, Babogaya, Arenguade and Bishoftu are closed with respect to surface water outflow. The main water loss of these lakes is basically via evaporation and minor groundwater outflow. Abstraction of water for domestic, agricultural and industrial use is negligible. Geology, climate, hydrology and geochemical reactions in the lakes therefore basically control the chemistry of the four lakes.

4.2.2. Lake Chelekleka

Lake Chelekleka occupies a shallow tectonic depression bordering lake Hora from the west and lake Babogaya from the North and West. At its maximum level during the 1972-1973, the lake occupied 1.7km^2 and a maximum depth of 1.5m (Getachew Tefera, 1980). After rainy season the lake commonly reduceds in depth, or is separated into many small lakes (the major one occupying the western part of lake Hora) or completely dries up in dry years. The smaller Chelekleka which is found in the Northern part of lake Babogaya dries up between the months of March and May. The Larger lake Chelekleka which is located in the western side of Lake Hora and Babogaya has remained a permanent body of water only since 1968-69 (Getachew Tefera, 1980). The likely reason for this is on the one hand the high precipitation that prevailed in late 1960's and early 1970's and on the other hand due to a prolonged siltation of the basin by the flood reducing infiltration loss so that the lake remained a permanent body of water.

The water balance of lake Chelekleka has not been yet studied. It is observed that the net input of water to the lake comes from direct rainfall on the lake and flood runoff from the catchment.

It is observed that as the lake shrinks during the dry seasons the bottom of the lake is exposed to the surface. This exposed surface is made of silt and clay materials which reduces percolation loss. The minimum vertical permeability of the volcaniclastic rocks (Tamiru, 1992) making up the basin also reduces the water loss by percolation. The electrical conductivity of the lake on the other hand ranges between 0.15-0.2 mS/cm which is characteristic of surface waters indicating that the lake is close to groundwater inflow. It is believed that there is no hydraulic connection between lake Chelekleka and the crater lakes although the lake levels of Hora, Babogaya and Bishoftiu are found below the level of lake Chelekleka. The net water loss from the lake is via evaporation. The role-played by groundwater inflow and outflow is believed to be negligible and the lake is considered as a drying up pond (a lake that dries if there is no surface water inflow).

4.2.3. Artificial Lakes

Mohr (1961) recognized more that fifteen crater depression of which only five are filled with a permanent body of water. One of these dry depressions, is later filled by diverting Wedecha river, to form an artificial lake called Kuriftu (fig. 3) for irrigation practice in the area. The lake gains a large part of its water from the river and a small proportion comes from precipitation on the lake. Groundwater inflow plays a minimum role in the water balance of this lake as the static water level in the area is well below the lake. The lake has an approximate depth of 8m. The seepage loss from this lake is not well known. Another artificial lake which is often confused with crater lakes, as some authors observed from satellite image processing is lake Dibi. It is a lake filling a valley depression rather than filling a volcano-tectonically formed depression.

Lake Kilole a natural crater lake was influenced by diversion of the Mojo river in order to use the lake as an artificial reservoir. The chemistry, trophic status and hydrology of the lake are influenced accordingly.

4.3. Precipitation

The precipitation of the area shows large seasonal and inter annual variability. The record of precipitation is available since 1953. The precipitation is recorded in the Agricultural Research Institute and the Air Force stations located in the town of Debre Zeyit. There is a minor difference in record of rainfall between the two stations which are less that 3Km apart. The average of five years mean annual rainfall for the Airforce station is 820mm/yr. The 38 years average of mean annual rainfall at the Agricultural research station (appendix 1) is 838mm/yr. For this work the average of the two stations which is about ***830*** mm/yr. is considered. The rainfall distribution shows high rainfall in the months of June, July and August and small rain in March and April (see fig. 6). There is a slight decrease in rainfall in the month of May which is the period of transition from the small spring rains to the big summer rains.

The average precipitation of Addis Ababa station, which is located at elevation of 2300m and found within 30Km radius, is 1100mm/yr. This testifies the great spatial variability of rainfall in the region and an increase in precipitation with altitude.

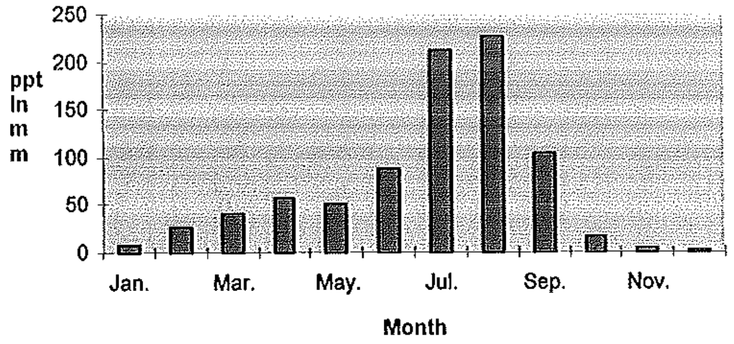


Figure 6 precipitation pattern of Debrezeyit, at IAR station

The rainfall record at IAR station shows large inter-annual variability (fig.7). The highest rainfall record is observed in the early and late 1960's. This high record in precipitation in Debre Zeyit region corresponds with the East African high lake levels (Tanganyika, Victoria) and the Nile discharge at Dongola. Grove (1996) has reported this high lake level and high river discharges and it implies a regional effect.

The five years moving average trend shows that the rainfall has a rising trend between late 1950's and late 1960's and a general decreasing trend since late1960's.

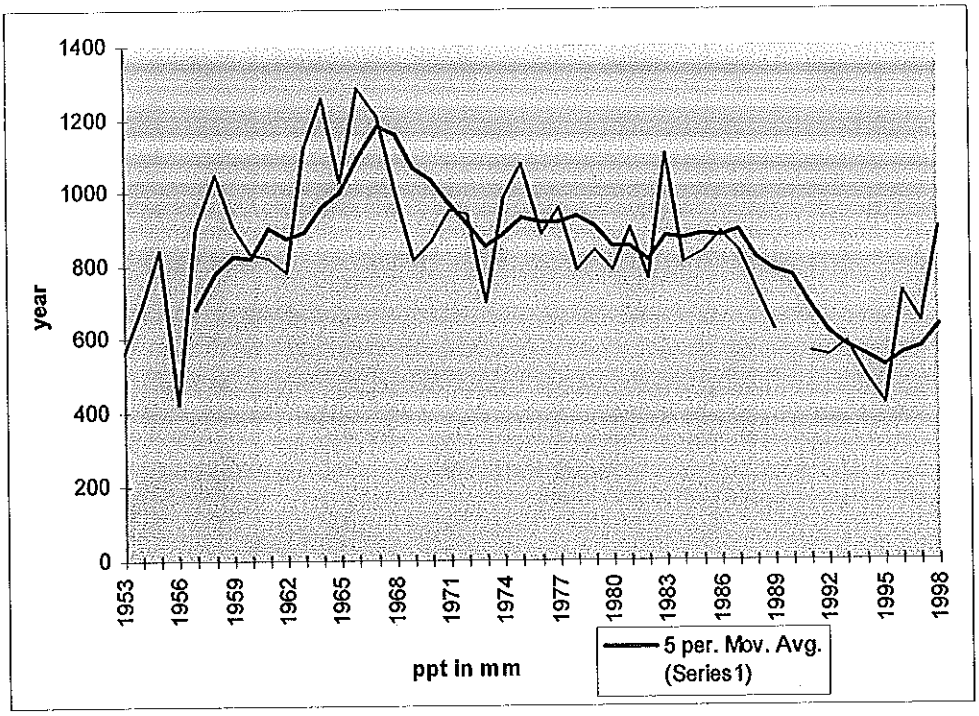


Figure 7. Annual variability in rainfall at IAR station, Debre Zeyit.

4.4. Evaporation

Evaporation from lakes represents the largest percentage of water budget component. Therefore its accurate determination is crucial in order to optimize the water budget of the lakes. There are no sufficiently reliable methods for the determination of evaporation from open water bodies. In this study, in order to arrive at a good representative figure of open water evaporation for the region, various methods have been employed. These are **Penman method, energy balance, mass transfer and pan evaporation approachs.** The meteorological data required in these evaporation calculations are summarized in table 2.

The required data

a. Solar short wave radiation

The direct short wave and long-wave radiation measurement is not available for the Debre Zeyit station. A KIPP & ZONEN Solarimeter record is available in Addis Ababa University Geophysical Observatory. This instrument measures the incoming short-wave radiation (Kin). When measurement is unavailable in a given region, clear sky solar radiation obtained from standard tables after being corrected for cloud cover, can be substituted for the measurement. The corrected incoming short-wave radiation determined by this method and the measurement taken at the Geophysical Observatory show a fairly similar value (table3)

In fact, the value at the Geophysical Observatory is slightly lower, which may be attribute to a larger fraction of cloud cover over Addis Ababa than Debre Zeyit, because the fraction of cloud cover used to correct the clear sky solar radiation is that of the Debre Zeyit area..

From the table, it is observed that the highest net short-wave radiation is in the month of May and the lowest is in the months of July and August. The value obtained from a standard table is used in this work to for the Penman's method and energy balance evaporation estimations.

b. Solar long-wave radiation

The long-wave radiation measurement is apparently unavailable in the region. Therefore the net long-wave radiation is calculated based on Kohler and Parmele (1967) method in the Penman approach and from the relations based on Stefan-Boltzmann equation in the Energy balance approach.

c. Temperature, relative humidity, wind speed and sunshine hours

The monthly mean wind speed at 2m is available for Debre Zeyit IAR station (Table 2 and appendix 2). The value is given in a unit of m/s. The data shows that the months of February, March, April and May are the most windy months. August and September are less windy. A fifteen years wind speed data is averaged and used in this work.

	Jan	Feb.	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
Va	195	209	227	228	235	169	157	131	114	186	189	196
Ta	18	19	20.6	21	21	20	19	18.7	18.6	18	16.7	16.9
Sun hr	8.7	8.3	8.4	6.7	9.0	6.8	5.6	5.5	6.9	9.2	9.5	9.7
Kcs	755	820	870	895	885	870	870	885	880	830	770	730
Kin	511	537	574	506	610	496	425	428	508	579	547	525
1-C	0.7	0.69	0.7	0.6	0.8	0.6	0.5	0.46	0.58	0.8	0.79	0.8
C	0.3	0.31	0.3	0.4	0.3	0.4	0.5	0.54	0.42	0.2	0.21	0.2
Wa	53	54.2	53.7	58	51	64	74	76.8	73.6	57	52.1	52.3

Table 2. Summary of meteorological data at Debre Zeyit, wind speed in m/s (va), air temprature in oC (ta), sunshine hours, clear sky solar radiation at 10o latitude (cal/cm2/day), fraction of sky covered by cloud (C), and relative humidity (Wa)

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Spt	Oct	Nov	Dec	
481	496	534	508	510	394	331	366	403	601	582	539	a
511	537	547	506	610	496	425	428	508	579	547	525	b

Table 3. Incoming short-wave solar radiation (Kin) in cal/cm^2/day. a: measurement at Geophysical Observatory; b: value calculated from clear sky radiation for cloud cover at 10° latitude.

The maximum and minimum air temperature data of seven years (appendix 3a, 3b) have been averaged and used (table 2). The average annual temperature of the study area is around 19.5 °C. Highest temperature is observed for the months of March, April, May and June. The driest months: October, November and December have the lowest temperature.

A ten years (1987-96) relative humidity record at 0600, 1200 and 1800 hours is integrated (appendix 4a, 4b, 4c,4d) to calculate the daily mean relative humidity of the area which is 0.59. The months of July, August and September are the most humid months and May is the driest (table 2).

Eight year's sunshine hours is averaged for the Debre Zeyit stations. The data reveals that, out of 12 maximum possible hours only 2-4 hours are covered by cloud in the months from October to December, and in the months of January, February, March and May. July and August have the lowest sunshine hours. The fraction of sky covered by cloud (C) is calculated from the ratio between the observed and the maximum possible sunshine hour and it is presented in table 2. See also appendix 5.

4.3.1 Pan evaporation approach

A ten-year pan evaporation data is available in the Airforce meteorological station and IAR of Debre Zeyit (appendix 6). The average annual pan evaporation is 2177mm. Open water evaporation have been calculated after multiplying this value by a pan coefficient.

The evaporation from evaporation pan differs from a lake in having a far less storage capacity, in lacking surface or ground water inputs, and in having sides exposed to air and sun. For the Ethiopian Rift open water evaporation, a pan coefficient between 0.75 and 0.85 is usually taken. Tenalem Ayenew (1998) took a pan coefficient of 0.83 for Ziway - Shalla lakes. As the crater lakes are much more protected from wind a pan coefficient of 0.79 is taken in this work. The average pan evaporation after being multiplied by the pan coefficient gives an evaporation value of ***1720*** mm/yr. The result reveals that the months of maximum evaporation are January, February, March, April and May and minimum evaporation takes place in the months of July and August.

4.3.2 Penman method

The Penman approach requires representative data on net short-wave radiation, net long-wave radiation, wind speed, air temperature and relative humidity to determine open water evaporation. This method combine both the mass transfer and the energy balance methods. In the separate cases a meteorological data that is not usually available and practically difficult to measure, surface kinetic temperature is required. The Penman (combination equation) does not consider this kinetic temperature.

The Equation can be written as

$$E = \frac{s(T_a)(K+L)+\gamma K_E \rho_w \lambda_v V_a \left[e_{sat}(T_a)\right](1-W_a)}{\rho_w \lambda_v \left[s(T_a)+\gamma\right]}$$ **(Equation 1)**

E is evaporation in cm/day

The Empirical constants are given as:

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

ρ_w is mass density of water, 1g/cm^3

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

Va is wind speed in cm/s, from meteorological data

Wa is relative humidity, form meteorological data

s(Ta) is slope of saturation vapor pressure vs. temperature of the air

$$s(T_a) = \frac{25083}{(T+237.3)^2}\exp\left(\frac{17.3T}{T+237.3}\right)$$

$e_{sat}(T_a) = 6.11\exp\left(\frac{17.3T}{T+237.3}\right)$ is saturated vapor pressure of the atmosphere

γ is psychrometric constant , about $0.66mbC^{o1}$

γ* the modified psycrometric constant

The empirically determined $s(Ta)$, $e_{sat}(Ta)$, the modified psycrometric constant γ^* an effective emmisivity of the atmosphere are given in table 4. K the net short-wave radiation in cal/cm^2/day is given as:

$$K = K_{in}(1-a) \quad \textbf{(Equation 2)}$$

a, albedo, Koberg (1964) in Dingman 1994 presented an empirical way relation giving albedo of a water surface as a function of K_{in}

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

K_{in}, incoming short wave radiation, calculated from the equation

$$K_{in} = Kcs\,(0.803-0.340C-0.458C^2), \text{ Leopold 1978}$$

C is the fraction of sky covered by cloud, table 2.

Kcs is the clear sky solar radiation at 10 °N, table 2.

The result of incoming short-wave radiation determined from empirical equations and the record at the Geophysical Observatory of Addis Ababa University is given in table3.

The net short-wave solar radiation is the difference between the incoming short-wave radiation and the reflected short-wave radiation (equation 2). By using the empirically determined incoming short-wave radiation the net short-wave radiation is calculated and given in table 5.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
$S(T_a)$	1.3	1.38	1.5	1.51	1.54	1.46	1.4	1.36	1.34	1.3	1.21	1.23
$e_{sat}(T_a)$	20.8	22	24.3	24.6	25	23.6	22	21.7	21.42	20	19	19.3
γ^*	0.82	0.77	0.72	0.72	0.7	0.96	1	1.23	1.409	0.9	0.83	0.81
ε_{at}	0.83	0.85	0.86	0.91	0.84	0.92	1	0.97	0.921	0.8	0.8	0.79

Table 4. The slope of saturated vapour pressure vs. air temperature (s (T_a)), saturated vapor pressure of the atmposphere $e_{sat}(T_a)$, modified psycrometric constant (γ^*) and emmisivity of the atmosphere (ε_{at})

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
K	474	499	535	469	570	460	391	393	471	540	508	487

Table 5. Net short-wave radiation in cal/cm^2/day at Debre Zeyit

	Jan.	**Feb.**	**Mar.**	**Apr.**	**May**	**Jun.**	**Jul.**	**Aug.**	**Sep.**	**Oct.**	**Nov.**	**Dec.**
Lat	695	722	746	795	735	794	818	822	780.3	687	658	658
L^*	-142	-126	-121	-76	-137	-69	-32	-26	-64.8	-145	-163	-165

Table 6. Incoming (*Lat*) & net long-wave radiation (L^*) in cal/cm^2/day determined by Kohler & Parmele equation.

L net long-wave radiation (cal/cm^2/day)

While Penman (1948) intended his approach to eliminate the need for surface temperature data, such data are required to evaluate the long wave energy exchange (see energy balance method). Kohler and Parmele (1967) showed that another approximation could be made to avoid this problem with little error, and arrived at the following modifications of Penman equation.

replace L with $\varepsilon_w L_{at} - \varepsilon_w \sigma(Ta + 273.15)^4 = L^*$

replace γ with $\gamma + \dfrac{4\varepsilon_w \sigma(Ta + 273.15)^4}{K_E \rho_w \lambda_v v_a} = \gamma^*$

where,

ε_w is emmisivity of water, 0.97

$L_{at} = \varepsilon_{at}\sigma(Ta + 273.15)^4$, incoming atmospheric long-wave radiation

ε_{at} is effective emmisivity (table 4) of the atmosphere that is a function of humidity and cloud cover (table)

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

e_a is vapor pressure of the air in mb, see section mass transfer approach, table 7.

σ is Stefan-Boltzmann constant, 1.17×10^{-7} cal cm^{-2} day^{-1} K^{-4}

Ta is average air temperature in °C , table 2.

The empirically determined, Koheler's psycrometric constant γ^* and effective emmisivity of the atmosphere is given in table 4.

Using the empirical constants given in this section (the incoming long-wave radiation and the Koheler's net long-wave radiation substitute are determined and given in table 6.

4.3.3 Mass transfer approach

Mass transfer approach uses the fact that evaporation is a diffusive process. The mass transfer approach considers the temperature of evaporating surface. The temperature of evaporating surface T_s is estimated from the surface temperature of Ziway-Shala lakes that Tenalem (1998) determined from satellite images.

The kinetic temperature of the Ziway -Shalla lakes shows that on a lake the highest temperature is attained over the lake near geothermal influence, the lowest kinetic temperature is observed near the entrance of surface water/or groundwater to the lake. The part of the lakes which are not influenced by geothermal and river-groundwater input show a surface temperature that vary between 25-27°C. There is a close similarity between the lakes water temperature at the surface and the kinetic surface temperature determined from satellite image. The Ziway Shalla lakes water temperature varies between 24 and 28 °C. By extension the average lake water temperature of Bishoftu crater lakes is estimated to represent the surface kinetic temperature at the evaporating surface. The average lake water temperature is 23°C. The same value is taken for kinetic surface temperature of BCLs.

The evaporation rate in mass transfer method can be written as:

$E = (bo + bVa)(e_s - e_a)$ **(Equation 3a)**

Where bo and b_1 are empirical constants that depend chiefly on the height at which wind speed and air vapor pressure is measured. If wind speed measurement is taken at 200cm above the ground surface the equation can be rewritten as,

$E = K_E Va(e_s - e_a)$, *where E is in cm/day* **(Equation 3b)**

e_a vapor pressure of the atmosphere is given by

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

e_s vapor pressure of the evaporating surface, depend on the temperature of evaporating surface, T_s.

$$e_s = 6.11\exp(\frac{17.3T_s}{T_s + 237.3})$$

The estimated kinetic surface temperature is 23 °C, vapor pressure of evaporating surface is 28.2 mb and atmospheric vapor pressure is presented in table 7.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
e_a	11	11.9	13.1	14.1	12.8	15.1	16	16.6	15.8	12	9.9	10.1

Table7. Atmospheric vapor pressure in mb.

	Jan.	**Feb.**	**Mar.**	**Apr.**	**May**	**Jun.**	**Jul**	**Aug.**	**Sep.**	**Oct**	**Nov.**	**Dec.**
L	-198	-173	-149	-102	-160	-103	-80	-75	-116	-206	-235	-235

Table8. Net long-wave radiation in cal/cm^2/day determined by Stefan-Boltzmann equation.

	Jan.	**Feb.**	**Mar.**	**Apr.**	**May**	**Jun.**	**Jul**	**Aug.**	**Sep.**	**Oct.**	**Nov.**	**Dec.**
B	0.17	0.15	0.1	0.09	0.08	0.13	0.2	0.22	0.212	0.2	0.21	0.2

Table 9. Bowen's ratio.

4.3.4 Energy balance approach

The energy balance approach to determine the average rate of evaporation over a time period of Δt involves measuring or otherwise determining the rates of energy input and output by various modes, along with a change in energy stored in the water body. The energy balance method can be expressed as:

$$E = \frac{K + L - G - H + Aw - \frac{\Delta Q}{\Delta t}}{\rho_w \lambda_v} \quad E \text{ in cm/day} \qquad \textbf{(Equation 4)}$$

But the sensible heat H can be substituted by Bowen ration so that the data of sensible heat exchange is not required.

$$H = B\lambda_v \rho_w E \qquad \textbf{(Equation 5)}$$

Substituting equation 5 into equation 4 we get a modified energy balance equation which can be expressed as,

$$E = \frac{K + L - G + Aw - \frac{\Delta Q}{\Delta t}}{\rho_w \lambda_v (1 + B)} \qquad \textbf{(Equation 6)}$$

Where,

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

K: Net short-wave radiation, table 5.

L: Net long-wave radiation, table 8.

The net long-wave radiation in this approach is determined from the Stefan - Boltzmann equation that is expressed as,

$$L = \varepsilon_w \varepsilon_{at} \sigma (T_a + 273.15)^4 - \varepsilon_w \sigma (T_s + 273.15)^4 \qquad \textbf{(Equation 7)}$$

T_s is surface kinetic temperature which is estimated to be 23°C

The empirically determined net long-wave radiation using Stefan-Boltzmann equation is given in table 8.

B: Bowen Ratio, which is a function of kinetic temperature and vapor pressure of evaporating surface and overlying air

$$B = \frac{c_a P(Ts - Ta)}{0.622\lambda_v (e_s - e_a)}$$

ca is heat capacity of air, 0.24cal g^{-1} C^{o-1}

P atmospheric pressure in mb, determined from elevation pressure graph

The B value obtained from the equation is given in table 9.

Aw: water advected energy, assumed to be negligible

$\frac{\Delta Q}{\Delta t}$: change in stored energy over the time of observation, is assumed to be negligible

4.3.5 Results and Discussion

After running mathematical operation of the empirical formulae, evaporation in cm/day is calculated from meteorological data and empirically determined values integrated over a month (table 10). The daily evaporation result is summed up to give annual evaporation.

The annual evaporation value is summarized and is given in table 11. The calculation shows unreasonably low evaporation if mass transfer approach is followed. Because the vapor pressures used in the mass transfer equation are determined from measured temperatures via the nonlinear relation of equation 3b, and because wind speed and vapor pressure differences may be correlated, one cannot assume that a mass transfer equation will give the correct time averaged rate of evaporation when time averaged temperatures and wind speeds are used as independent variables.

Method	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	annual
Energy	0.4	0.48	0.6	0.57	0.65	0.53	0.4	0.44	0.497	0.5	0.38	0.39	177
Mass	0.42	0.43	0.43	0.4	0.46	0.28	0.2	0.19	0.178	0.4	0.44	0.45	130.7
Penman	0.44	0.5	0.58	0.55	0.62	0.47	0.4	0.37	0.377	0.5	0.43	0.42	171

Table 10. Daily evaporation integrated over a month and annual evaporation estimate in cm, Energy (energy balance method), mass (mass transfer method), Penman (Penman method)

Method	Annual evaporation average in mm/yr.
Penman	1710
Mass transfer	1307
Energy balance	1770
Pan evaporation	1720

Table 11. Annual evaporation in mm

Penman, energy balance and pan approaches produce a reasonable annual evaporation value. Excluding mass transfer evaporation the average of the three approaches give an open water evaporation rate of ***1730 mm.***

4.5. Variability in evaporation rate between the crater lakes.

The evaporation value calculated above, based on the three approaches have not considered the evaporation difference among the crater lakes. Due to their varying size, heat content and degree of exposure to wind the lakes should have different rate of evaporation. In order to assess this the energy balance that contains the heat storage expression (equation 6) in its equation is reconsidered.

In the forgoing energy balance approach discussion, the heat content of the lakes is neglected. In order to compare the evaporation rates, the heat content determined by Wood *et al.,* 1976, is considered. *Wood et al.,* 1976, based on temperature measurements determined the heat content of the five Bishoftu Crater Lakes. The annual heat content of the lakes in cal/cm^2 and cal/lake is given in table 12. The energy balance approach equation can be written as

$$E = \frac{K + L - \frac{\Delta Q}{\Delta t}}{\rho_w \lambda_v (1 + B)}$$

(Equation 8)

Lake	cal/cm^2	cal/lake
Kilole	1300	1x10^{13}
Bishoftu	4.950	4.6x10^{13}
Babogaya	5700	3.3 x 10^{13}
Arenguade	3100	1.7 x 10^{13}

Table 12. Annual heat content of Bishoftu Crater Lakes, Wood *et al*, 1976.

Substituting the heat content of the lakes given in table 12, the open water energy balance evaporation rate is modified. This modified evaporation rate is presented in table 13.

Babogaya	1686
Bishoftu	1697
Kilole	1751
Arengude	1725

Table 13. Evaporation difference between the Bishoftu Crater Lakes in mm/yr

The figure shows that there is a slight difference in the rate of evaporation among the Bishoftu Crater Lakes. The highest rate of evaporation is calculated for the shallowest and less protected lake Kilole. A single representative value can be taken for the lakes evaporation in the water budget calculation. The average evaporation rate of ***1710mm/yr*** can be conveniently taken as a representative of open water evaporation over the Bishoftu region.

4.6 Recent lake level fluctuation

Data on historical lake level fluctuation is available intermittently since 1982. Since this time the lake level shows a rising trend (figure 8). Although the data of lake level fluctuation is not obtained in the 1990's, observation has shown that it is in this period that the lakes rose by more than 3 meters as compared to the 1980's lake level. The 1990's lake height is estimated from drowned houses and road around the lakes that are now submerged below the lake.

As indicated on the figure the correlation between the annual precipitation and lake level measured in October (the month immediately after the rainy season) shows a good positive correlation before 1988. The highest peak in precipitation of 1984 for example corresponds with a rising lake level. After this short peak in precipitation the lake continued to rise until 1986. Where as the rainfall pattern starts to decline since 1986. This declining rainfall pattern corresponds to the falling limb in lake level between 1986 and 1888.

The positive correlation between rainfall and precipitation breaks since 1988. The rainfall has a declining trend in this period of the decade and the lake level has still a rising trend.

The break in positive correlation between the lake level and annual rainfall most probbly be the result of a change in hydrology of the basin induced by human activity: such as construction of dams and irrigation activities and diversion of rives into some of the lakes which started to take place since early 1980's.

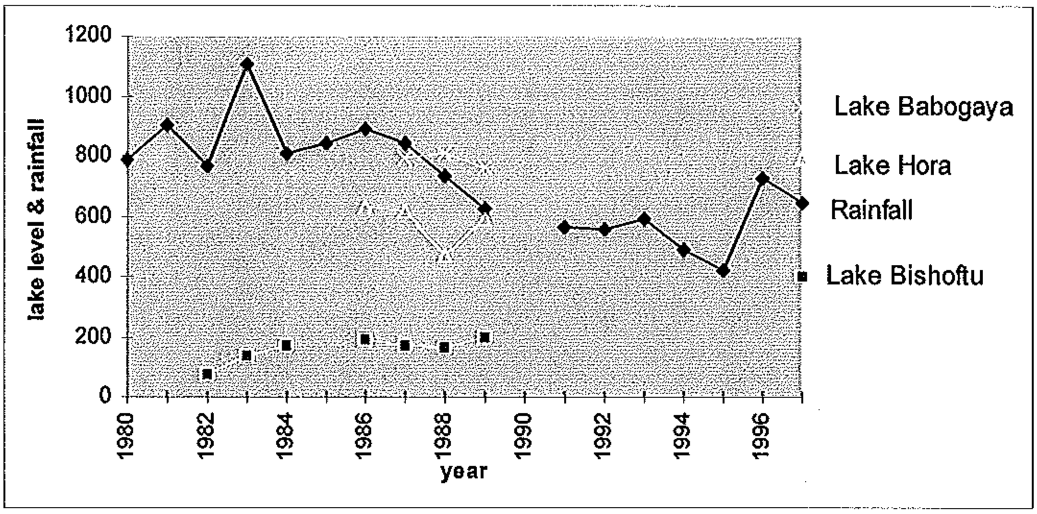


Figure 8. Precipitation pattern and lake level fluctuation. Note: the 1998 lake level is estimated from drowned trees, houses and road, rainfall in mm/yr., lake level in mm above the datum.

Although complete lake level data is not obtained it can be concluded that land use practice affected the status of the lakes in recent decades.

CHAPTER FIVE

HYDROGEOLOGY

5.1 Introduction

The objective of hydrogeological investigation is to determine the rate of groundwater-lake (surface) water interaction along with geochemical and isotope mass balance approaches. The idea obtained from hydrogeological investigation helps to give an idea about the quantity of groundwater inflow and outflow component into and out of the lakes. Apart from this, the data obtained from hydrogeological investigations is used to determine the aquifer characteristics and distinguish major water bearing rocks for groundwater utilization.

In the region more than 50 bore wells and numerous hand-dug wells are found. The location and the names of these wells are indicated in figure 2. The depth of the bore wells ranges from 30 to 180m. The static water level varies from 20m to 150m.

5.2 Hydrostratigraphy

From the existing geological well log and geophysical information two kinds of aquifers can be distinguished. The old basalt (Addis Ababa Basalt) and the basic pyroclastic rocks making up the vicinity of the lakes and the town of Debre Zeyit.

The Old basalt

The old basalt is fractured. It covers the base of the volcanic units of the study area. This aquifer is penetrated only by very few deep bore wells (eg. Yerer Buti well). The geological well log of Yerer Buti well indicate that this basaltic unit is made up of fresh fractured basalt interbeded with clay, unwelded pyroclastic rocks and scoria. This aquifer covers an extensive area in the region between Addis Ababa and Debre Zeyit. The same aquifer provides water for the Akaki well field for the supply of Addis Ababa and Akaki town. Aynalem Ali (1999) determined the transmisivity of this aquifer to range between 389 to 21600 m2/day. Tesfaye Cherinet (1988) considered this aquifer as the most productive in the region.

The young basic pyroclastics and associated rocks.

The young basic pyroclastic rocks interbeded with minor acidic products make up the largest part of the Debre Zeyit area. The formation of this unit is contemporaneous with the explosion of the craters. Most of the groundwater in Debre Zeyit area is abstracted from this aquifer. The aquifer constants of these rocks have been determined by various works (Berhane Melaku, 1982; Tamiru Alemayehu, 1992). What hydrogeologic boundary conditions this authors assumed is not clearly indicated.

The Yerer and Bede Gebabe Volcanic rocks.

These rocks are made up of acidic and intermediate volcanic rocks which are cut by numerous NE-SW running faults. The Yerer volcanic unit is located in the Northern part of the study area and the Bede Gebabe volcanic unit is located in the southern part of the study area. These rocks are unimportant as far as groundwater exploration is concerned. The faults, joints and fractures common on these rocks however permit fast infiltration and recharge of the above two aquifers.

Scoria cones

The age of this unit is equivalent to the age of explosion craters and the formation of basic pyroclastic rocks. This cones dotted the flat plain in the Debre Zeyit area. The thickness reaches up to 40m. This unit has a good porosity and permeability. Because of their limited aerial extent and position, this unit is also unimportant for groundwater exploration. But it provides recharge for the underlying aquifers.

5.3. Static Water Level and Peizometric Map

A problem with collecting hydrogeological data in the Debre Zeyit region is that the wells have no access for water level measurements because they are blocked. Therefore, water levels are taken from existing bore hole records. These data refer to the data at the time of well completion, which is between 1960 and 1999. This introduces errors in defining peizometric contours, because of the temporal variation in groundwater levels. The peizometric level can also be influenced by the depth of penetration of the wells into the aquifers. This also introduces error into the peziometric map. The third source of error comes from the measurement of the ground elevation. The ground elevation is measured using a Terra altimeter with an error up to 5m and the position of the wells are determined using Magellan Px GPS. Because of these it is not easy to precisely show the actual local groundwater flow direction in the region. The regional groundwater flow direction is, however said to be towards SE (Tesfaye Cherinet, 1988).

Figure 9 shows an attempted local peizometric map. The figure is constructed using SURFER computer program. There is a clear southward flow from the northern region (Base of Yerer) towards the town and the Genda Gorba well field. In the vicinity of the three lakes however the direction of groundwater flow is not well defined but there is an indication of a westward flow. This piezometric map conforms with the hydrogeological map of Tamiru Alemayehu (1992)

5.4. Transmisivity and permeability of the aquifers.

AQTESOLVE for Windows computer program has been run for the analysis of the aquifer properties using pumping test data. Geological well log and geophysical evidences shows that the groundwater condition is semi-confined. The Leaky Aquifer Boundary Condition is taken to determine the aquifer characteristics. The data that are

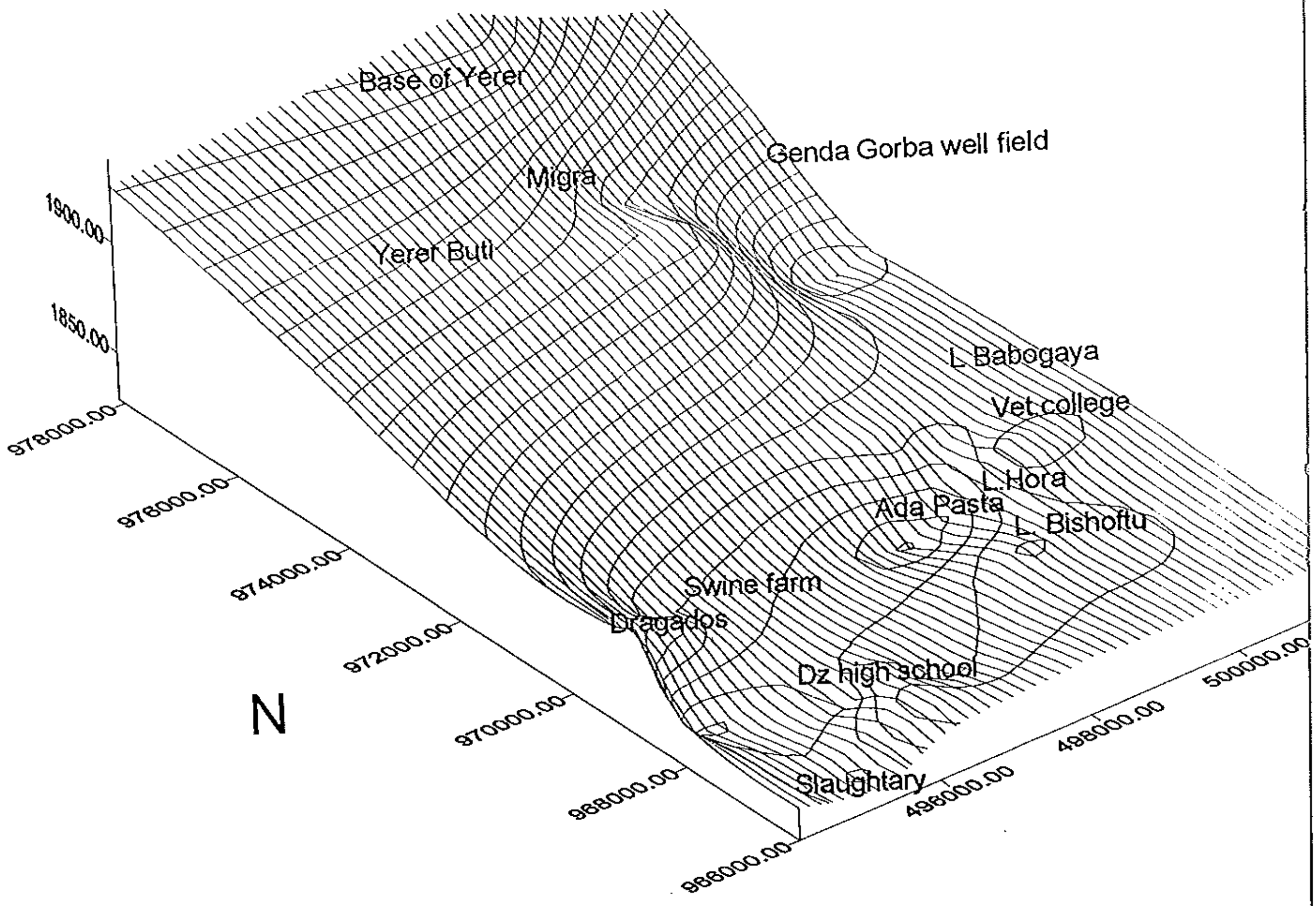


Fig 9A. Piezometric map of Debre Zeyit Region required: the well depth, casing radius, aquifer thickness and screen position is available only for few wells in the area. No complete data is available for the fractured basalt aquifer.

The aquifer characteristics are determined only for the younger basic pyroclastics. A constant rate of pumping test is utilized. The aquifer thickness is observed from the geologic well log. Isotropic and homogenous media and a fully penetrating well is assumed. Since there are no observation wells nearby the discharging well to measure the draw down further away, no good measure of storativity were possible. The permeability of the aquifers is calculated by dividing the transmisivity by the aquifer thickness.

The transmisivity of the aquifers ranges from 1100 to 18000 m2/day. The strict validity of these values are questionable, while factors such as partial penetration, anisotropy, and errors during pumping test results are likely to be common. The aquifer property values are equally variable as that of the Old basalt aquifer at the Akaki well field determined by Aynalem (1999).

5.5 Geothermal waters

Unlike the Ethiopian rift valley, the Bishoftu area is characterized by normal geothermal gradients. This is evidenced by minimal hot water activity and the geologic history of the area. The various rock units in the area are thought to originate under fractional crystallization of mantle-derived magma (Gasparone *et al.*, 1993, Gezahegn, per. communication). The youngest basalts and scorias, however, are derived from mantle and emplaced rapidly along extension fractures. The areas geologic history shifted from fractional crystallization in a magma chamber to mantle derived scorias and basalts, the geothermal gradient shifted accordingly, from high during the first acid volcanic generation stage to low during the emplacement of younger volcancics: maars and scoria cones.

Temperature depth variation in Lake Babogaya (section 6.4) indicate a uniform lowering of temperature from 24°C at the surface to about 20°C at the lake bottom, the same decreasing temperature depth gradient is observed by Baxter *et al*, (1978). This may indicate the absence of a geothermal water influx or that the inflowing thermal water is so slight that the temperature of geothermal waters is masked by lake temperature at least for lake Babogaya.

Based on environmental isotope studies it is possible to decipher the role played by geothermal waters in water balances studies of lakes (Pincini, 1967). The $\delta^{18}O$ values of silicate rocks are somewhat higher. Oxygen in meteoric water tends to equilibrate with the large reservoir of oxygen in silicate minerals and acquire $\delta^{18}O$ values approaching those of the rocks through which it moves. The resulting 'oxygen shift' to higher $\delta^{18}O$ values usually occurs at a nearly constant deuterium value that is inherited from the local meteoric ratio, because little if any is exchanged with the hydrogen poor silicate rocks.

Oxygen and deuterium isotope data show that the lakes are isotopically well mixed, as the surface and lake bottom water have more or less similar isotopic values (Appendix 12). If the geothermal influence is greater the water from lake bottom would have shown positive oxygen shift particularly if the water to rock ratio is small. The problem to use this approach is that the geothermal waters in the Ethiopian Rift as a whole are isotopically depleted, which most researchers relate it with high altitude source and high water-rock ratio (Faber and Schoel 1978, Darling 1996, Panich 1995, Tenalem Ayenew 1998, etc). Therefore this approach can not be used to test geothermal activity in the area.

The chloride residence time indicates (section 9.2) that of all the lakes lake Arenguade is influenced by geothermal water flux.

CHAPTER SIX

HYDROCHEMISTRY

6.1. Introduction

The main objective of using hydrochemical and isotope data in this study is to discriminate the origin of the different bodies of water, for understanding the groundwater flow systems and the hydraulic relations of the crater lakes. Information obtained from the hydrochemical and isotope data analyses has also been used to calculate the water balance estimation of the lakes. The chemical data is also used to study the nutrient budget of the lakes and the geochemical cycling of the nutrients.

Existing hydrochemical data on lakes and groundwater chemistry were collected from the Ministry of Mines and Energy and water drilling enterprises. Additional samples were collected for one year from February 1998-February 1999 from the lakes, groundwater and rain from the study area. Some of the lakes were sampled on monthly basis (lake Babogaya) and seasonally (lake Hora), from arms depth, mid and bottom of the lakes. The aim of seasonal and monthly water collection is to see the variability in lakes chemistry with season.

A total of 72 samples were collected; 27 from groundwater, 43 from the lakes and 1 from rainfall. All samples were collected in a 100-ml acid, washed and pre rinsed plastic bottles. The sample bottles have been sealed and stored in a refrigerator at the Geochemistry lab. of Addis Ababa University, before they were sent to the Institute of Earth sciences at Aberystwyth, university of Wales for trace and major element analysis. Oxygen and Deuterium, and stable carbon analysis were conducted at the British Geological Surveys lab, Kenthworth, Nottingham. The pH, conductivity and temperature measurements were conducted in the field.

6.2. Rain water chemistry

Recently, an increasing amount of attention has been given to the chemical composition of precipitation. This is largely due to the concern over acidic atmospheric deposition near industrialized areas and its impact on ecosystem functioning and nutrient budget of lakes. Some studies (Bootsam *et al.,* 1996) state that atmospheric input may account for a significant proportion of nutrient flux to lakes of tropical Africa. It is believed that the largest input of aerosols into the atmosphere in developing nations comes from vegetation burning and land exposure resulting from deforestation and intense agricultural activities.

Data on precipitation chemistry in Ethiopia is limited. A one time rainwater sample that is collected over a night of August of 1998 shows the composition listed in table 14, presented along with the mean chemical composition of bulk precipitation collected near lake Naivasha & Nairobi (Gaudet *et al.,* 1996).

	K	Na	Ca	Mg	Cl	SO4	NO3	source of the data
Naivasha	0.31	0.54	0.19	0.23	0.41	0.72	-	Gaudet et al, 1996
Debre Zeyit	0.6	1.9	-	1	-	0.56	0.78	this work

Table 14. Major ion composition of rainfall in the Debre Zeyit region in mg/l

There is a compositional difference in major ion chemistry between the two regions of Africa. Without additional data from Ethiopia and more frequent samples from the Debre Zeyit area, an evaluation of the sources of the solutes in the rain is premature. The slight chemical difference between the two regions of Africa may be attribute to difference in the sources of precipitation.

Rainwater trace element analysis data on ICP-MS shows results well above the analytical background value indicating that the rainwater itself constitutes some of trace elements. The most pronounced elements well above the detection limit in ppb are: Ni (3.34), Li(0.10), Mn(3.45), Cu(13.04), I(5.97), Hg(0.19), Pb(0.02), Eu(7.50), Cs(7.61), Cr(1.14), Ga (916), Sc(1.19), Rb(0.58), Sm(0.31). Some of the heavy elements are below the detection limit, these include: As, Mo, In, Ce, Nd, Yb, Ti.

Some of these elements especially the heavier ones may not be originated from oceanic environments, as the source of moisture at this time of the year is very far from the region. The presence of this heavy metal in the rain sample may be therefore attribute to industrial aerosols from the region, such as Addis Ababa. In the lakes geochemical budget calculation a chloride concentration in the rainwater of 0.41mg/l is concidered (chapter 8).

6.3. Ground water chemistry

Groundwater chemical data is available since 1972. Additional groundwater were sampled from new groundwater wells. The chemical composition of the groundwater is very variable. The previous major element data is presented in appendix 7 and the modern data is presented in appendix 8. The average of the data results is given in table 15.

Ca	Mg	Na	K	Cl	HCO_3 +CO_3	NO3	SO_4	T	F	Alk.	SiO_2	Cond	TDS
2.48	2.26	1.85	0.24	0.4	5.8	0.155	0.18	24.3	0.03	302	63.3	686	566

Table 15. Average groundwater chemistry of Bishoftu region. Ions in meq/l, silica and TDS in mg/l, conductivity in μScm^{-1}

	Arenguade	**Babogaya**	**Bishoftu**	**Hora**	**Kilole**		**Kuriftu**	**Cheleleka**
					pre*	**post***		
Na	63.1	4.6	13.79	19.6	78.73	4.41	0.21	0.22
K	7.95	0.88	1.72	1.39	5.07	0.12	0.11	0.09
Ca	0.67	1.44	0.98	0.68	0.6	0.64	1.2	1.24
Mg	0.64	4.01	5.55	5.52	0.08	0.42	0.44	0.52
HCO3+CO3	59.8	8.74	20.05	20.36	63.4	1.73	0.64	0.65
Cl	21.3	0.68	3.32	4.98	15.4	0.57	0.06	0.07
SO4	3.28	0.07	0.15	0.6	0.4	0.02	0.001	0.00
NO3	7.49	0.07	0.04	0.139	0.56	0.02	0.04	0.02
SiO2	57.3	62.13	33.02	53.82	6			-
F	0.24	0.0475	0.03	0.04	0.32			-
conductivity		831	1500	2240			211	181

Table 16. The average major ion chemistry of Bishoftu lakes, in meq/l silica in mg/l conductivity in μS/cm. * pre and post refers to pre and post Mojo river diversion chemistry of lake Kilole.

	Omer 1938	Prosser 1963	Wood 1964	Igzaw 1973	Mines 1987	Tamiru 1992	Zinabu 1992	Richard 1998	Thesis 1999	
Na		5.5		5.3	4.7		3.65	4.6	3.76	Babogaya
Cl		0.9	0.79	0.68	0.69	0.56		0.57	0.60	Babogaya
Na		16		13.59		12.6		13		Bishoftu
Cl		4	3.49	2.62		2.14				Bishoftu
Na		23.9		23.9			17.95	16.5	15.8	Hora
Cl	5.01	5.67		5.9		3.35	5.16	4.8	4.22	Hora

Table 17. Twentieth century chemical variability of the Bishoftu Crater lakes in meq/L

The major element groundwater chemistry data shows that Na, Ca and Mg are more or less equally dominant cation and bicarbonate is the most dominant anion. Chloride, sulfate and nitrate follow bicarbonate. For the groundwater's that are uninfluenced by lake water mixing the HCO_3 value rarely exceeds 400mg/l. The pH ranges between 6.9 and 7.7 and the average value is 7.29 and the average conductivity is around 686μScm^{-1} . The average chloride composition of wells unaffected by lakes and anthropogenic impact is 14mg/l. In most of groundwaters calcium is dominant over Magnesium and the average Ca/Mg ratio is greater than unity.

6.4. Chemistry of lakes

The chemical investigation of the Bishoftu Crater Lakes has been done intermittently since the late 1930's. The chemistry of the lakes have been analyzed by Omar (1938) Prosser *et al.,* (1963), Wood et al., (1964), Igzaw Solomon (1973), G/Tsadik Eshete (1981), Berehane Melaku (1982), Getahun Kebede (1987), Ministry of Mines (1987), Tamiru Alemayehu(1992), Zinabu Gebremariam (1992), and Richard, (1998). The analysis results by the various authors is presented in Appendix 9 and shows variable major ion chemistry for a single one lake. For most of the lakes (except Kilole) the reported unreasonably large variability in major ion chemistry is most probably attributed to analytical errors rather than to change in chemistry of the lakes. The average major ion composition of the lakes are calculated by ignoring the extreme analytical results and is presented in table 16.

Sodium and bicarbonate are the most dominant ions in all the crater lakes. The high bicarbonate and carbonate concentrations are coupled with very low amounts of calcium and magnesium. For the three central lake: Hora, Babogaya and Bishoftu, unlike the groundwaters, the Ca/Mg ratio is less than unity, the chloride concentration of the lakes is greater than that of the groundwaters and lake Babogaya has the lowest chloride concentration which is 24 mg/l.

At present the freshest crater lakes are Kilole and Babogaya and the most saline lakes are lake Arenguade and Hora. Lakes Bishoftu have intermediate salinity. The salinity order from the lowest to highest is Kilole: Babogaya: Bishoftu: Hora: Arenguade.

As can be observed from the recent depth chemistry variation determination (appendix 10), in lake Babogaya, there is a drop by 3°C in temperature, the pH decreases from 9.02 to 7.5 and the conductivity rises with depth (appendix 10). The bottom water has nearly a uniform temperature that ranges between 19 and 20°C. The surface water temperature varies seasonally from 25 to 21°C. The decline in pH with depth may be the result of decomposition of dead organic matter at the lakes bottom which results in the release of CO2 which eventually decrease the pH. Similar pattern of variation is observed for lake Hora.

6.5 Groundwater chemistry in relation to lake groundwater interaction

In order to test the influence of lake-groundwater interaction and hydraulic connection between the lakes, chemistry of the groundwater around the circumference of the lakes is surveyed. The effect of lakes on groundwater is not obviously seen from the chemical composition (Cl, EC, Ca/Mg, etc). The groundwater chemistry both in upgradient and downgradient of the area are equally variable within a similar range of chemistry variation. However Darling (1996) on the basis of a single high TDS value (1100mg/l) observed for a well in Debre Zeyit, suggested the influence of lakes on groundwater chemistry.

Groundwater wells found between lake Hora and Babogaya (Hora Tannery, N.Franco, Hora Agro industry, Almaz Doro wells) show a similar range of chemistry as compared to groundwater wells in the region. Few wells in the downgradient of the lakes according to previous and this work show high chloride concentration as compared to the average groundwater (14mg/l Cl). These wells are Air force well 2 (28.4mg/l), Airforce well 3 (21.3mg/l), Airforce well 4 (35.5mg/l). The absence of obvious signature of chemistry of the lakes on the rest of the groundwater in downgradient may therefore be due to the fault or fracture controlled lake water out flow. Therefore only wells that are located over these fractures would be influenced by the lakes chemistry. The rest of the groundwater located out zide the fracture or fault zone would not be influenced by the lakes.

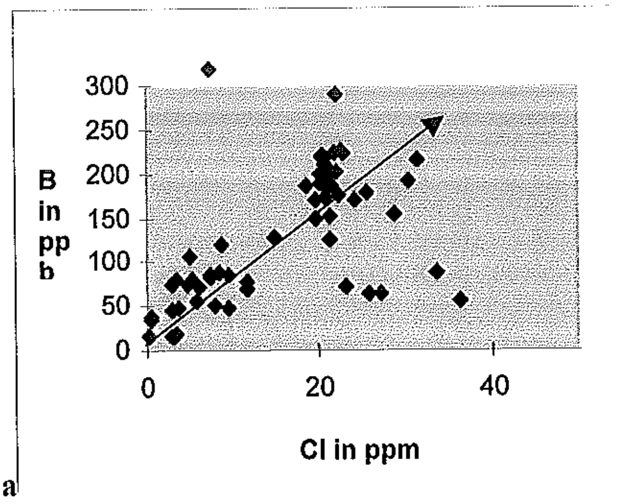
6.6. Trace Element Hydrochemistry

Only few trace element hydrochemical investigation have been carried out in the lakes of the Ethiopian Rift valley. Baumann *et al.*, (1975) carried out heavy metal analysis on lake Shalla and its sediment to investigate the importance of geothermal input to the lakes.

The main objective of the present trace element hydrochemical survey was, firstly, to see the presence of the geothermal activity and possible magmatic water addition beneath the lakes which can affect the solute and water budget of the lakes. Secondly, by comparing the trace element composition of the lakes water and the surrounding catchment geology, it is aimed to understand the control of rock weathering on the chemistry of the lakes. Thirdly, identification of conservative elements which can be used in constraining lake water budget is attempted.

Of the analyzed trace elements (appendix 11) boron is observed to be conservative like chlorine as there is a positive correlation between the two elements (fig.10a). Lithium, which is commonly used as a conservative element in hydrology, however, shows low value in the lakes irrespective of chlorine content (fig. 10b). The low Lithium concentration in the lakes might be due to loss of this element via exchange with clay minerals settling to lake bottoms. Therefore boron can be used instead of chlorine and isotopes in constraining hydrologic budget.

a



b

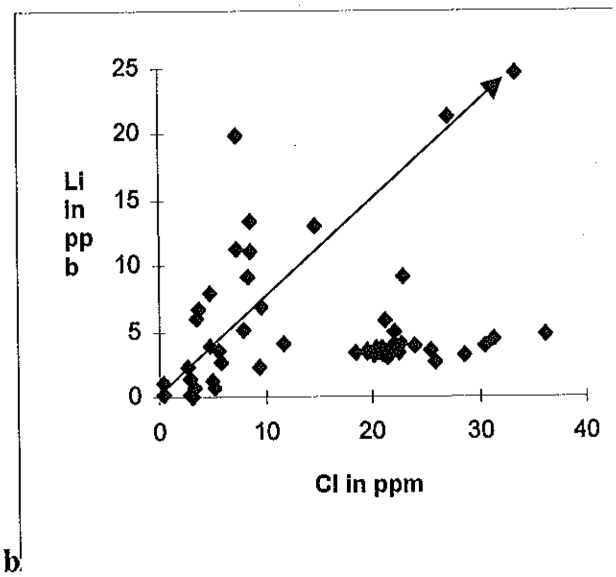


Figure 10. Chloride vs. Boron (a) and lithium (b), bivariate plot of groundwaters and lakes of Debre Zeyit area. Note that lithium is not conservative in lakes (cluster at the right corner of figure b).

Trace element data on the catchment geology is presented by Gasparone *et al.,*(1993). The comparison between the average ratio of immobile elements in surrounding catchment rocks shows an exactly similar value as that of the average ground and lake water . The La/Ce ratio of the waters and the rocks is 0.6. La/Y ratio in waters of the area is 0.9; the ratio in the adjacent volcanic rocks is not far from this value and is 1.1. The Ba/Sr of the surrounding volcanic rocks is 2.3 while that of the waters is far lower and is 0.344.

The similarity in trace element ratios of the volcanic rocks of the region and the waters leads to an idea of the importance of rock weathering in controlling the chemistry of subsurface water and via groundwater input the chemistry of the lakes. The low Ba/Sr ratio in the waters as compared to the rocks is basically due to the relatively high mobility of Sr in hydrologic systems.

Baumann *et al.*, (1975) reported that the heavy metal concentration in the lake Shalla water corresponds to that in the hot springs. Their analysis shows that Cu>3ppb;Zn>20ppb and Pb>4 ppb both in lake waters and the surrounding hot springs. In the Bishoftu crater lakes Cu never exceed 1ppb, Zn rarely exceed 20 and Pb is almost absent. This may be due to the low initial composition of this elements in volcanic rocks of the region or may testify the limited geothermal water activity and absence of sedimentary rocks in the study area. Sedimentary rocks have higher concentration of these elements.

6.7 Water types

From the Piper tri-linear (fig. 11) plot of the average composition of the waters of the area, three kinds of water can be identified. *Ca-Mg-bicarbonate type*, *Na-Ca-Mg bicarbonate type* and *Na-bicarbonate(chloride)type*.

Water bodies influenced by surface water and surface waters such as Cheleleka swamp and Artificial lake Kuriftu plot in the first group. Average groundwater plots in the *Na-Ca-Mg bicarbonate* group water in which the three cations are equally important. The crater lakes plot in *Na-bicarbonate* water field, but a shift towards *Na-bicarbonate-chloride* type is observed for pre Mojo Kilole and lake Arenguade. A slight shift of post Mojo lake Kilole towards *Ca-Mg-Na* bicarbonate type is observed. Although lake Kilole has been significantly diluted by Ca-Mg type river water, the chemistry of the lake is still Na-bicarbonate type after the diversion. This may be related to the escape of alkalies from lake sediments to raise the importance of Na and precipitation of carbonate to decrease the importance of Ca.

The reason for the occurrence of the three types of waters can be related to geochemical reactions taking place as the water moves in the different compartments.

Surface waters, artificial lakes and swamps are characterized by *Ca-Mg bicarbonate* water. Because of the very low residence time of the water in the geomedia, only very soluble minerals can be leached to change the chemistry of the waters. Most probably the dissolution of carbonate from the soil gave rise to *Ca-Mg bicarbonate* water of the swamps and surface water influenced artificial lakes (Kuriftu and Cheleleka swamp). As the water moves through the geomedia due to the increasing residence time the importance of mineral transformation reaction increases. Mineral transformation reaction results in release of alkalis such as Na and K and bicarbonate ions; for example,

$$NaAlSi_3O_8 + CO2 + 2H2O = Na^+ + HCO_3^- + Al(OH)_3 + SiO_2$$

As the water moves through the aquifer the relative importance of alkalis Na and K increases. The importance of Ca and Mg in groundwater may decline by precipitation of carbonates particularly in acidic volcanic rocks where further source of Ca and Mg is limited. In basic volcanic rocks dissolution of pyroxenes and amphiboles releases Ca and Mg to the water. Therefore, in basic volcanic rocks of the region the importance of the three cations may be equal.

As the water enters the lakes the concentration of calcium declines due to precipitation of carbonates aided by fauna in the lake and by inorganic precipitation.

Mg may also be lost by formation of inorganic aluminosilicate minerals. The lakes therefore have a chemistry dominated by Na -HCO_3 *and Cl.*

6.8. 20th century lakes chemical variation

Although a good amount of chemical data is available since 1938, the reliability of the analytical value is questionable. The equivalent weight of cations and anions does not match for many of the reports (Omar, 1938); (Berehane Melaku, 1982); (G/Tsadik Eshete,1981). Taking the most conforming values by different authors, as presented in table 17, it may be possible to see 1), a significant drop in chloride in lake Babogaya, Bishoftu and Hora in 1990's as compared to 1970's and 80's; 2) a slight drop in Na in lake Babogaya, Hora and Bishoftu in 1990's; 3) considerable change in chemistry of lake Kilole.

Lake Kilole was the most saline lake (see table 16). The salinity of this lake was diluted by diversion of Mojo river. Taking Cl and Na as conservative elements the pre and post Mojo chemistry shows that the lake is diluted by nearly 40 %. Except Mg all ions drop in concentration. The depth of the lake also changes by more than 50 %. The pre Mojo maximum depth was 6.5 (Prosser *et al.,* 1968) and the post Mojo depth measured in January 1999 is 9 meters.

6.9. Non climatic factors that control lakes status

In attempting to reconstruct climate proxy records and in hydrological modeling, care must be taken to distinguish between climatic and non-climatic signals. The non-climatic signals are: antropogenic activity, volcanic activity and changing lake and ground water interaction (due to change in basin morphology).

Human activity in the area played a role in affecting the trophic state and chemistry of the BCLs. The diversion of the Mojo river into lake Kilole for irrigation purposes affected the chemistry and trophic level of the lake significantly. This can be observed by comparing pre-diversion chemistry and the present chemistry of the lake. After the diversion, the lake is usable for domestic water supply. To what factor the slight drop in Cl and Na in lake Hora, Babogaya and Bishoftu is related is not clearly known. Hydrological and Hydrological modeling (Chapter 9) shows that it is impossible to relate this to climate variation. It is believed therefore that the change in chemistry is related to inflow of fresh water from land use: irrigation water inflow , and seepage from newly constructed dams in the area

The Mojo river has been diverted to lake Kilole for less than four years. A recent sediment core taken in January 1999 shows that more than 2m of the core from the center of the lake is made up of river mud stated here as post Mojo mud. This implies that the sedimentation rate is greater than 50 cm/y. This has great implication on sedimentation rate in water ways and severe soil loss via erosion of the upper Awash basin. Although no major work is apparently published on the sedimentation rate in hydropower lake Koka, it is believed that the high sedimentation is threatening the lakes service time.

The natural change in ground water-lake interaction, which can be induced by faulting and fracturing, may change the water budget and therefore the chemistry of the lakes accordingly. In some parts of the Ethiopian rift recently developed fractures are speculated to change the lake-ground water interaction rates. This phenomena of changing lake-ground water interaction due to fracturing is believed to be responsible for the change in surface area from 2.5km^2 to 35km^2 of surface area lake Beseka near the junction of Afar rift with the main Ethiopian rift (Tenalem Ayenew, 1998). There is no indication of the development of neofractures in the study area although there are reports that show that new fractures are developing on many parts of the Ethiopian Rift (near Beseka, Awassa, Ziway, Mohammed per. communication). The influence of neofractures on the recent lake level rise and chemistry of the BCLs is not obvious.

6.10. Carbonate Chemistry

One of the use of carbonates in laminated lake sediment is to gain an idea about the isotopic composition of water at the time of precipitation of the carbonate. This gives an instantaneous idea about the climate and hydrology at the time of deposition. Precipitation of carbonate is controlled by various factors such as evaporative concentration, temperature, photosynthetic activity, mixing of different water and supply of allogenic carbonate to the lakes. The data on the timing of precipitation of carbonate and the number of laminae that are formed per year has therefore critical importance in calibrating the climate data from laminated sediments against climate record.

Based on calcium budget calculation and similarity of $\delta^{18}O_{lakewater}$ and $\delta^{18}O$ value of aragonite from the top most part (surface) of the Hora lake sediment in the month of January, Lamb *et al.,* (1997) hypothesized that the aragonite layers in the laminated lake Hora are deposited in February or March of each year, at the start of the wet season stratification. In some years aragonite layers may form after mixing events in July or August.

To test this hypothesis seasonal sediment trap material have been collected from Babogaya lake. Due to security reasons the sediment traps were dismantled by local people at various times. The sediment trap of the months of February and March is also not obtained. A complete record of sediment trap is obtained for the months from June to December 1999. Preliminary petrographic analysis on the sediments shows that the are no carbonate grains in June to November samples. In the December sample few needle shaped aragonite crystals are observed suggesting precipitation of carbonate to take place as early as December. It is therefore believed that carbonate precipitation takes place starting from the months of December to March which are dry months. In these months of the year the lakes are on one hand at a stage of highest evaporation, on the other hand, due to lake overturn in the months from December-March (Wood *et al.,* 1976) there is maximum algal flourishing. Photosynthesis by algal community consumes much of the CO_2, which promotes precipitation of carbonate by influencing partial pressure of carbon dioxide and thus carbonate equilibrium.

6.11 Water Quality Assessment

Lakes and groundwater have been assessed for suitability for drinking and irrigation. The suitability of water for drinking are based on 1) the presence of objectionable tastes, odors, colors, hardness etc., 2) the presence of substances with adverse physiological effects (Pb,F,SO_4,Na, Cl,NO_3,Se,Cr etc.) and the total dissolved solids (TDS).

The total dissolved solids of 99% of the groundwater wells are within the admissible WHO (1984) standard of 1000mg/L. The concentration of the elements of adverse physiological effect including F is far lower than the WHO limits.

The deterioration of groundwater quality due to human impact is not obvious from the observation of the chemical constituents. In some wells the level of NO_3 however, is considerably higher or even greater than the WHO 50 mg/l limit (Eg. CIM mission well-51mg/l, Slaughter well-53mg/l). Some other wells that show high nitrate content but lower than the WHO limit are: Almaz Doro well (26.5mg/l),Hora Tannery well-(25mg/l), Elfora-(20mg/l), Hora Agro Industry well -(17 mg/l).

Except for lakes Babogaya and post Mojo Kilole, all other lakes have TDS greater than the maximum admissible WHO (1984) limit (1500mg/l). From the TDS point of view Babogaya and the present lake Kilole are potable.

The Wilcox (1985) method of irrigation water quality procedure if followed to characterize the suitability of the waters for irrigation. According to this work, irrigation water quality are dependent on the types of plants, amount of irrigation water used, soil and climate. Salinity estimate from electrical conductivity and sodium hazard estimated from SAR (sodium adsorption ratio) are considered to characterize the quality of the waters in the region for irrigation. SAR is given as,

$$SAR = \frac{Na}{\sqrt{\frac{Ca + Mg}{2}}} \quad \text{Concentrations in meq/l} \qquad \textbf{(Equation 9)}$$

The salinity affects the osmotic pressure and causes the swelling of plants. Sodium on the other hand reduces permeability and hardens the soil. The status of groundwater and lakes, salinity and sodium hazard is reported in table 18.

	conductivity µScm^{-1}	SAR	Salinity hazard	Sodium hazard
Ave GW	680	1.20	Medium	Low
Cheleleka	181	0.23	Low	Low
Kuriftu	211	0.4	Low	Low
Babogaya	831	2.79	High	Low
Bishoftu	1500	7.64	High	High

Table 18. Irrigation water quality.

It is obvious that Hora and lake Arenguade with the highest SAR and salinity are unsuitable for irrigation. Of the waters listed in table 18 groundwater, lake Cheleleka and Kuriftu are suitable for irrigation. For salt tolerant plants lake Babogaya may be used for irrigation. The post Mojo Kilole with salinity comparable with Kuriftu and Cheleleka is equally suitable for irrigation.

6.12 Fluoride chemistry

6.11.1Fluoride Hazard in East African and Ethiopian Rift

Many published and unpublished investigations reveal that the East African rift valley in general and the main Ethiopian rift groundwater and lakes, in particular have high fluoride concentrations (Kiliham and Hecky, 1973; Tesfaye Chernet, 1982; Brihanu Gizaw, 1996; Ashley and Burley, 1994; Gezahegn Yirgu *et al,* 1998; Tamiru Alemayehu *et al,* 1998).

Fluoride is essential for potable water in order to reduce the risk of dental caries. However, it causes tooth and skeletal flourisis when the intake exceeds the optimal range for drinking water, which is 1.5 mg/l (WHO, 1984). In the Main Ethiopian Rift (MER), tooth flourosis is very common. The extent of fluoride effect on aquatic animals and ecosystem is particularly not well understood. But its effect on silica uptake by diatom fauna is reported (Kiliham and Hecky,1973) and is believed that it has an adverse effect on the other aquatic life.

The source of high fluoride concentration in East African ground and lake water is attributable to two reasons. The primary source is leaching from acid volcanics (Kilham and Hecky, 1973; Yirgu Gezahegn *et al* , 1998; Berhanu Gizaw, 1996; Tamiru Alemayehu *et al* , 1998) and the second source is associated with fluoride that is directly contributed into subsurface water from magmatic juvenile gases (Tamiru Alemayehu , 1998; Gezahegn Yirgu *et al* , 1998). The minerals that contain fluoride and release it during leaching are amphiboles, micas, pyroxens and accessory apatite and fluorite in silicate rocks.. Atmospheric and anthropogenic dust contributions are not considered significant in the region (Kiliham and Hecky, 1973; Berhanu Gizaw, 1996).

Various hypothesis have been forwarded to explain the extent of fluoride concentration in MER subsurface waters. The extent of fluoride concentration in the waters of the East African rift depends on the hydraulic properties (permeability, porosity) of the rocks (Yirgu Gezahegn *et al,* 1998) which controls degree of water-rock interaction; calcium concentration in the soil (Ashley and Burley, 1994) which influence fluorite equilibrium conditions; concentration of fluoride in volcanic rocks (Yirgu Gezahegn *et al,* 1998; Birihanu Gizaw, 1996); HCO3 concentration and pH of circulating water (Koga, 1973) and rate of evaporative concentration in lakes.

The lakes of the Ethiopian rift region are closed to surface outflow. Due to this reason, the fluoride accumulates and is enriched in lakes during evaporative concentration. It is reported (Berhanu Gizaw, 1996) that all the lakes are fluorite under saturated.

6.11.2. Fluoride in waters of Debre Zeyitarea

The water fluoride concentration in the area is viewed in terms of the above mentioned factors that control fluoride enrichment and extent. The ground waters of the Debre Zeyit area have low fluoride concentrations. The average fluoride concentration for the groundwater in the region is low (0.57 mg/l), unlike the Ethiopian Rift ground water which have fluoride concentration above 1.5mg/l (Tamiru Alemayehu, 1992).

In the Ethiopian Rift the highest concentration of fluoride is observed in ground waters abstracted from acidic tephra, pumice in particular (Yirgu Gezahegn *et al*, 1998). This is because of the high rate of rock groundwater interaction due to the high permeability of such rocks coupled with the mineralogy of the rocks. Such rocks cover a very small area in Bishoftu. Where they occur the ground water has high fluoride content (see table 19).

well location	fluoride mg/l	aquifer type
Dire Arerti medical center	1.32	weathered ignimbrite & fractured ignimbrite
Ethiopian Air force well 3	1	ignimbrite, pumice, and fractured basalt
Dragados well Mojo camp	0.77	fractured trachyte
Air force well 4	0.97	volcanic ash, ignimbrite and pumice
Sample wells with fluoride above 0.75 mg/l, major aquifer: acidic tuff		
Blue Nile p.f. well, DZ town	0.67	scoraceous basalt and fractured basalt
DZ Air force hospital well	0.57	vesicular and weathered basalt
Genda Gorba well 6	0.4	fractured basalt and weathered basalt
Dragados DZ camp well	0.56	fractured scoraceous basalt
Genda Gorba well field	0.4-0.6	fractured basalt & weathered basalt
Defense construction well 1&2	0.4	basic volcanic sand, scoria & weathered basalt
Sample wells with fluoride below 0.75 mg/l, major aquifer: basalt		

Table 19. Relation between aquifer lithology and fluoride concentration.

The low fluoride content can also be attributed to the minimum geothermal water activity (section 5.6) in the area, that would have brought juvenile gases including fluoride.

The fluoride concentration in the Bishoftu crater lakes is also less than 1mg/l for all of the lakes except pre Mojo lake Kilole (6 mg/l). The low fluoride concentration in the lakes is explained by the geology of the catchment. The Bishoftu Crater Lakes have relatively higher fluoride concentration as compared to the groundwater in the region. This is due to the evaporative enrichment of fluoride in the lakes.

6.11.3. Fluorite solubility index calculation for the lake and groundwater

To test the possible loss of fluoride through fluorite precipitation in the lakes and groundwater the saturation index of fluorite has been calculated for the waters in the area (table 20). The saturation index calculation involves determination of concentration unit in molality, determination of ionic strength, and activity coefficient. The activity coefficient is calculated based on the Debye-Huckel equation (Fetter, 1988). Debye Huckel equation is used only if the ionic strength of the solution is less than 0.1 which is in terms of concentration about 5000mg/l. Lake Arenguade has a TDS greater than 5000mg/l. The solubility index is calculated for the average groundwater, lakes Babogaya, Bishoftu and Hora.

The various coefficients that are used in the activity coefficient calculation have been performed for water at 25°C. The calculation suggests that the solubility index is far lower than 1. This indicates that the lakes are fluorite undersaturated. The low fluoride concentration in the regions' water can not be explained by loss of fluoride via precipitation of fluorite but can be explained by geology (because of the fact that the major aquifers are basic volcanic rocks and such a rock contain low amount of F bearing minerals stated above) and anion exchange (section 9.1).

	Babogaya	Bishoftu	Hora	Average Groundwater	Explanation
Na	0.0046	0.01379	0.02013	0.00185	molality of Na, M_{Na}
K	0.00088	0.00172	0.00143	0.00024	M_K
Ca	0.00072	0.00049	0.00034	0.00124	M_{Ca}
Mg	0.001475	0.002775	0.00277	0.00113	M_{Mg}
HCO3+CO3	0.00874	0.02005	0.01998	0.0058	$M_{bicarbonate}$
Cl	0.00068	0.00332	0.00498	0.0004	M_{Cl}
SO4	0.00003	0.000075	0.000125	0.00009	M_{SO4}
NO3	0.00007	0.00004	0.00016	0.000155	M_{NO3}
F	0.00005	0.00003	0.00004	0.00003	M_F
I	0.01196	0.026155	0.02983	0.009158	Ionic strength, $\sum m_i z_i^2$
$-\text{Log}\gamma_{Ca}$	-0.18304	-0.24951	-0.26216	-0.16379	$(AZ_{Ca}\sqrt{I})/(1+a_{Ca}B\sqrt{I})$
$-\text{Log}\Upsilon_F$	-0.05021	-0.07094	-0.07506	-0.04447	$(AZ_F^2\sqrt{I})/(1+a_FB\sqrt{I})$
γ_{Ca}	0.656091	0.562974	0.546811	0.685823	Activity coeff. of calcium
Υ_F	0.890828	0.84929	0.841271	0.902668	Activity coeff. of flouride
α_{Ca}	0.000472	0.000276	0.000186	0.00085	chemical activity of calcium, $M_{Ca}\gamma_{Ca}$
α_F	4.45E-05	2.55E-05	3.37E-05	2.71E-05	chemical activity of flouride, $M_F\gamma_F$
K_{iap} CaF_2	9.37E-13	1.79E-13	2.11E-13	6.24E-13	ion activity of product, $\alpha_{Ca}\,\alpha_F^2$
K_{iap}/K_{sp}	0.023541	0.004498	0.005288	0.015665	solubility index (K_{sp}, solobility product of the mineral)

Table 20. Solubility index calculation for fluoride at 25°C. The various coefficients are given in Fetter, 1988. A= 0.5085; B=0.3281; a_F = (effective diameter of fluoride) 3; a_{Ca}= 6; $Ksp=10^{-10.4}$

CHAPTER SEVEN

ISOTOPE HYDROLOGY

7.1. Introduction

The objective of undertaking environmental isotope analysis in the region is to characterize the groundwater-surface water interaction that determines the water budget. Effective management of groundwater resources for potable water supply and agriculture and accurate water budget calculation of the lakes for environmental change studies requires a good understanding of water movement. The environmental isotopes in conjunction with hydrochemical techniques help to determine water movement in its various hydrologic compartments. For example,

- Precipitation and therefore stream flow and groundwater bodies are depleted in heavier isotopic species as compared to oceans.
- If in a given region the δ values for deuterium and oxygen are plotted against each other, they fall on the precipitation line (Meteoric Water Line). The points representing stream flow and groundwater are also found on this line, provided that they do not undergo significant evaporation.
- When water is subjected to evaporation in ponds, lakes, and reservoirs, its isotopic composition changes, and it is enriched with respect to the heavy isotopic species of water.

The concentration (C) of deuterium and oxygen-18 is usually expressed in units of deviation per mil from SMOW (Standard Mean Ocean Water).That is

$$\delta = \frac{C_{sample} - C_{SMOW}}{C_{SMOW}}$$

7.1.1. Sampling

Water samples were collected from the lakes, groundwater and rainfall of the region from April 1998 to January 1999. The waters were collected in clear 100ml plastic bottles capped with plastic and masked by tape. The samples are stored in a refrigerator before they were sent to NERC laboratory at Kenworth. The analytical data is presented in appendix 12.

7.2 Rain Water

7.2.1. Isotopic Composition of Addis Ababa Rainfall

The International Atomic Energy Agency (IAEA), in co-operation with the World Meteorological Organization (WMO), initiated in 1961 a worldwide survey including Ethiopia of the isotope composition of the monthly precipitation.

The long term weighted mean oxygen and deuterium isotopic composition of precipitation over Ethiopia and East Africa is summarized by Rozanski, *et al.*,(1996). The $\delta^{18}O$ of precipitation during months of abundant rainfall (summer) is in general more depleted than precipitation during the rest of the year. The weighted value for $\delta^{18}O$ is determined to be -1.3 ‰ and that of deuterium is calculated to be 1.8‰ for Addis Ababa (35 km NW of the study area), at an elevation of 2360 m. The $\delta^{18}O$ value of the Addis Ababa station is more enriched as compared to the East African region. This is speculated to be attributed to the recycled moisture derived from transpiration by the vegetated Congo basin which is more enriched than the maritime source (Rozanski *et al.,* 1996). The $\delta^{18}O$ Vs δD plots for the Addis Ababa station show the data points clustering along the Local Meteoric Water Line which is defined as [$\delta D = (6.95 \pm 0.22)\delta^{18}O + (11.51 \pm 0.58)$]. The same work also explains the more positive value of the small rains of Addis Ababa to be due to the source of the rain that is the equatorial Indian Ocean and Arabian Sea. This part of the ocean and the sea are characterized by high sea surface temperature, which can generate isotopically positive moisture.

7.2.2. Rainwater samples from the Ethiopian Rift

Very few rainfall samples have been collected in the Ethiopian rift valley. The isotopic composition of previously collected rainfall from the Ethiopian rift is presented in table 21. One rain water sample collected in the study area in the end of the month of August shows more depleted oxygen (-3. 13‰) and deuterium

(-3.2‰) values as compared to the average Addis Ababa precipitation The oxygen value is however comparable with the average composition of the Addis Ababa rainfall of the same month (-3.5‰ $\delta^{18}O$).

Location	$\delta^{18}O$	δD	Season of collection	Source
Bishoftu	-3.13	-13.2	August 98	This issue
Sodo	-4.50	-19.2		Craig, 1977
Langano NW shore	-2.70	-3.7	September,1996	Tenalem 1998
Butajira	0.49	8.05	September,1996	Tenalem, 1998
Ziway	-0.7	12.95	September,1996	Tenalem, 1998

Table 21. Isotopic composition of Ethiopian rift precipitation

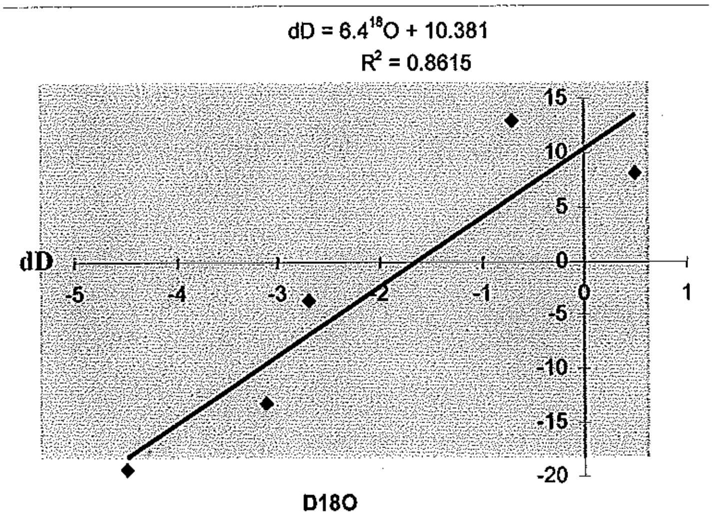


Figure 12. Local Meteoric Water line of Ethiopian Rift valley

The plot of the few $\delta^{18}O$ vs δD rainfall samples at different times from the Ethiopian Rift (fig. 12) plot more or less along a local meteoric line defined by an equation which is very similar to the local meteoric water line defined for a higher altitude station at Addis Ababa defined by Rozanski (1996). The local meteoric water line from the few available data is defined by the equation:

$$\delta D = 6.4\ \delta^{18}O + 10.4 \qquad \text{(Equation 10)}$$

The Ethiopian Rift located at a relatively lower elevation (1500-2000) as compared to the 2360m of Addis Ababa shows similar precipitation isotopic composition. Three of the samples plot lower than the mean oxygen isotope composition of Addis Ababa rainfall (-1.3‰).

This observation oppose the general idea of altitude effect which states that isotope value on higher altitudes are more depleted than the lower altitudes. The average global gradient of oxygen isotopic composition for a 100 m rise in altitude is about -0.26 ‰ (Mazor, 1997).

The disagreement of the present observations with this general rule can be explained by a moisture derivation mechanism over the Ethiopian region. The Ethiopian Rift is located in the lee ward side of the moisture sources. The moisture passes over the southwestern highland towards the rift when the source of moisture is the Atlantic and Congo basin and passes over the southeastern highland when the source of moisture is the Indian Ocean.

Therefore, keeping all other factors constant it may be possible to give a crude generalization that Ethiopian rift rain water are isotopically more depleted as compared to the rain water in the highlands. This is probably due to moisture movement mechanism. This observation should be confirmed by further studies of rainwater samples from the Ethiopian rift and the adjacent plateau.

The slight positive shift of the Local Meteoric Water Line (gentler slope) can be attributed to a temperature effect rather than an altitude effect. With very few (4) samples Siegenthaler and Oeschger (1980 in Mazor, 1996) found a very good correlation (r^2>0.95) between altitude and isotopic composition of Swiss precipitation. But Darling *et al.*, (1996) found very poor correlation between Kenyan rainfall isotopic composition and altitude. The very poor correlation (r^2=0.32) (which they relates to the limited number of the data points) may indicate the questionability of the of altitude effect over the East African rift valley, as moisture bearing air masses that rises from the rift towards the bordering high lands is not obvious.

Due to the similarity in isotopic composition of Ethiopian Rift and Addis Ababa Rainfall the MWL of Addis Ababa is taken as being representative of the LMWL of the region.

7.3. Isotopic Composition of Runoff

Water samples from the perennial streams Mojo and Wedecha and a tributary stream show isotopic values more enriched than the groundwater and rainfall (appendix 12 and fig 13) in the study area.

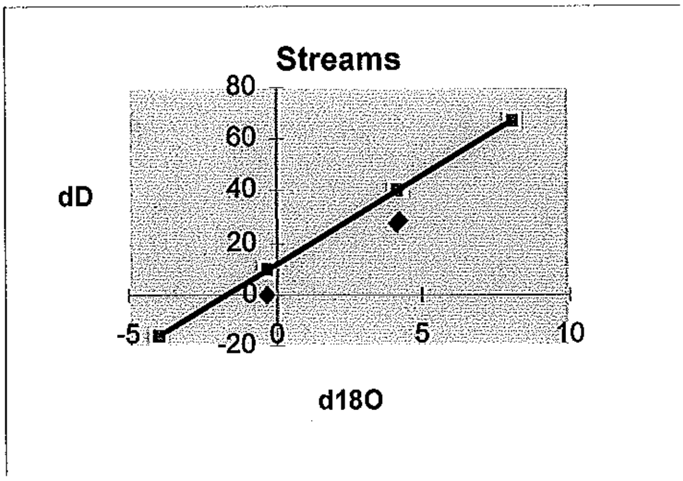


Figure 13. $\delta^{18}O$ vs. δD plot of stream samples along the LMWL.

En route evaporation of the river waters as the only reason to explain the enrichment of the Wedecha and Mojo rivers may not be logical. Because most of the rivers in Ethiopian rift valley as reported by Darling *et al.*,(1996), show relatively depleted isotopic composition: (Awash at Koka -0.1‰ $\delta^{18}O$ and 3‰ δD; Awash at Sodere -0.7‰ $\delta^{18}O$ and 1‰ δD; Awash at Metahara -1.1‰$\delta^{18}O$ and 0‰δD; Melka -1.9‰

$\delta^{18}O$ and 6‰ δD) after traveling long distances and even after realeased from reservoirs (eg. Awash at Sodere and Awash river at Metahara).

The enrichment isotopic composition can be explained by *en route* evaporation coupled with leakage from the lakes.

Although data is unavailable, surface runoff that enter the crater lakes from the crater rims is believed to have isotopic composition which is similar to that of the precipitation due to the short distance between the crater rim and the lake.

7.4. Isotopic Composition of Lakes and Ground water

From the plot of surface, lake and ground water along with the local meteoric water line (fig 14 and 15)the following observation can be made:

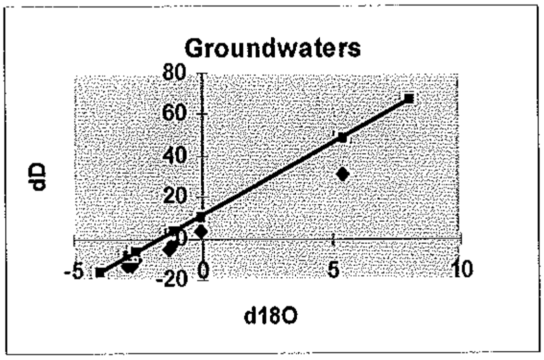


Figure 14. $\delta^{18}O$ vs. δD plot of groundwater samples along the LMWL.

- The Shimbra Meda groundwaters (N of the region) plot close to the meteoric water line (fig. 14) ruling out secondary processes, such as evaporation prior to infiltration, or isotopic exchange with aquifer rock. Therefore the ground water is probably recharged rapidly through fractures, faults, joints and scoria cones with little influence of evaporation before recharge.

- The isotopic composition of enriched wells (Royal hotel well and Kebele well) found in the town is therefore probably due to ground water mixing with lakes. A similar observation is reported by Darling *et al.*, (1996).

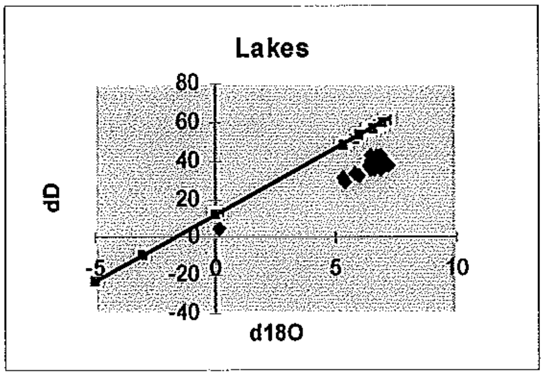


Figure 15. $\delta^{18}O$ vs. δD plot of lake samples along the LMWL.

- Enrichment of the lakes in heavy isotopes indicates that they are in a state of evaporation with respect to present day precipitation. The isotopic composition of the lakes, open dug wells and river water follow the evaporation line defined by the equation $\delta D = 5.23\delta^{18}O + 2.94$ which is close to the East African Lakes evaporation line. The Ziway Shalla basin lakes show an evaporation line of $\delta D = 5.5\delta^{18}O + 8.5$ (Tenalem, 1998; Craig, 1977).

- The lake with highest enrichment is Hora. Mass balance calculation shows that this lake is a terminal lake. The lowest isotopic concentration is observed for lake Babogaya a lake with considerable groundwater inflow and outflow (chapter 9). Post Mojo lake Kilole and Artificial lake Kuriftu show a relatively depleted value as compared to the other lakes. This may be due to flushing by isotopically depleted river water.

CHAPTER EIGHT

LAKES WATER BUDGET

Geochemical and isotope Mass balance Approach

8.1. Introduction

A common application of stable isotope and chloride (or other conservative elements such as Li or B) to lake studies is as an aid in determining the water balance of lake systems, particularly in determining and quantifying ground water-lake interaction. In a lake water balance study, it is usually possible to measure the inflow and the lake surface outflow, but it may be difficult to estimate ground water inflow and outflow from a lake as well as evaporation from lake surface. Stable isotope balances have been used either by themselves or in conjunction with chloride balances, and classical piezometric / permeability equations to estimate water balances of lakes.

Once chloride is dissolved in water it remains in water. It does not react with geomedia and is not influenced by biological and biochemical reactions. Chloride is, from this point of view, a nearly perfect tracer for water. Secondly, igneous rocks have low concentrations of chloride.

The chloride ions are no more conservative under very high salinity due to the precipitation of chloride containing compounds. Chloride balance method also fails when saline seepage contributes unknown amounts of salt. Under such conditions stable isotopes are mainly used.

8.2 Chloride Budget Approach

The water budget of the lakes can be written as

$$\Delta V/\Delta t = PA_l + RA_c + EA_l + G_i - G_o \quad \textbf{(Equation 11)}$$

Where;

ΔV = change in volume of the lake, If a long-term average is considered $\Delta V/\Delta t = 0$

P = Average precipitation of the area = *830 mm/yr.*

E = Evaporation rate from the lakes *1710 mm/yr.*

A_l = Area of the lake under consideration from table 1.

A_C = Area of the lake catchment, from Telford (1998b)

R = runoff from the craters' wall, but $R = \kappa P$

κ = Runoff coefficient, assumed to be 0.5

G_i = groundwater inflow

G_o = groundwater outflow

Over one year and steady state condition the water budget equation can be written as

$$PA_l + \kappa PA_c + EA_l + G_i - G_o = 0 \quad \textbf{(Equation 12)}$$

The chloride budget equation can then be used to separate the groundwater inflow and outflow components:

$$C_pPA_l + C_r\kappa PA_c + C_eEA_l + C_iG_i - C_lG_o = 0 \quad \textbf{(Equation 13)}$$

Where,

C_p = average concentration of chloride in precipitation = $0.01 mol/m^3$

C_r = average concentration of Cl in runoff, but it is assumed that ,$C_r = C_p$

Ce = average concentration of Cl in evaporating water = 0

C_i = average concentration of chloride in the ground water, *14 mg/l*

C_l = average concentration of chloride of the lakes which is also equal to concentration of chloride in groundwater outflow

Combining equations (12 and 13), the unknowns G_i and G_o can be constrained.

The water budget based on chloride balance approach is given in table 12.

Lake	Gi(m^3)	Go(m^3)	P(m^3)	E(m^3)	R(m^3)
Hora	594406	42051	854070	1759590	353165
%	33	2.3	47.4	97.7	19.6
Bisoftu	740379	76824	771070	1588590	153965
%	44.5	4.6	46.3	95.4	9.2
Babogaya	758539	379329	480570	990090	130310
%	55.4	27.7	35.1	72.3	9.5
Kilole	58051	2071	639930	1318410	622500
%	4.4	0.2	48.5	99.8	47.1
Arenguade	20323	743.7	449030	925110	456500
%	2.2	0.1	48.5	99.9	49.3

Table 22. Water budget of Bishoftu Crater Lakes, chemical mass balance method

8.3. Oxygen isotope budget approach

In combination with other geochemical parameters, such as geochemical mass balance method, isotopic survey may be used to quantify water balance of lakes. Such a method can be used if geochemical mass balance calculation is not possible for example in saline lake systems, geothermal water input systems, and when the chemistry of the hydrologic components is variable.

Similar to geochemical mass balance method, in isotope mass balance method the isotope balance equation and the water balance equation is solved simultaneously to separate the groundwater components into inflow and outflow.

The water budget of a lake closed to surface water input and output is given by equation

$dV/dt = P+ R+ Gi-E-G_o$ **(Equation 14)**

Equivalently, the expression for the isotope mass balance of a lake is given by

$d(\delta_L V)/dt = \delta_p P+\delta_p kP +\delta_{gi} Gi-\delta_{go}Go-\delta_E E$ **(Equation 15)**

δ_L = isotopic composition of a well mixed lake

δ_I = isotopic composition of inflow (groundwater and precipitation weighted)

δ_E = isotopic composition of evaporating water

$I, Q_o E$ = Inflow ($P+Gi$), groundwater outflow and evaporation respectively.

In using isotope balance approach difficulties arise mainly due to two reasons.

- The δ_E, isotopic composition of evaporating water is difficult to measure. It can however be determined theoretically by the equation

$$\delta_E = \frac{\alpha^{*}\delta_{l} - h\delta_a - \varepsilon}{1-h} \qquad \textbf{(Equation 16)}$$

Where,

α is equilibrium fractionation factor, 1.0098 for $\delta^{18}O$ at 25°C

$\alpha^* = 1/\alpha$

δ_a isotopic composition of vapor in the environment

ε total isotopic separation factor

h is relative humidity normalized to water surface temperature= e_a / e_{sat}

but equation 16 introduces a number of new unknowns namely the atmospheric variables (h, δ_a) as well as the mechanistic parameter ε.

- The solution of the isotope balance equation works well only under a steady state regime. In practical situations, however, one rarely encounters such a simple steady state situation. Not only are surface water systems strongly changeable due to random processes, but there are inherent seasonal changes in both the isotopic composition of inflow and the isotopic composition of atmospheric moisture, in hydrologic balance and in the relationship between inflows and evaporation rates, as well as mixing in lakes. Most of quantitative isotope mass balance method assume isotopic steady state.

8.3.1. Semi-empirical isotope balance for the Crater Lakes

Some workers try to solve the isotope mass balance equation semi-empirically with out reverting to the ambient parameters, through measurement of the isotopic enrichment in a 'model evaporation system', such as a terminal 'index lake' (Dincer, 1968), a drying up pond (Gat and Levy, 1978) or evaporation pan (Gat, 1977).

The Bishoftu Crater Lakes provide a unique opportunity to solve the isotope balance without directly measuring all of the ambient parameters δ_{a}, h and ε. Hydrological and chemical mass balance approach shows that among the Bishoftu Crater lakes, Lake Hora, pre Mojo Kilole and Arenguade can be considered as index terminal lakes because of the very negligible groundwater outflow. Lake Cheleleka can be considered as a drying up pond and Bishoftu and Babogaya can be considered as lakes with groundwater inflow and outflow.

Since the isotope status of lake Cheleleka is unavailable, methods using drying up ponds as an index lake is not used here but methods considering terminal lakes as an index lake is used to calculate the isotope budget of the other through flow lakes. Of the three terminal lakes isotope composition of Arenguade is not available and that of Kilole is disturbed by human activity. Therefore lake Hora is here considered as a suitable terminal index lake.

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

$$\delta_E = \delta_I \qquad \text{(Dincer, 1968; IAEA, 1981)}$$

δ_I here is considered to be -2.5 ‰ for oxygen isotope average of precipitation and groundwater

For lake Hora the isotope balance approach can be solved by directly substituting $G_o=0$ in equation 14 and calculating the unknown G_i or by substituting δ_E in equation 15 to calculate the unknown Gi.. The solution of the equations gives water budget components listed in table 23.

	E (m^3)	P (m^3)	R(m^3)	Gi (m^3)	Go(m^3)
Hora	1759590	854070	353165	552355	0
%	100	48.5	20.1	31.4	0

Table 23. Water balance of lake Hora determined from oxygen isotope balance

8.3.2. Use of lake Hora to constrain regional environmental parameters

The total separation (mechanistic) factor ε can be determined from equilibrium separation factor ε^* and diffusion controlled fractionation factor $\Delta\varepsilon$.

Where $\Delta\varepsilon = \varepsilon - \varepsilon^*$

$\Delta\varepsilon$ can be estimated from equation:

$\Delta\varepsilon = (1-h).C_k$, C_k = 14.3‰ for ^{18}O (Krabbenhoft *et al.*, 1994)**(Equation 17)**

h for Bishoftu area is obtained from e_a / e_s (table 7) and meteorological data of Debre Zeyit (table 2), = *0.59*

ε^* is 1000 times the small deviation α have from unity i.e.,

$\varepsilon^* = 1000(\alpha-1)$ (Krabbenhoft *et al.*, 1994) **(Equation 18)**

Therefore,

$\varepsilon = 1000(\alpha-1)+\Delta\varepsilon$ **(Equation 19)**

and putting the ε value into equation 16, and using lake Hora as an index lake ($\delta_E = \delta_{in} = -2.5$ ‰) we can solve for the unknown δ_a. . It is calculated to be *-12.04*‰

These two environmental parameters (ε *and* δ_a) can be used to calculate the limiting isotopic composition δ^* for the Bishoftu area.

The limiting isotopic composition is given as:

$\delta^* = \delta_a + \varepsilon / h$ IAEA (1987) **(Equation 20)**

This limiting isotopic composition for the region is calculated to be *14.1*‰.

8.3.2.1 Discussion

The isotopic composition of atmospheric vapor determined from the semi-imperical approach gives a value which is reasonably closer to that of Afar region determined by Gonfiantini *et al.*, (1973) which is -15 ‰ and that of lake Bosumtwi (West Africa, Ghana) region which is -9‰.

8.3.2.2. Lake Babogaya and Bishoftu budget

These lakes have considerable groundwater inflow and outflow component. In the general case of a lake open to both inflow and outflow, the enrichment of heavy isotopes in the lake is reduced in proportion to the weight of the non-fractionating outflow rate relative to evaporation.

Gat *et al.*, (1978) proposed an isotope budget equation written in different form;

The equation is written as

$$\delta_{Lss} = \frac{\left[\left(\frac{\varepsilon}{h} + \delta_a\right) + \frac{I}{E}\frac{1-h}{h\delta_I}\right]}{\left[1 + {}^{I}\!/_{E} + \left(1 - {}^{h}\!/_{h}\right)\right]}$$

(Equation 20)

where δ_{Lss} is the steady state isotopic composition of the lake

Equation 20 can be rewritten as

$$\frac{I}{E} = \frac{h}{1-h}\frac{\delta * - \delta_{Lss}}{\delta_{Lss} - \delta_I}$$

(Equation 21)

Substituting the various results in to equation 21 the water budget of the two lakes can be determined. The water budget of the three lakes is given in table 24.

	E (m3)	P(m3)	R(m3)	Gin	Go
Babogaya	990090	480570	130310	585452	206242
%	83	40	11	49	17
Bishoftu	1588590	771070	153965	815511	151956
%	91	44	9	47	9

Table 24. Water balane of lake babogaya and lake Bishoftu determined by isotope balnce approach.

8.4 Discussion

The Geochemical mass balance and isotope budget calculation shows that the Bishoftu Crater Lakes have a wide variation in their hydrologic characteristics. The following conclusion can be made:

- There is a good agreement between water budget determined by isotopic and geochemical mass balance approaches.
- The hydrology of lake Babogaya is different from the rest in that it has significant amount of groundwater outflow and inflow. This lake is considered as a through flow lake.
- Lake Arenguade and pre Mojo Kilole are lakes with virtually no outflow. These lakes are also least affected by groundwater inflow. The minimum groundwater inflow to these lakes is most probably attributed to the elevated altitude that these lakes occupy relative to the region.
- Lake Bishoftu has an intermediate property between the terminal lakes and the through flow lake.

- The Hydrology of all of the lake except lake Babogaya is dominated by rainfall and evaporation. The freshness of the chemistry of lake Babogaya is therefore related to solute loss through groundwater outflow. There is an inverse relationship between the salinity and rate of groundwater outflow.
- The similarity between the geochemical mass balance and isotope budget calculation shows that the Bishoftu Crater Lakes provides a promising hydrology to isotope budget calculation and isotope modeling with out depending on the measurements of environmental parameters ($h, \delta_a,$ *and* ε).
- The isotope budget for lake Kilole can not be made because of the influence of the diversion, the lake shows a relatively depleted isotope content signifying that it has not reached isotopic steady state.

CHAPTER NINE

SOLUTE RESIDENCE TIME AND HYDROCHEMICAL MODELS

9.1 Solute and Water Residence time

Residence times were calculated in order to gain some idea of the evolution of the present lake water chemistry. The residence time also help in planning the lakes for recreation purposes. Water budget has been taken from table 22. The mean chemical composition of the different water sources has been discussed in chapter five. Chloride was assumed to be a conservative element. This is a reasonable assumption for BCLs as they are fresh. Chloride is thus used to calculate the time taken to produce waters with chemical composition of the present day lakes. This assumes that all chloride was derived from the inflow waters. It was further assumed that the average chemical compositions of the inflow waters have been constant over the same time taken to produce the present day lake water. The 'chloride age' was computed from the equation

$$T_{Chloride} = \textit{chloride quantity in the lake (moles)/ chloride annual flux(mole/yr.)}.$$

(Equation 22)

The residence time of the rest of major chemicals is calculated in a similar fashion. The residence time of water in a lake is the mean time a water molecule stays in a lake. It is calculated as the volume of water in the lake divided by the amount of influx of water in a given time (Table 25).

$T_{water} = \textit{rate of influx/ volume of the lake}$ **(Equation 23)**

T_{Na}	T_{Ca}	T_{Mg}	T_K	T_F	T_{SO4}	T_{SiO2}	T_{Cl}	T_W	
72	19	50	106	45	9	28	57	16	Babogaya
514	31	164	494	69	45	36	569	30	Bishoftu
320	9	71	175	40	79	26	364	10	Hora
1469	9	1	729	368	60	3	869	1.5	Kilole
16797	149	135	16313	3940	7084	444	12489	11	Arenguade

Table 25. Residence time of major ions in Bishoftu Crater Lakes in year. T_w is residence time of water

The calculated 'chloride budget' shows that a minimum chloride residence time greater than 50 years. The chloride residence time ranges from 50 years for lake Babogaya to the highest lake Arenguade with a chloride residence time of 12500 yr. Lake Arenguade is the only crater lake with chloride residence time over 1000 yrs. Lake Babogaya is the only lake with chloride residence time of less than 100 yrs.

9.1.1. Discussion

The chloride residence time of lake Babogaya is short as compared to the other lakes. This suggests a strongest hydraulic connection between lake Babogaya and the ground water system. The strong connection of lake Babogaya with the ground water system may be responsible for the lake's freshness, Lake Babogaya being the most fresh of the five crater lakes. The unusually high chloride residence time of lake Arenguade is most probably attributable to additional input of chloride rich geothermal water from beneath the lake bottom which is not accounted for in the water budget and solute residence time calculation. The true chloride residence time of lake Arenguade is therefore probably lower than the indicated value.

There is no major hydrology difference between the crater lakes and the Great East African lakes in respect to chloride residence times. The chloride residence time in the Great East African lakes ranges from below 10 years to more than 2000yrs. The three linked lakes of the Ziway-Shala basin, for example, have a chloride residence time of 970 years. Lake Shala has a chloride residence time of greater than the three linked lakes (2500 yr.) (von Damm, 1984). Contrary to the Ziway-Shalla lakes some large lakes of the East African rift show far less chloride residence time. Lake Awasa has a chloride residence time of about 76yrs (Telford, 1998a) and Lake Nivasha has only 5.4years (Ojimbo *et al.*, 1996).

The residence time of the eight major ions shows that, all ions except Na and K have a residence time lower than that of chloride. Na and K are enriched in the lakes with respect to chloride in lake Babogaya, the freshest lake and pre Mojo Kilole the most saline lake.

In the rest of the lakes all ions have a residence time lower than that of chloride. In these lakes Na and K are lost by ion exchange with detrital clay minerals or by clay mineral formation in the lake i.e. 'reverse weathering'.

Ca is most probably lost by calcite/aragonite precipitation and uptake by calcite secreting organisms. Mg may be lost by magnesian calcite precipitation or precipitation of authegenic aluminosilicate such as of sepiolite: $MgSi_3O_6(OH)_2$.

Rippey *et al.,* (1985) related the removal of silica in Bishoftu Crater Lakes basically with incorporation into authegenic alumino silicate as suggested for magnesium and formation of amorphous/opaline silica cements. According to Rippey diatoms and are not important in silica removal. But microscopic analysis of the lakes sediment in this work suggests that the lakes contain a large percentage of diatom community, this fact testifies to the importance of diatom uptake for the removal of silica along with amorphous silica precipiatation due to reduction in solbility at high ionic strength.

As the bottom of the lakes water is characterized by high sulfide activity, observed from the foul odor, it is believed that reduction of sulfate to sulfide and incorporation of iron sulfide into sediments is responsible for sulfate removal.

The fluorite equilibrium calculation shows (section 6.11) that all the lakes are fluoride undersaturated, and it is therefore not possible to relate low residence time of fluoride to fluorite precipitation as fluorite precipitation is not possible due to the lakes undersaturation in fluorite. But fluoride residence time is much lower than that of chloride indicating a loss of fluoride. The possible way of fluoride removal is believed to be anion exchange with hydroxyl bearing clay minerals. Although removal of fluorite by anion exchange in East African lakes is not apparently reported (except von Damm *et al.,* 1984). Laboratory experiments (Chemistry Department, AAU, per. comm.) shows that clay minerals act as anion exchanger.

9.2 Oxygen isotope and Hydrological modeling of selected lakes

In order to test the sensitivity of the lakes isotope and chemical composition to climate and hydrological variation; oxygen, hydrological and hydrochemical modeling is made. The modeling can also help to quantitatively interpret paleoclimate and paleohydrology from the lacustrine carbonate, diatom and other proxy records. The modeling is also used to explain the recent changes in chemistry and hydrology of the lakes stated in section 4.6.

The modeling is performed on two of the Bishoftu Crater Lakes: lake Hora and lake Babogaya. The reason for selectingthese is that they have different hydrology, as demonstrated by geochemical and isotope mass balance calculation. Hydrochemical modeling have been run only for lake Babogaya.

9.2.1. Oxygen Isotope modeling

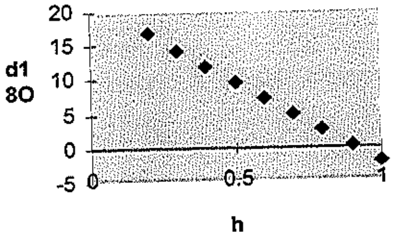
Model Formulation

The isotopic balance of a well-mixed lake can be expressed by the equation (Turner *et al.*, 1994) calculations were performed to demonstrate the sensitivity of the model to changes in water balance. For this calculation, the values for the climate conditions described above were held constant while the water balance components were varied.

Model Output

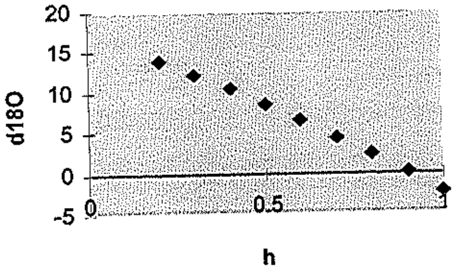
The results of lake Hora and Babogaya calculation, shown in figure 16, indicate that the stable isotopic composition of the lake water is relatively sensitive to changes in the climate controlled parameters h and δa as compared to isotopic composition of inflow δ_i. As far as climate controlled parameters are concerned, increasing h and δa by 10 units shifts the isotopic composition by 20 and 7 units respectively. On the other hand shifting δ_I by 10 units changes the isotopic composition by no more than 4 units.

Fig. sensitivity of oxygen isotopic composition of Lake Hora to change in humidity



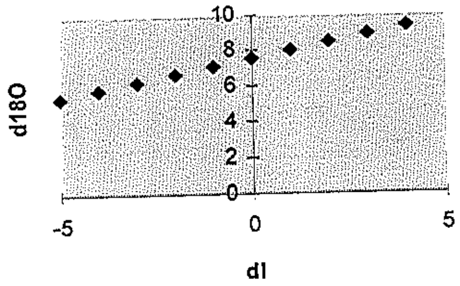
A

Fig sensitivity of isotopic composition of lake Babogaya to change in humidity



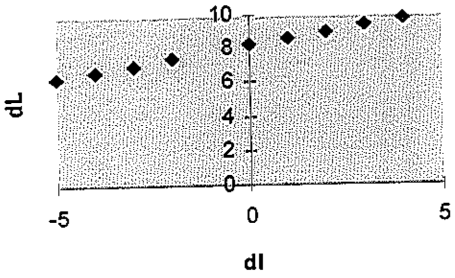
B

Fig. sensitivity of lake Babogaya to change in isotopic composition of inflow



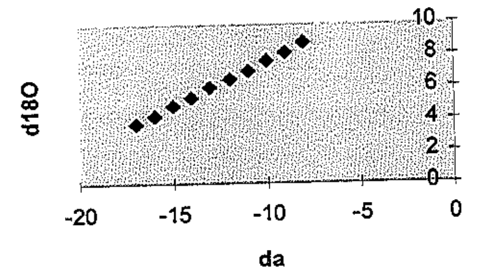
C

Fig sensitivity of isotopic compostion of lake Hora to change in isotopic composition of inflow



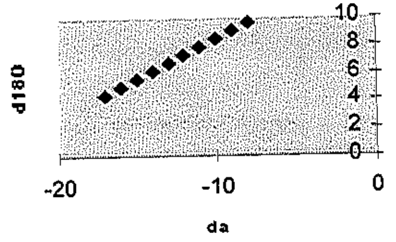
D

Fig. sensitivity of isotopic composition of lake Babogaya to change in isotopic composition of water vapour



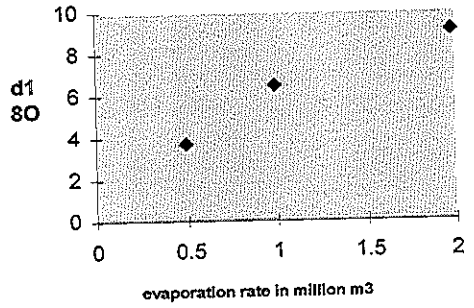
E

Fig sensitivity of isotopic composition of lake Hora to change in isotopic composition of water vapour



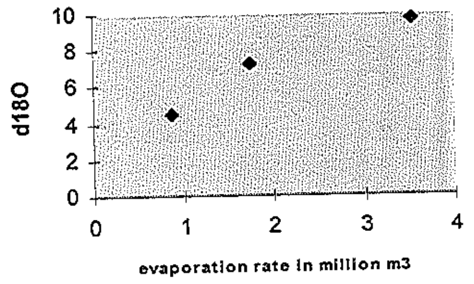
F

Fig. sensitivity of lake Babogaya to change in rate of evaporation



G

Fig. sensitivity of lake Hora to change in rate of evaporation



H

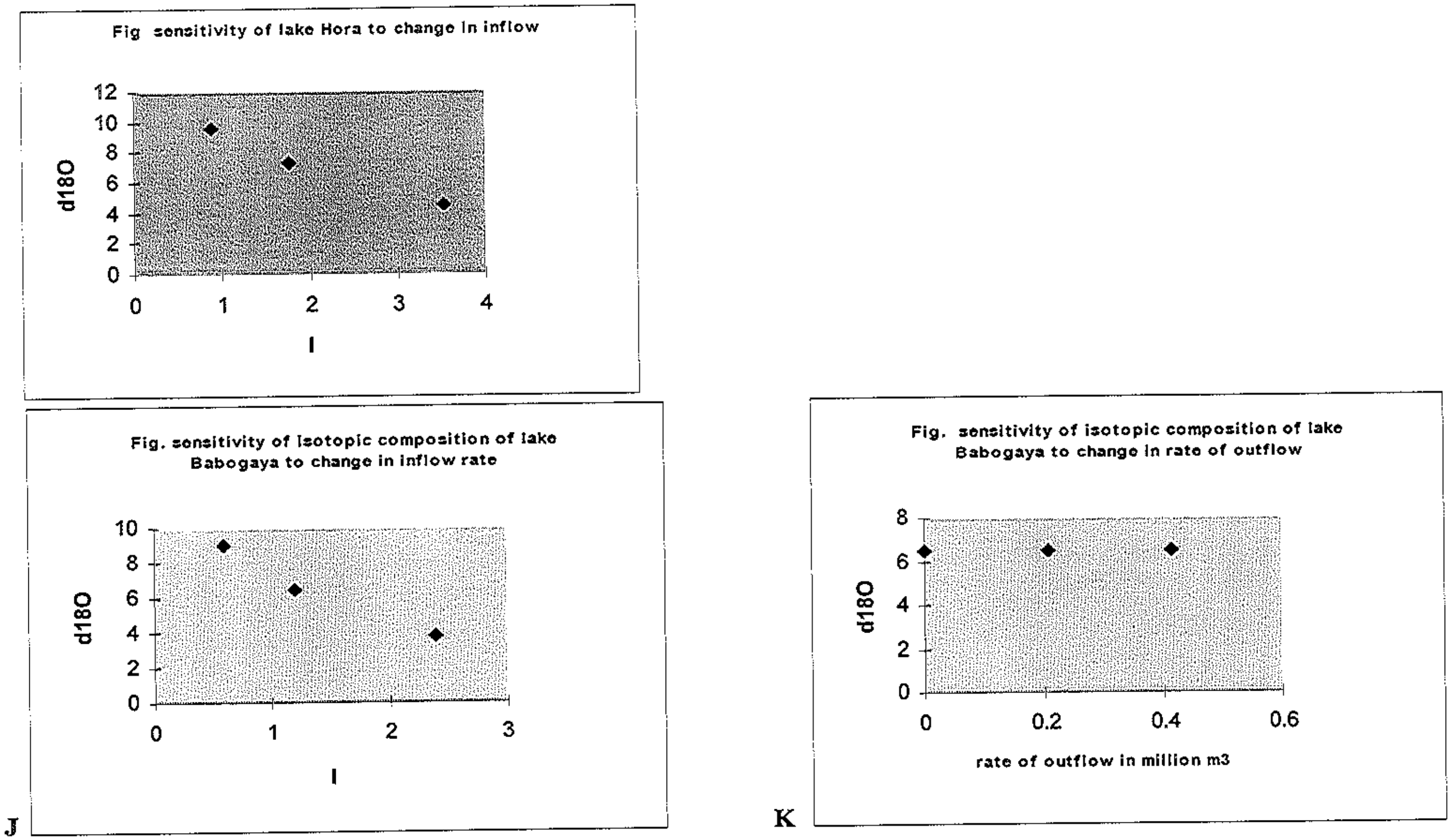


Figure 16. Sensitivity of Lake Hora (A,D,F,H,I) and lake Babogaya (B,C,E,G,I,J,K) to changes in humidity (A,B), isotopic composition of water vapor (E,F), isotopic composition of inflow (C,D), rate of evaporation (G,H) inflow (I,J) and outflow (K).

The sensitivity of lake Hora is nearly similar to that of lake Babogaya to changes in humidity, isotopic composition of atmospheric vapor, isotopic composition of inflow and change in water budget components.

The two atmospheric moisture parameters that most strongly control the stable isotopic composition of the lake water, h and δ_a, are negatively correlated (Turner *et al.*, 1996). The δ value of water vapor in the atmosphere is positively correlated with δ of rainfall and negatively correlated with relative humidity, so these climate factors will mutually reinforce one another to produce a lower δ_L under higher rainfall condition.

Running the model by shifting the rate of groundwater outflow shows that the isotopic composition of the lake is insensitive to change in rate of outflow.

The rate of change in isotopic composition is not linearly correlated with change in rate of evaporation and inflow. At very high evaporation rate and very low inflow the sensitivity of the lakes to change in evaporation and inflow is reduced.

9.2.2 Hydrological modeling

The effect of change in input or output parameters on the lake volume, area, depth and isotope is assessed by combining hydrological and oxygen isotope modeling. The use of such model is to predict the possible cause of recent lake level rise. The modeling work is however done only for lake Babogaya. Water budget quantified by isotope approach is taken in the model ($G_i = 585453\ m^3$; $G_o = 206242\ m^3$; $P = 480570\ m^3$, $E = 990090\ m^3$ and $R = 130310\ m^3$)

Model Formulation

$dV/dt = N + (P-E)A\ N = Gi - Go$ **(Equation 27)**

To characterize the change in volume of the lake in terms of change in depth and area of the lake the three elements should be related by a mathematical equation, characteristic to the lake. The area and depth of a lake is related to lake volume by a function specific to that lake. We need to obtain this function. The crater lakes can be conveniently assumed to occupy a circular basin, with parabolic cross-section of radius R, then

$A = \pi R^2$ and $R = (A/\pi)^{0.5}$ **(Equation 28)**

The parabolic relationship between depth D and radius R can be written as

$D = aR^b$ (Telford, 1998a) **(Equation 29a)**

a and b are constants

$R = (D/a)^{1/b}$ **(Equation 29b)**

$D = a(A/\pi)^{b/2}$ **(Equation 30)**

$$V = \int_{o}^{D} \pi R^2 dD$$

$$= \int_{0}^{D} \pi\left(\frac{D}{a}\right)^{2/b} dD$$

$$V = \pi\left(\frac{1}{a}\right)^{2/b} \frac{D^{b+2/b}}{b+2/b}$$ **(Equation 31)**

Value for a and b can be determined by solving equation 29b and 30 simultaneously using the modern values of lake Babogaya: $D = 65m$, $A = 579000\ m^2$, and $V = 22000000m^3$. This yields values of $2.76x10^{-6}$ and 2.82 for a and b respectively.

Area can be related to volume by equation

$$A = \pi a^{-2/b}\left[\left(\frac{b+2}{b}\right)\frac{V}{\pi}\right]^{2/b+2}$$ **(Equation 31)**

Depth is related to area by the equation

$$D = a\left(\frac{A}{\pi}\right)^{b/2}$$

Equation 27 better solved iteratively as:

$V_{t+1} = V_t + N + (P\text{-}E)A_t$

where Vt and Vt+1 are the volume of the lake in year t and t+1 respectively. For the model, P is varied, N is assumed to be constant.

CHAPTER TEN

CONCLUSION AND RECOMMENDATION

The major observations and conclusions found from this study may be summarized in terms of the following relevant parameters.

Water Budget: The Bishoftu Crater Lakes have a wide range of hydrologic properties. The rate of groundwater influx is greatest for lake Babogaya followed by lake Bishoftu. Lakes, Hora, Kilole, and Arenguade are least affected by groundwater outflow. Lake Kilole and Arenguade are least affected by groundwater inflow and outflow. Geothermal water presumably constitutes a significant amount of the lake Arenguade's water budget.

Chemistry of the Lakes: The chemistry of the five crater lakes is different, although the lakes catchment area has fairly similar geology. The difference in the chemistry of the lakes is mainly controlled by the rate of groundwater outflow as opposed to previous idea which related chemistry to the rate of evaporative concentration (Rippey *et al,* 1985). The more saline lakes; Aregnguade, pre Mojo Kilole, and Hora are the least affected by groundwater flux. The freshest lake; Babogaya is the most affected by groundwater outflow and inflow. Lake Bishoftu has an intermediate hydrology and chemistry.

Chemical Budget: In the studied lakes the chemical budget indicates loss of calcium, magnesium, alkalies, silica supthate and flouride. This could be related respectively to carbonate precipiatation, Mg-aluminium silicate formation, cation exchange with clay

Model output

Starting from the present condition,

- Doubling the precipitation over a period of one year increases the lake depth by 1m, the volume by *61000*m^3 and the lake area by *6407*m^2
- Increasing precipitation by 50% over a period of one year will increase the lake level by *0.5 m*, the volume by *305440*m^3 and the area by *3246*m^3
- Doubling precipitation by *50%* over a period of more than 5 years is required to raise the lake level by *2.5m.*
- Decreasing precipitation by *50%* over a period of one year reduce the depth by 0.5m.
- Transfer of *1527200* m^3 of water is required to raise the lake level by more than 2.5m keeping P, E, and N constant

9.3 Implication of the oxygen isotope and hydrological models.

The model output suggests that the area, volume, depth, and isotopic composition of lake Babogaya (and by extension the other lakes) are sensitive to change in climate. The recent raising trend in lakes level can not be explained by a change in climate. The climate change required to raise the level of lake Babogaya by 2.5 m is not observed in recent decades.

minerals, diatom uptake and reduction of sulfate to sulfide. As evidenced by chloride budget approach there is no major difference in water and solute residence times between the Bishoftu crater lakes and the Great East African lakes. The chloride residence time of Bishoftu crater lakes ranges from 50 yrs (lake Babogaya) to about 1000yrs (lake pre Mojo Kilole). The chloride and major ion residence time calculated for lake Arenguade is doubtful (most probably because of geothermal water input). The water and chloride residence time of the Great East African lakes is equally variable.

Human Impact: The recent rise in the level of some of the Bishoftu crater Lakes (Hora , Babogaya, and Bishoftu) and dilution of their chemistry over the past 4 decades is presumably due to the human impact. The construction of dams and irrigation activities are believed to have affected the lake levels and chemistry. Of all the lakes, lake Kilole is most significantly affected by human activity. The diversion of Mojo river into the lake has changed the chemistry, hydrology and possibly the trophic status of the lake. Sediment core taken from lake Kilole shows that after the diversion of the river the sedimentation rate has been more than 50 cm/yr. (the Large East African lakes have a sedimentation rate in the order of a mm/yr.). This may be related to the recent deforestation and land use changes which have contributed to the high sediment yield and sedimentation rates resulting from intensive erosion. This observation has direct relevance to the rate of siltation in artificial reservoirs in the region such as Koka reservoir in the upper Awash valley. Human impact on precipitation chemistry and pollution of groundwater by nitrate has also been noted.

Isotope and Hydrological Modeling: The Bishoftu crater lakes and the drying up ponds in the area provided a unique opportunity for stable isotope budget determination and isotope modeling. The environmental parameters have been determined by semi empirical approach without reverting to measurements. The δ_a (oxygen isotope composition of vapor in the environment) and δ^* (the limiting oxygen isotopic composition) of the region are determined to be -12.04‰ and 14‰, respectively, which are within reasonable range. A value of δ_a=-15 ‰ (Gonfiantini *et al.,* 1973) and δ_a =-9‰ (Turner *et al.,* 1994) is determined for the Afar and West Africa respectively. Oxygen isotope modeling shows that the isotopic composition of lake Babogaya and lake Hora, by extension of the other lakes is more sensitive to climate controlled parameters (*h* and δ_a) than water budget components *(P,E, and I)*. The hydrological model output reveals that the recent rise in lake levels cannot be explained by recent climate variability.

Future Work: The previous hypothesis which related the depleted isotopic composition of rift ground and geothermal waters to the high altitude sources is not based on systematic data collection. However the recently collected data points and the speculation about the moisture source (not rising from the rift to the adjacent highlands) go against the altitude effect. More evidence should however confirm this hypothesis.

The geochemical mass balance indicates that fluoride is lost from the lakes as compared to chloride. Fluorite equilibrium determination on the other hand shows that the lakes are undersaturated in fluorite. It is, therefore, suggested that the loss of fluoride from the lakes occur via anion exchange with clay minerals. This hypothesis should be tested by analyzing the geochemistry of clay sediments from cores taken out from lakes.

Groundwater modeling to help constrain the water budget of the lakes has not been attempted in this work and is recommended for further studies. Based on the isotopic modeling done in this study a quantitative paleoclimate study from the lake sediment carbonates is also a promising future line of research. Further study on precipitation chemistry and source of solute in the precipitation in order to understand human impact and geochemical cycling is also recommended.

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Appendix1. 'Mean monthly rainfall IAR station in mm, Debre Zeyit

	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	mm/yr
1953	0	24.4	11	88	18	77.8	97	165	53.2	0	2	24.7	561
1954	0	0	57	30.5	6.6	70.5	160	161	174.2	29	0	0	688
1955	0	0	23	36.4	0	80.1	354	208	142.9	0	0	0	845
1956	1.5	1.4	8.9	48	7.1	84.3	135	78	0	51	8.5	0.4	424
1957	0	25.6	65	91.5	48.1	123	210	305	24.8	5	1	1	900
1958	65.5	52.3	23.8	49.7	7	176	244	245	172.2	16	0.8	0	1053
1959	18	34	33.4	43.9	42.1	108	244	197	154.2	15	0	16	906
1960	0.8	5	48.1	16.6	99.5	56.3	168	270	161	0	5.2	0	830
1961	0	3.2	111	41.9	28.2	107	154	227	89.9	39	16.7	0	819
1962	0	1	62	24.7	2.7	0	203	237	181.8	47	0.9	21	780
1963	3	1.6	0	61.9	104	76	281	457	105.2	0	2.7	27.5	1120
1964	0	0	0	184	46.9	5.6	435	365	187.1	23	0	11	1257
1965	37.8	0	58.5	29.5	0	38.2	409	249	125.6	77	6.7	0	1030
1966	0	161	15.1	150	9.9	120	265	381	147.6	37	0	0	1287
1967	0	0	100	76.9	164	62.1	314	260	136	16	79.1	0	1208
1968	0	190	12.6	102	5	60.1	272	140	203	0	17.8	0	1003
1969	11	0	56.7	104	24.9	137	125	279	64.6	7.5	3.2	0	813
1970	44.1	31.1	7.5	21.4	45.3	56	251	290	112	5.9	0	0	864
1971	0.7	0	16.5	63	108	121	216	281	123.1	2.9	3	14.4	949
1972	0	95.2	53.7	136	47	102	214	225	66	2.6	0	0	942
1973	0	0	0	2.7	28	100	139	252	133.7	42	0	2	699
1974	0	12.5	104	7.6	98.1	114	307	199	140	3	0	0	986
1975	0	20	19.5	72.1	54.5	150	375	223	154	7	0	0	1075
1976	0	0	71.1	75	81.7	103	240	232	42.2	3.8	35.2	0.8	885
1977	43.1	1	87.7	90.2	57.6	101	273	203	82.2	15	3.4	0	957
1978	1.4	69	34.5	47.7	28.5	134	132	191	122.3	25	0	0.1	785
1979	77.7	0	54.7	13.4	76	111	225	188	83.8	13	0	0.1	842
1980	20	10.1	32.3	24.2	69.4	76.1	242	216	58.1	41	0	0	789
1981	0	20.5	164	62.1	7.1	35.8	295	152	162.8	4.2	0	1.2	904
1982	20.8	75.4	34.5	47.3	57.7	91	124	234	46.1	26	9.4	0	765
1983	0	10.2	46.8	105	209	149	129	345	88.6	23	0	0	1106
1984	0	0	19.3	0	109	80.7	221	290	85	0	0	3.6	808
1985	3.5	0	14.5	51.9	112	74	307	273	1.1	1.1	0	0.6	838
1986	0	23.6	51.7	142	72.4	167	179	163	90.2	3.2	0	0	891
1987	0	61.4	138	90.1	164	65.5	83	156	80.9	4.6	0	0	844
1988	8	14.9	6	44.6	36.8	101	146	237	121.4	17	0	0	732
1989	0.9	12.2	35.1	47	0.4	59	139	172	135.2	21	0	0	621
1990													
1991	0.3	37.6	53.7	7.9	1.9	48.2	170	191	50.1	4.6	0	0	565
1992	6.8	51.2	2	8.3	3.9	42.2	150	156	101.4	29	1.3	1	553
1993	0	53.7	0	76.5	42.9	52.3	113	143	93.9	12	0	1.7	590
1994	0	0	9.5	23.1	19	36.2	169	124	98.9	0	11.3	1	491
1995	0	17	3.6	33.9	6.2	19.3	140	143	56.3	0	0	0	419
1996	10.4	0	79	20.6	80.9	148	130	189	65.3	0.2	0.9	0	725
1997	13.4	0	16.7	38.7	6.1	150	147	148	46.5	74	7.5	0	647
1998	15.4	56	16.2	54.5	60.7	77.1	198	322	100.9				901
Average	8.98	26	41.3	57.5	51	87.7	212	226	103.7	17	4.92	2.91	838

Appendix 2. Monthly average windspeed(m/s) at 2m at IAR station, Debrezeyit

Year	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
1983	2.1	1.9	2	2	2	2	1.6	1.5	1	1.6	1.7	1.7
1984	1.9	2.3	2.4	3.3	2.1	1.8	1.6	1.4	1.6	2.2	1.9	2.2
1986	1.7	2	2.4	2	2	1.8	1.6	1.6	1.3	1.9	2.2	2.2
1987	2	2.4	1.7	2.1	2	1.2	1.6	1.4	1.3	1.9	1.9	1.9
1988	2	2.3	2.8	2.2	2.3	1.6	1.8	1.2	1	1.7	1.7	1.9
1989	1.9	2.2	1.9	1.7	2.4	1.7	1.6	1.4	1.1	1.6	2	1.7
1990	2.1	1.5	2.3	1.6			1.6	1.4	1	1.8	1.7	2
1991	2.1	1.8	2.1	3.3	3.3	2	1.6	1.4	1.2	1.9	1.9	2
1992	1.8	1.6	2.5	2.4	2.8	1.6	1.6	1.2	1.1	1.7	1.9	2
1993	2	1.9	2.3	2.1	2	1.4	1.6	1.3	0.9	1.5	1.8	1.9
1994	2	2.5	2.2	2.5	2.6	1.7	1.6	1.2	1.3	2.3	2	2.2
1995	2	1.9	2.5	2.1	2.4	1.8	1.6	1.2	1.1	2.2	1.9	2
1996	2.1	2.4	2.2	2.3	2.1	1.2	1.3	1.2	1	1.9	1.8	1.7
1997	1.6	2.8	2.4	2.3	2.8	2	1.3	1	1.2	1.9	2	2.1
1998	1.9	1.8	2.4	2.3	2.1	1.8	1.6	1.2	1			
Average	1.9467	2.09	2.27	2.28	2.35	1.69	1.6	1.31	1.14	1.9	1.89	1.96

Appendix 3a Mean monthly maximum temprature of IAR station Debrezeyit

Year	Jan	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
1991	27	27	27.9	29	29.9	28.9	23	23.6	25.1	26	25.4	25.4
1992	25.5	26.2	29.3	29.3	30.4	28.2	24	22.7	23.8	25	23.9	25.2
1993	25.3	25.1	28.4	27.2	27.5	26.6	24	24.1	24.5	25	25.4	26.1
1994	27.1	27.9	28.8	29	29.9	28	25	23.8	24.1	26	24.7	25.9
1995	26.3	28.1	28.2	27.4	29.9	29.3	24	23.6	25.2	26	26.2	26.6
1996	26	28.7	28.3	28.3	27.9	24.2	24	24.1	24.4	27	25.2	25.4
1997	25.3	27.3	29.1	27.5	30.3	28.1	25	24.7	26.6	26	25.4	25.7
Average	26.071	27.2	28.6	28.2	29.4	27.6	24	23.8	24.81	26	25.2	25.8

Appendix 3b Mean monthly minimum temprature, IAR station Debre Zeyit

	Jan	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
1991	10.5	12	12.7	12.5	12.8	13	14	13.7	12.4	8.5	7.3	7.6
1992	10.9	12.2	12.8	13.5	12.3	12.1	13	13.9	11.9	9.6	7.8	9.6
1993	11	11.4	9.7	13.6	12.5	11.9	13	13.3	12.9	9.9	7.5	6.4
1994	7.3	9.9	12.9	13.6	13	12.5	14	13.5	11.8	7.9	8.1	6.6
1995	8	11.5	13.4	14.3	13	11.5	14	14.1	11.9	9.9	7.7	10.7
1996	11.7	10.1	13.6	12.5	12.5	13.3	14	13.7	12.4	8.4	7.5	7.2
1997	11.1	8.3	12.9	12.8	12.5	13.5	14	13.6	12.7	12	11	8.4
Average	10.071	10.8	12.6	13.3	12.7	12.5	14	13.7	12.29	9.5	8.13	8.07

Appendix 4a Mean monthly relative humidity at 0600, IAR, Deb

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
1987	89	73	90	88	84	92	88	91	90	84	75	75
1988	82	82	71	80	71	89	89	93	94	91	86	86
1989	88	80	84	91	79	87	91	91	92	90	86	92
1990	83	92	89	89			90	91	93	87	85	81
1991	82	88	88	82	72	82	92	92	92	88	86	88
1992	91	93	88	82	79	86	90	93	93	89	86	89
1993	84	88	76	84	88	91	91	91	93	91	88	80
1994	76	73	79	79	83	85	89	91	90	88	85	85
1995	80	83	84	88	78	82	92	93	93	82	83	82
1996	84	74	85	86	87	92	92	93	94	87	87	84
Average	**83.9**	**82.6**	**83.4**	**84.9**	**80.1**	**87.3**	**90**	**91.9**	**92.4**	**88**	**84.7**	**84.2**

Appendix 4b Monthly mean relative humidity at 1200

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul,	Aug.	Sept.	Oct.	Nov.	Dec.
1987	45	38	52	48	51	53	54	61	49	36	25	31
1988	41	39	25	40	32	51	68	69	63	42	30	38
1989	43	42	41	52	33	49	65	67	63	42	39	51
1990	37	55	47	48			67	68	63	34	35	32
1991	38	48	45	34	31	44	69	69	61	39	35	32
1992	48	55	37	40	31	48	65	74	63	46	41	45
1993	47	49	29	48	46	55	66	67	64	47	36	32
1994	27	29	40	40	35	52	67	72	64	35	40	40
1995	34	40	44	50	35	44	68	69	60	32	33	37
1996	12	28	45	42	49	67	70	70	60	33	36	33
Average	**37.2**	**42.3**	**40.5**	**44.2**	**38.1**	**51.4**	**66**	**68.6**	**61**	**39**	**35**	**37.1**

Appendix 4c Monthly mean relative humidity at 1800, IAR Debrezeyit

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
1987	37	37	54	47	48	57	54	58	51	37	29	30
1988	38	35	23	42	23	54	69	71	74	51	35	40
1989	43	39	39	55	30	51	73	66	70	49	42	56
1990	33	54	45	48			66	69	72	42	37	29
1991	33	38	40	34	32	41	69	71	68	40	37	38
1992	46	47	31	36	30	48	65	73	67	51	39	40
1993	44	48	25	47	46	58	65	68	74	53	41	26
1994	26	25	33	35	31	55	70	78	64	42	35	29
1995	33	30	41	51	35	42	66	74	66	39	36	36
1996	41	24	42	39	45	75	72	71	67	36	35	33
Average	**37.4**	**37.7**	**37.3**	**43.4**	**35.6**	**53.4**	**67**	**69.9**	**67.3**	**44**	**36.6**	**35.7**

Appendix 5. Mean monthly sunshine hours

Year	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept	Oct.	Nov.	Dec.
1991	9.6	7.7	7.9		8.5	7.2		4.9	6.1		9.3	
1992	7	6.9	7.5	7.2	9.2	6.9	4.9	3.9	6.6	8.9	9.3	8.7
1993	8.1	7.3	9.7	9.2	8.3	7	5.6	6.9	5.7	8.8	10.2	10
1994	10.2	9.8	8.3	8	9.4	6.1	4.9	4.9	6.4	10	9	10.3
1995	10.2	7.9	8.3	6.1					7.5	10		
1996												
1997	8	10.7	9	7.3	10.1	6.7	6.4	6.8	9.3	8		9.6
1998	8.1	7.9	8.1	9.3	8.5	7	6					
Average	***8.7***	***8.3***	***8.4***	***6.7***	***9.0***	***6.8***	***5.6***	***5.5***	***6.9***	***9.2***	***9.5***	***9.7***

Appendix 6. Mean monthly pan evaporation IAR station Debrezeyit in mm.

	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.	
1980	256.9	251	298	308	338	179	19	41.1	124.3	205	247	270	
1981	298.6	252	113	162	297	265	114	125	130.3	256	275	249	
1982	165.8	173	268	209	280	183	132	49.9	122.8	213	165	208	
1983	206	186	211	190	182	173	123	88.3	128.4	189	215	199	
1984	235.8	280	323	352	289	174	182	146	245	209	121		
1985	124.8	130	233	119	106	139	91	98.8	135.5	184	187	32.3	
1986	229.4	146	250	158	189	111	125	117	129.4	212	234	213	
1987	238	155	150	196	185	142	159	122	157.9	206	237	213	
1988	211.9	226	345	221	271	155	114	128	171.1	164	200	164	
1997	152.1	180	171	138	191	141	74	92.3	115.3	125	112	165	
													***E** pan*
Average	211.93	198	236	205	233	166	113	101	146	196	199	171	2177

Appendix 7. Major ion chemistry of groundwaters in Dedre Zeyit region, 1974-1998, diffent sources

Location	Analysis da	Alkalinity	pH	Ca	Mg	K	Na	Cl	HCO3	NO3	SiO2	F	TDS
Mac.fact	18/10/83	360	7.4	56.1	41.8		25.4	11.3	439.2	0.5	59	0.3	
Mac.Factory	29588			54	34	14	19	9	380		57	0.6	
Defence Eng.	14/6/88	335	7.7	40.1	36.2	11.9	30.6	14	408.7	2			
Air Force BW	17/8/87	260	8.6	51.3	20.4	9.6	44.2	14.2	316.8	7.1	82	0.8	
Air Force BW	17/8/87	330	7.8	44.9	29.2	11.9	64.6	28.4	402.6	8.9	75	0.8	
Air Force BW	22/8/88	320	7.8	73.7	15.6	12.4	47.6	21.3	390.4	11.2	71.5	1	
Air Force BW	32569	300	7.2	64	30	11.2	44.2	35.5	366	5.9	84	0.97	
Air Force BW	30/8/89	280	7.5	32.2	25.3	8.9	50	14.2	341.6	0.9	70.5	0.57	
GendaGorba	29072	250		51	16	8	30.5	14.2	305	2.8	68	0.4	
GendaGorba	31168	260	8.4	51.3	19.5	6.9	34.9	15.6	316.8	1.8	72.7	0.5	
GendaGorba	20/1/85	260	7.9	54.5	18.5	7.4	30.6	14.2	317.2	1.6	60	0.3	
GendaGorba	28923	255	8.4	52	17.3	9	32	10.6	310	2	61	0.6	
GendaGorba	28950	255	7.8	52.1	17.5	5.6	31	15.9	311.1	2.65	71	0.35	
GendaGorba	29072	275	8	54.5	16.8	9.9	33.2	10.6	335	2.6	70	0.5	
GendaGorba	15/12/84	275	8.1	62.1	17	10	34	17.7	335.5	1.8	32.5	0.6	
GendaGorba	15/1/85	356	8	57.3	18.7	8.9	28.6	10.6	341	1.2	66	0.4	
Dire BW	1982		7.6	50	46	12	63	14	398		87	0.4	
Teferi L. Bw	1974		7.9	29.6	24.2	9	22.5		283		69.6	0.75	452
Slaughtery B	1974		7.6	38.8	32.6	11	60	15.6	403		45	1.3	607
Vetrnary Sch	1974		7.4	42.6	32.5	9.5	67.5	15.6	442		63.7	0.75	
Blue Nile PF	1996		7.69	44	36	9	34	7	392	5	57	0.62	
Dire Arerti	27/11/95	458	7.1					22		0.76			640
Dragados W	35832		7.23	41	14	5	26	18	242	18	71	0.56	
Hora Tannery	1993	312	7.4	43.3	26.3	5.6	57.8	12.8	380.6	6.7	67.5	0.68	
Averge in meq/l		302.4	7.75	2.48	2.12	0.241	1.722	0.45	5.814	0.0708	63.5	0.033	566

Appendix 8. Major ion, pH and temprature data 1998-1999, temprature in oC,Cocuctivity in nS/cm and ions in meq/l

Location	date of sampli	T	pH	Cond	Ca	Mg	K	Na	Cl	CO3+C	NO3	SO4
Almaz Doro	17-Jul-98	21.1	7.04		24	33	6.8	36.2	5.99	140.30	5.68	33.68
CIM-mission	17-Jul-98	23.7	7.04		66	28	12.3	29.3	36.22	66.30	50.98	13.11
Almaz Doro	17-Jul-98				24	31	7.3	38.7	2.81	166.71	0.17	0.13
CIM	4-Oct-98				58	31	13	50.5	3.50	217.73	13.66	2.26
Hora Tannary	,,	23.1	7.12	590	46	28	5.8	59.4	7.36	221.18	2.00	4.61
Kalehiwot BW	,,	23.6	7.44	687	36	34	11.1	68.2	14.77	237.68	5.10	2.59
Almaz Doro	,,				13.3	29	6.5	37.4	25.81	82.38	26.51	11.18
Kalehiwot, sout	,,	24.2	7.4	585	34	26	10.7	42.4	4.21	171.77	7.99	4.04
Almaz Doro	,,	24.7	7.51	784	26	33	8.4	50.2	11.74	180.05	5.43	7.82
Hora Tannary	25-Dec-99	24.4	7.15	784	47	28	6.5	63.1	27.08	176.45	24.06	7.18
Elfora	14-Jan-99	21.7	6.86		47	1.6	5.5	22.5	8.08	69.47	20.83	7.23
Hora Tannary	13-Jan-99	23.9	7.4		42	28	6	59.8	33.43	150.48	25.40	8.45
AdaPasta&mac	14-Jan-99	21.3	6.97		42	28	10.9	28.2	4.80	144.72	4.99	4.97
Agri Res.Cente	14-Jan-99	26.7	7.4		32	24	7.9	43.4	7.42	162.34	5.29	6.48
N.Franco	15-Jan-99	22.2	7.33		36	33	15.8	64.4	7.45	245.30	3.33	11.08
Agri Res Inst.	14-Jan-99	23.2	7.57		28	27	7.5	51.7	8.73	180.00	5.09	14.17
Managment ins	14-Jan-99				36	28	12.1	49.4	8.47	186.06	9.77	8.66
Defence Eng.	15-Jan-99	33.5	7.27		38	36	10.9	27.4	4.94	149.16	5.28	5.02
Defence Eng	15-Jan-99	29.46	7.58		36	36	12.8	29.9	7.95	147.69	9.30	6.34
Dragados	14-Jan-99	27.1	7		35	16	4.7	21.5	9.66	70.62	21.63	9.16
BlueNilePF	15-Jan-99	25.8	7.45		34	43	9.1	33.7	8.71	155.99	11.95	4.66
HoraAgroInd.	15-Jan-99	22.2	7.36		36	36	10.9	81.7	21.20	260.12	4.79	17.81
AlmazDoro	13-Jan-99	22.7	7.5		26	29	7.5	45.8	11.70	163.66	3.84	7.40
Slaught House	15-Jan-99	25.6	7.5		30	43	8.7	53.9	23.02	134.80	53.46	22.47
Kalehiwot Wes	15-Jan-99	22.7	7.5		41	21	6.5	36.5	5.74	144.80	9.12	4.08
Kalehiwot East	13-Jan-99	21.4	7.64		36	24	9.8	41	3.80	167.16	7.02	4.47
Ato Gizaw HD	15-Jan-99	24.4	6.68		88	64	29.4	60.6	68.95	159.48	62.07	50.71

Appendix 9. Major ion chemistry of Bishoftu crater lakes in meq/l from 1943-1999

						Lake Arenguade										
ION	1938	1963	1964	1976	1981	1988	1973	1978	1982	1987	1987	1992	1992	1998	1999	Average
	Omar	Posser	Wood	Igzaw	G/Tsadik	Wood	Igzaw	Tefera	Berhane	Getahun	Mines	Tamiru	Zinabu	Richard	This work	
Na		67					63.4		23.4				59		37.2956522	
K		8.1					6.65		1.8				11.5		5.56410256	
Ca		0.67					0.57		0.325				0.8		0.12	
Mg		<0.6					0.84		1.33				0.4		0.33333333	
HCO3+ CO3		51.4					74		14.2				54			
Cl		22					17.6		2.48				22		23.3521127	
SO4		0.7					<0.02		0.15				0.04		7.93548387	
NO3																
SiO2							57.3		34							
F							0.26		0.22							
						Lake Babogaya										
Na		5.5					5.3				4.7	1	3.65	4.63		
K		1.05					0.74				0.67	1.27	2.7	0.79		
Ca		0.55	0.46				0.52				0.14	2.44	3	1.64		
Mg		4.65	4.87				3.63				0.94	2.78	1.54	4.21		
HCO3+ CO3		10.2	10.8				9.3				8.31	6.8	9.5	10.13		
Cl		0.9	0.79				0.68				0.69	0.56	1.97	0.57		
SO4		<0.1					0.19				0.01	0.02	0	0.05		
NO3											0.05					
SiO2(mg/l)		38	77				66.5				67		25			
F							0.05				0.045	0.01				
						Lake Bishoftu										
Na		16					13.59		1.30434783			12.6	33	13		
K		1.5					1.11		1.53846154			5.1	1.82	0.9		
Ca		0.37	0.35				0.16		0.0625			2.26	1	1.76		
Mg		5.8	6.44				5.19		1.66666667			1.13	4.22	6.12		
HCO3+ CO3		20	19.3				17.1		25.942623			18.87	17	22.16		
Cl		4	3.49				2.62		6.1971831			2.14	4.34	0.26		
SO4		0.35					0.12		0.21875			0.02	0.018			
NO3		0.02										0.06				
SiO2			38				39.1		21			48	19			
F							0.01052632		0.05789474			0.02				
						Lake Hora										
Na	9.39	23.9					23.91		1.91304348			0.26	17.95	16.5		
K	0.67	1.31					1.46		1.23076923			0.2	1.92	0.9		
Ca	0.8	0.34					0.57		0.075			1.78	0.8	0.9		
Mg	0.64	3.94					6.52		1.25			4.8	5.93	6.5		
HCO3+ CO3	21.5	26.8					24.82		17.2759563			3.52	16.8	22		
Cl	5.01	5.67					5.9		2.81690141			3.35	5.16	4.8		
SO4		0.4					0.25		0.125				0	0.1		
NO3												0.1	0.015	0.01		
SiO2		55					93		21			71.1	29			
F							0.02		0.04210526			0.07				
						Lake Kilole										
Na		70.5								86.9565217			4.07			
K		4.5								5.64102564			0.123			
Ca		0.7								0.1			0.122			
Mg		<0.6								0.08333333			0.203			
HCO3+ CO3		63.4								24.1775956			2.4			
Cl		13.6								17.1830986			0.99			
SO4		0.4											0.02			

NO3										0.56451613							
SiO2										6							
F										0.31578947							
						Lake Cheloleka											
Na					0.28086957												
K					0.25641026												
Ca					0.2375												
Mg					0.1875												
HCO3+ CO3					0.16393443												
Cl					0.05633803												
SO4					0.08333333												
NO3																	
SiO2					13												
F					0.04210526												

Appendix 10. Lakes chemical analysis result 1998/99, average major ion conc. in meq/l conductivity in µS/cm and T in oC.

No.	Location	date of sam	T	pH	Cond	Ca	Mg	K	Na	Cl	HCO3+	NO3	SO4
1	Babogaya-Arm	4-Apr-98	24.8	9.09		1.8	44	29.7	85.8	30.44	277.14	0.86	3.19
2	Babogaya-Mid	4-Apr-98	21.1	8.17		6.9	47	31.6	87.3	21.77	239.64	62.04	24.74
3	Babogaya-Bott	4-Apr-98	21.6	7.73		8.3	48	30.9	88.8	22.07	306.37	6.22	2.38
4	Babogaya-Arm	21-Apr-98	25.8	9.09		3.6	47	31.6	81.3	24.10	283.77	1.37	3.12
5	Babogaya-Mid	21-Apr-98	21.4	7.69		6.8	49	30.4	84.3	20.28	302.12	1.02	1.92
6	Babogaya-Bott	21-Apr-98	21.2	7.59		8.8	50	30.9	88.8	20.31	317.54	1.03	2.03
7	Babogaya-Arm	18-May-98	26.9	8.95		3.9	45	28.9	82.8	25.41	278.79	1.50	3.25
8	Babogaya-Mid	18-May-98	21.3	8.26		6.3	47	29.4	81.3	20.91	286.76	2.68	2.59
9	Babogaya-Bott	18-May-98	20.7	7.7		8.1	50	30.9	88.8	20.64	314.65	2.88	1.90
10	Babogaya-Arm	16-Jun-98	25.1	8.87		4.2	46	28.7	84.3	22.24	288.49	2.54	2.91
11	Babogaya-Mid	16-Jun-98	21.6	7.92		6.1	48	30.2	85.8	20.97	302.67	0.98	2.44
12	Babogaya-Bott	16-Jun-98	21.6	8.17		8.3	47	29.2	85.8	20.73	300.82	2.21	2.11
13	Babogaya-Arm	17-Jul-98	24.8	9.11		4.5	46	30.4	81.3	22.02	282.82	3.50	2.99
14	Babogaya-Mid	17-Jul-98	21.2	7.73		7.5	49	30.9	78.4	21.27	285.54	1.52	2.10
15	Babogaya-Bott	17-Jul-98	21.6	7.55		8.3	51	31.4	81.3	20.41	297.05	2.56	3.92
17	Babogaya -Ar	27-Aug-98	24.2	8.91	714	4.5	43	28.2	88.8	21.40	297.92	2.24	2.52
18	Babogaya-Mid	27-Aug-98	20.1	7.6	798	6.5	49	30.9	77	20.65	277.72	5.81	2.69
19	Babogaya-Bott	27-Aug-98	20.3	7.91	782	6.4	48	30.2	78.4	18.53	286.68	1.85	2.20
25	Babogaya,arm	4-Oct-98	26.8	8.96	614	4.9	43	29.2	74.2	19.68	263.18	3.04	2.72
26	Babogaya,mid	4-Oct-98	21.7	8.02	807	6.4	50	32.1	77	22.04	280.94	3.30	2.48
27	Babogaya,bott	4-Oct-98	23.4	7.04	910	20	48	30.4	74.2	22.62	264.61	16.79	1.87
29	Babogaya,arm	12-Nov-98	22.5	8.83	817	5.1	43	28	82.8	28.73	268.75	2.75	3.48
30	Babogaya,mid	,,	22.7	8.14	892	6.1	47	28.9	84.3	21.59	292.25	3.04	2.56
31	Babogaya,bott	,,	20.8	7.35	951	8.3	48	29.7	84.3	20.39	298.49	3.29	1.87
40	Babogaya, Ar	24-Dec-98	22.4	8.63	844	5.5	47	31.4	97.5	31.28	315.50	1.89	1.59
41	Babogaya, mid	,,	21.7	7.84	884	6.6	47	29.7	88.8	22.79	305.58	1.22	2.48
42	Babogaya, bot	,,	21.4	7.42	965	8.6	49	30.2	104.9	2.93	388.99	0.21	0.13
48	Babaogaya,ar	12-Jan-99	23.1	8.77		5.8	45	28.4	102.2	19.59	339.43	3.32	2.28
49	Babagaya, mid	12-Jan-99	21.1	8.41		5.8	45	28.2	100.7	9.55	333.52	20.61	8.14
50	Babaogaya,bot	,,	20.6	7.25		8.5	52	32.4	110.9	21.11	378.77	1.72	1.99
	Averege		22.46	8.16	831.60	0.32	3.92	0.77	3.76	0.60	4.89	0.09	0.08
23	Hora-Arm	27-Aug-98	24	8.5	2290	3.4	69	46.1	433.9	345.24	589.24	42.04	281.18
24	Hora-25m	27-Aug-98	22.4	7.84	2210	4.1	74	49	420.3	156.31	907.59	103.31	33.65
33	Hora,int	13-Nov-98	23.5	8.25	2440	3.7	73	47.3	454.8	112.30	#####	15.19	88.33
51	Hora, arm	14-Jan-99	24.3	8.33		4	74	48.2	403.6	140.00	990.06	10.51	6.11
52	Hora,25m	,,	22.1	8.01		3.9	74	48.4	427.1	149.41	#####	9.50	6.29
53	Hora,10	,,	22.4	8.31		3.9	76	48.7	400.3	145.22	969.57	16.49	6.52
	Average		23.12	8.21	2313.3	0.16	5.24	1.064	15.776	4.21921	13.19	0.454	1.24
34	Arengude,shor	13-Nov-98				4.8	8	217.4	8578.6	829.00	#####	492.00	158.00
						0.24	0.68	6.67	372.98	23.35	346.67	7.94	3.28
35	West/north Ch	,,	20.6	7.12	149	10.6	3	3.4	6.7	5.22	25.87	0.14	0.00
36	East Cheleka,s	,,	19.7	7.95	147	23	4.8	2.9	3.1	3.42	28.93	1.36	0.81
46	East Chelelcka	24-Dec-98	18	7.45	246	30	7.7	3.4	4.6	0.39	47.69	1.72	0.39
56	East Chelelcka	13-Jan-99	20.7	7.53		35	9	3.9	5.6	0.44	57.00	1.28	0.17
	Average		19.75	7.61	180.67	1.24	0.52	0.09	0.22	0.07	0.66	0.02	0.00
32	Kuriftu, shore	,,	21.4	7.8	191.9	24	5	3.9	4.5	2.95	37.44	0.15	0.10
43	Kuriftu,SW sh	25-Dec-98	26.7	8.4	232	24	5.6	4.4	5.1	3.16	35.36	5.12	0.00
55	Kurift,SW sho	16-Jan-99	22.2	8.25		25	5.8	4.5	5	0.42	43.48	2.35	0.67
	Averege		23.43	8.15	211.95	1.20	0.44	0.11	0.21	0.08	0.64	0.04	0.00
54	Kilole,intig.	13-Jan-99	20.2	8.8		23	7.7	4.4	15.3	5.05	64.94	1.18	0.00
	Averege		20.2	8.8		1.16	0.64	0.11	0.67	0.14	1.06	0.02	0.00

Modern trace element composition of the Bishoftu waters in ppb, 1998-1999

No.	Location	Li	Be	B	Sc	V	Cr	Mn	Fe	Co	Cu	Zn	Br	Rb	Sr	Y	Mo	Sn	I	Ba	La	Ce	W	Pb	U	Ba/Sr	La/Ce	La/Y
1	Babogaya-Arm	3.85	2.67	190.64	40.41	7.02	9.03	0.92	123.88	0.08	0.63	2.68	33.92	25.04	13.27	0.00	2.69	0.11	38.23	1.85	0.01	0.03	5.69	0.02	1.38	0.14	0.46	
2	Babogaya-Mid	3.66	3.46	222.37	39.86	5.56	10.62	0.87	396.63	0.10	0.00	19.40	28.19	26.05	76.15	0.01	1.83	0.00	161.17	12.14	0.02	0.03	1.36	0.00	1.15	0.16	0.62	1.41
3	Babogaya-Bottom	3.45	2.88	201.97	40.43	4.75	9.81	1.39	432.61	0.22	0.00	0.00	35.04	26.50	93.76	0.03	0.87	0.00	8.87	15.00	0.02	0.02	1.40	0.00	1.03	0.16	0.75	0.69
4	Babogaya-Arm	3.82	2.30	169.70	37.91	6.58	8.69	0.86	198.87	0.15	0.00	0.00	30.33	24.68	33.64	0.03	2.15	0.00	41.50	4.18	0.00	0.00	2.55	0.00	1.43	0.12	1.23	0.12
5	Babogaya-Mid	3.57	3.28	198.73	40.56	4.93	9.70	1.53	367.61	0.21	0.00	7.54	32.84	25.75	76.49	0.00	1.94	0.02	49.33	12.23	0.01	0.00	0.82	0.01	1.07	0.16		
6	Babogaya-Bottom	3.17	2.65	189.49	39.62	4.45	9.02	1.64	444.46	0.16	0.00	0.00	31.72	24.76	94.22	0.05	1.48	0.02	46.76	15.42	0.00	0.15	8.28	0.00	0.95	0.16		
7	Babogaya-Arm	3.53	2.90	177.76	36.89	7.02	8.63	1.56	204.75	0.09	0.00	0.00	27.91	24.98	37.41	0.02	2.35	0.00	24.78	6.09	0.02	0.08	3.28	0.00	1.44	0.16	0.19	0.86
8	Babogaya-Mid	3.62	3.15	196.32	38.70	4.53	10.21	1.41	306.37	0.05	0.00	3.38	29.01	25.15	70.24	0.07	1.91	0.75	115.60	28.08	0.10	0.18	3.31	0.00	1.17	0.40	0.55	1.43
9	Babogaya-Bottom	3.31	3.41	209.84	38.26	4.99	10.44	1.39	398.09	0.16	0.00	6.11	31.44	25.65	90.24	0.00	1.25	0.00	55.88	13.95	0.01	0.06	1.77	0.00	0.99	0.15	0.21	
10	Babogaya-Arm	3.54	2.48	176.49	36.66	7.95	9.58	1.43	215.69	0.11	0.00	0.00	28.77	24.46	41.68	0.07	2.23	0.06	32.98	66.46	0.04	0.02	1.93	0.82	1.54	1.59	1.54	0.51
11	Babogaya-Mid	3.75	3.05	203.69	36.08	4.73	10.38	1.49	301.71	0.00	0.00	0.00	27.40	25.44	64.61	0.03	1.58	0.00	65.19	13.71	0.06	1.56	1.74	0.00	1.26	0.21	0.04	1.96
12	Babogaya-Bottom	3.61	3.56	217.51	38.52	4.91	10.29	1.40	400.85	0.19	0.00	0.00	28.15	26.46	96.45	0.01	1.20	0.00	60.18	17.49	0.01	0.05	1.10	0.00	1.01	0.18	0.21	1.00
13	Babogaya-Arm	4.06	2.76	201.91	37.40	6.04	6.10	1.62	252.90	0.08	0.00	0.00	26.84	24.94	45.72	0.02	1.63	0.00	16.57	4.88	0.04	0.94	2.25	0.00	1.34	0.11	0.04	2.18
14	Babogaya-Mid	3.51	3.22	203.65	38.71	4.64	9.95	2.03	363.74	0.14	0.00	0.00	28.77	26.31	82.27	0.04	2.03	0.03	129.07	327.06	0.07	0.03	2.86	0.02	1.10	3.98	2.50	1.50
15	Babogaya-Bottom	3.69	3.44	218.52	37.20	4.11	9.97	1.75	375.24	0.14	0.00	0.00	34.54	26.11	95.22	0.00	0.45	0.00	47.96	17.28	0.02	0.05	3.78	0.00	0.95	0.18	0.36	
16	Almaz Doro BW	2.71	1.51	71.82	34.60	2.72	5.90	2.22	712.00	0.13	0.00	52.57	9.20	10.23	257.29	0.01	2.18	0.00	16.16	10.97	0.01	0.60	47.49	0.00	0.15	0.04	0.02	0.99
17	Babogaya -Arm	3.00	2.07	150.01	30.10	7.01	8.61	1.66	208.70	0.04	0.00	0.00	26.89	23.73	47.16	0.07	2.35	0.00	19.73	7.03	0.04	0.07	-0.11	0.00	1.51	0.15	0.56	0.56
18	Babogaya-Mid	3.27	2.31	173.86	34.03	3.93	9.08	1.85	283.39	0.00	0.00	0.00	28.80	24.13	69.63	0.01	1.15	0.00	145.25	10.37	0.01	0.01	3.49	0.00	1.15	0.15	0.41	0.92
19	Babogaya-Bottom	3.32	2.91	186.20	33.69	4.00	9.94	3.23	301.65	0.06	0.00	0.00	25.88	24.11	72.15	0.01	1.40	0.04	98.63	11.79	0.01	0.05	6.05	0.10	1.14	0.16	0.26	1.05
20	CIM-mission BW	4.74	1.42	55.03	33.05	38.06	8.20	2.83	1675.0	0.37	6.78	91.71	83.74	9.16	352.06	0.03	0.07	0.00	10.69	105.52	0.01	0.01	3.57	0.00	1.98	0.30	1.47	0.27
21	Almaz Doro BW	2.33	0.87	45.53	32.12	2.04	4.71	3.87	644.07	0.07	0.00	111.46	12.13	10.02	241.61	0.01	1.66	0.00	34.84	20.34	0.09	3.40	37.97	0.02	0.19	0.08	0.03	
22	Debrazeyit	0.11	0.14	0.00	1.26	0.00	1.24	3.42	372.86	0.08	13.68	419.45	2.62	0.58	28.18	0.04	0.00	0.03	5.63	1297.0	3.98	0.06	3.70	0.02	0.02			
23	Hora-Arm	353.08	15.65	3849.9	45.52	8.09	16.50	1.37	185.21	0.01	0.00	9.21	64.79	71.63	60.12	0.03	2.31	0.00	6.04	117.66	0.17	7.28	28.16	0.00	0.97	1.96	0.02	
24	Hora-25m	373.81	17.76	4194.6	46.78	8.34	17.64	1.11	218.28	0.05	0.00	0.00	69.14	76.92	73.06	0.00	1.49	0.00	17.97	79.35	0.03	0.06	25.41	0.00	0.89	1.09	0.47	
25	Babogaya,arm	3.55	1.99	170.24	30.71	6.65	7.63	2.22	210.76	0.01	0.00	0.00	27.22	22.88	48.18	0.05	1.70	0.04	14.02	73.56	0.23	8.77	1.38	0.00	1.50	1.53	0.03	
26	Babogaya,middle	4.90	4.47	288.87	41.88	3.36	6.39	2.55	358.19	0.04	0.00	0.00	26.78	25.83	69.35	0.00	1.06	0.00	19.47	14.36	0.02	0.95	-0.25	0.00	0.95	0.21	0.02	
27	Babogaya,bottom	3.40	3.19	225.46	37.43	8.19	9.52	17.59	611.85	0.27	0.00	0.00	23.54	25.28	149.15	0.07	1.58	0.01	100.28	22.37	0.05	0.11	9.89	0.00	1.11	0.15	0.47	0.76
28	CIM, BW	5.95	1.69	78.77	33.37	28.28	6.64	4.39	1396.2	0.32	10.89	62.17	27.75	12.91	323.43	0.03	4.09	0.10	9.24	92.63	0.21	10.27	4.40	0.00	2.86	0.29	0.02	7.00
29	Babogaya,arm	3.13	1.76	155.17	32.10	5.80	7.34	1.85	225.63	0.03	0.00	0.00	27.91	23.50	51.74	0.03	1.87	0.00	30.22	6.18	0.03	0.04	2.78	0.00	1.46	0.12	0.68	0.78
30	Babogaya,middle	3.51	2.62	186.48	36.39	4.32	8.49	1.67	301.50	0.06	0.00	0.00	29.36	24.69	66.70	0.01	1.29	0.00	32.94	10.77	0.00	0.20	2.03	0.00	1.17	0.16	0.02	0.37
31	Babogaya,bottom	3.63	3.35	219.11	38.53	3.58	9.17	4.41	439.97	0.17	0.00	0.00	27.64	26.66	95.22	0.01	0.57	0.00	86.94	13.59	0.50	23.73	2.71	0.00	0.88	0.14	0.02	
32	Kuriftu, shore	0.15	0.25	15.91	7.51	0.00	2.45	34.10	861.49	0.20	0.00	0.00	12.34	2.06	111.69	0.39	1.16	0.00	255.35	43.58	0.57	5.55	2.23	0.00	0.18	0.39	0.10	1.44
33	Hora,int	398.77	19.56	4472.7	47.82	8.10	15.03	1.07	207.20	0.11	0.00	0.00	63.36	74.42	65.14	0.03	3.24	0.00	10.13	11.41	0.02	0.48	20.69	0.00	0.87	0.18	0.05	0.87
34	Arengude,shore, surface	11.74	27.42	4049.7	20.88	21.64	24.24	2.41	174.94	0.47	0.00	0.00	286.54	91.45	81.40	2.61	136.76	0.00	926.83	15.70	0.40	9.41	######	0.00	7.26	0.19	0.04	0.15
35	West/north Cheleleka,north,	0.73	0.46	78.67	15.61	0.00	3.30	121.56	1936.5	0.22	0.00	0.71	5.38	3.79	75.66	1.31	1.51	0.06	50.83	33.19	1.71	2.23	6.41	0.23	0.08	0.44	0.77	1.31
36	East Cheleka,shore	0.78	0.33	18.04	15.91	0.00	3.21	122.83	2074.7	0.26	0.00	1.56	3.71	3.20	106.53	1.31	0.31	0.17	153.84	52.01	1.77	2.15	9.57	0.18	0.15	0.49	0.82	1.36
37	Hora Tannary,BW	19.83	1.58	82.09	36.90	29.03	8.24	3.11	1249.8	0.17	0.00	1.99	54.19	29.74	290.68	0.03	5.52	0.00	23.73	19.69	0.02	0.03	14.78	0.00	3.40	0.07	0.83	0.79
38	Kalehiwot BW, east	13.03	2.05	127.49	33.67	3.06	8.43	176.39	991.95	0.17	0.00	0.00	39.97	20.72	305.63	0.03	2.59	0.00	59.36	26.51	0.02	0.00	21.85	0.00	0.07	0.09		0.65
39	Almaz Doro BW	2.58	1.31	64.38	35.39	2.20	6.20	3.00	671.11	0.05	0.00	15.77	71.73	11.04	267.75	0.00	2.32	0.00	102.80	10.87	0.02	0.01	49.77	0.17	0.05	0.04	1.81	
40	Babogaya, Arm	4.32	2.93	214.88	37.12	5.87	7.93	1.96	316.25	0.13	0.00	0.00	31.69	24.30	59.71	0.05	1.83	0.00	66.74	8.61	0.03	0.02	4.98	0.00	1.39	0.14	1.63	0.69
41	Babogaya, middle	4.13	3.01	222.42	40.65	4.53	9.35	2.47	340.89	0.05	0.00	0.00	28.59	26.48	76.30	0.04	1.86	0.01	175.45	14.61	0.02	0.02	2.22	0.00	1.14	0.19	0.97	0.53
42	Babogaya, bottom	1.38	0.90	74.98	16.97	2.59	4.45	4.57	120.25	0.00	0.00	0.00	13.95	12.24	45.89	0.00	0.35	0.00	61.73	8.58	0.00	0.00	2.21	0.00	0.42	0.19		
43	Kuriftu,SW shore	0.08	0.34	16.92	6.36	0.00	2.29	13.49	728.71	0.18	0.00	0.00	14.65	1.74	120.16	0.18	2.30	0.00	498.19	41.44	0.23	0.17	10.73	0.00	0.23	0.34	1.31	1.28
44	Kalehiwot, southBW	125.12	94.57	531.03	191.13	80.61	137.99	215.44	8199.5	28.79	634.55	738.68	796.55	269.30	66.74	68.90	374.35	106.62	1659.6	44.36	20.58	13.25	1156.5	27.53	4.30	0.66	1.55	0.30
45	Almaz Doro,BW	4.00	1.45	76.95	37.35	8.77	6.05	2.81	821.83	0.07	0.00	6.71	22.55	11.64	272.41	0.02	2.23	0.00	58.89	10.73	0.12	6.55	39.86	0.00	0.55	0.04	0.02	
46	East Cheleleka	1.06	0.87	16.20	20.84	0.00	6.09	217.47	3834.0	1.34	2.71	11.63	4.30	5.52	173.08	6.21	0.49	0.07	108.69	103.51	8.13	24.87	4.29	1.07	0.77	0.60	0.33	1.31
47	Hora Tannary BW	21.27	1.27	64.57	39.06	30.75	7.15	2.78	1375.8	0.19	0.00	1.19	76.74	31.06	278.53	0.00	3.63	0.00	20.77	15.53	0.01	0.07	21.02	0.01	3.52	0.06	0.11	
48	Babaogaya,arm	3.36	1.90	147.76	34.22	5.67	8.41	2.60	255.90	0.00	0.00	0.00	29.86	24.72	60.67	0.07	1.84	0.00	41.13	8.77	0.00	0.64	3.20	0.34	1.41	0.14		
49	Babagaya, middle	2.36	0.93	84.45	29.95	2.83	6.68	5.87	253.16	0.00	0.00	0.00	28.70	21.61	55.48	0.12	1.97	0.00	28.17	9.07	0.01	0.08	4.90	0.00	1.45	0.16	0.15	0.10
50	Babaogaya,bottom	3.12	2.64	184.24	38.76	4.62	10.21	27.31	364.91	0.18	0.00	0.00	25.69	26.02	93.76	0.02	0.91	0.00	200.55	17.73	0.01	0.01	3.13	0.00	0.89	0.19	2.39	0.76
51	Hora, arm	379.76	15.87	3927.8	43.85	8.79	17.72	1.81	194.51	0.04	0.00	0.00	66.58	69.86	68.67	0.03	1.34	0.00	29.32	13.67	0.01	0.03	26.45	0.00	0.96	0.20	0.40	0.36
52	Hora,25m	428.44	13.68	4261.5	49.04	8.88	18.44	3.12	244.15	0.00	0.00	0.00	70.82	75.06	71.74	0.03	1.84	0.17	18.70	13.50	0.03	0.05	32.88	0.36	1.06	0.19	0.46	0.85
53	Hora,10	383.51	12.81	3972.6	46.40	7.90	17.09	3.14	223.61	0.00	0.00	0.00	73.11	74.47	71.31	0.03	1.87	0.17	19.37	13.47	0.02	0.05	33.50	0.36	1.02	0.19	0.46	0.85
54	Kilole,intig.	1.21	0.96	106.01	14.67	3.77	2.46	4.25	803.29	0.34	0.00	0.00	12.61	1.86	141.39	0.00	2.50	0.02	367.56	35.45	0.02	0.01	3.24	0.00	0.26	0.25	1.26	
55	Kurift,SW shore	0.11	0.35	36.28	6.51	1.01	2.35	8.08	695.73	0.13	0.00	0.00	11.91	1.71	122.75	0.14	1.47	0.00	1194.6	40.33	0.08	0.09	3.82	0.00	0.27	0.33	0.87	0.56

No.	Location	Li	Be	B	Sc	V	Cr	Mn	Fe	Co	Cu	Zn	Br	Rb	Sr	Y	Mo	Sn	I	Ba	La	Ce	W	Pb	U	Ba/Sr	La/Ce	La/Y
56	East Cheleleka	0.26	0.60	35.49	6.84	0.00	3.36	6.72	985.50	0.27	0.00	0.00	3.98	1.63	190.82	0.11	1.49	0.20	342.16	66.33	0.09	0.09	4.05	0.05	0.81	0.35	1.02	0.89
57	Elfora BW	5.05	1.11	49.12	46.40	21.69	6.84	3.15	1244.6	0.20	3.44	265.88	27.78	9.14	265.26	0.01	1.22	0.00	16.82	10.57	0.07	2.57	2.73	0.36	0.98	0.04	0.03	
58	Hora TanneryBW	24.61	1.68	88.91	43.25	34.24	8.06	5.31	1549.6	0.32	0.00	3.66	140.01	31.12	302.14	0.00	4.65	0.00	22.92	18.62	0.00	0.04	16.25	0.05	3.40	0.06	0.08	
59	AdaPasta&mac.BW	3.95	1.66	73.45	35.32	41.13	7.57	2.91	1404.9	0.25	0.00	138.88	70.52	11.49	258.38	0.00	2.82	0.00	44.48	10.80	0.00	0.02	4.77	0.29	1.98	0.04		0.00
60	Agri Res.CenterEastBW	11.27	1.44	84.94	43.75	45.14	5.32	21.82	1086.2	0.13	0.00	6.48	125.46	12.59	227.45	0.04	4.43	0.00	38.82	7.26	0.00	0.02	11.34	0.08	1.79	0.03	0.22	0.12
61	N.FrancoBW	72.69	37.37	317.63	103.51	30.41	106.99	140.28	4537.1	14.98	379.79	351.55	711.39	202.21	14.28	23.36	199.51	47.26	700.85	19.17	7.89	7.96	569.45	2.96	1.32	1.34	0.99	0.34
62	Agri Res Inst.BW	13.41	2.46	119.32	45.57	29.46	10.99	29.09	1170.3	0.20	0.00	0.00	122.09	18.97	274.75	0.02	6.22	0.03	579.49	32.17	0.01	0.02	90.12	0.00	14.19	0.12	0.60	0.55
63	Managment Inst BW	9.10	1.69	87.13	39.76	60.77	7.40	3.77	1061.1	0.17	0.00	0.00	130.98	14.98	289.93	0.02	5.41	0.00	27.32	38.80	0.02	0.04	10.50	0.00	4.53	0.13	0.62	
64	Defence Eng.BW2	7.88	1.75	76.19	32.31	15.71	7.30	3.59	962.5	0.14	6.46	586.38	38.32	10.84	230.71	0.00	1.43	0.00	45.50	10.95	0.00	0.32	1.31	0.15	1.13	0.05		
65	Defence Eng BW	133.67	79.18	447.03	181.26	0.00	171.30	203.48	7678.4	17.93	594.58	651.85	548.41	325.65	23.90	43.39	369.93	81.08	1232.9	37.02	20.78	11.69	1894.2	15.51	3.33	1.55	1.78	0.48
66	DragadosBW	6.88	1.24	47.31	52.00	22.77	5.81	4.02	1454.1	0.31	50.78	2928.8	34.87	8.74	242.21	0.00	0.34	0.00	5.95	17.76	0.21	10.27	2.13	22.91	0.84	0.07	0.02	
67	BlueNilePF BW	11.12	2.52	118.56	41.37	39.94	10.94	2.55	1177.4	0.17	3.77	122.39	55.41	13.13	295.69	0.02	1.18	0.00	27.38	11.26	0.00	0.14	4.25	1.66	1.84	0.04	0.02	0.13
68	HoraAgroInd.BW	5.80	2.34	124.50	34.92	3.54	10.10	7.28	1123.4	0.17	0.00	0.00	74.89	12.67	286.09	0.00	3.96	0.00	143.93	22.00	0.00	0.05	64.52	0.22	0.74	0.08		
69	AlmazDoro BW	4.00	1.23	69.50	37.68	9.73	6.24	2.89	823.4	0.05	0.00	32.64	88.63	11.38	268.81	0.00	1.74	0.00	30.68	14.96	0.00	0.03	38.99	0.03	0.54	0.06		
70	Slaught House BW	9.22	1.15	70.46	35.15	47.30	9.75	3.08	910.0	0.02	0.35	107.54	324.35	13.40	274.38	0.00	3.33	0.05	28.74	15.84	0.00	0.01	7.45	0.34	2.02	0.08	0.04	
71	Kalehiwot WestBW/tap	3.47	1.19	55.03	48.47	28.53	8.37	5.52	1558.2	0.18	0.00	4.03	146.80	9.77	319.51	0.00	1.77	0.00	12.73	30.39	0.00	0.00	2.21	0.00	1.94	0.10		
72	Kalehiwot EastBW	6.72	1.24	48.24	28.73	130.62	6.02	3.02	1082.1	0.09	0.36	253.97	114.43	11.08	194.10	0.00	2.82	0.00	139.97	14.95	0.00	0.00	12.98	2.19	6.69	0.08		
73	Ato Gizaw HDW	207.22	159.41	1025.5	293.53	0.00	260.15	371.93	14968	71.14	711.29	1208.5	1626.8	481.31	72.11	78.46	663.38	206.78	1271.9	29.61	28.48	15.13	3382.3	31.07	5.07	0.41	1.88	0.36
																										0.34	0.60	0.92

Table1 : Modern water data for the Debra Zeit lakes and catchment

Sample no.	Site	Site type	Conductivity (gl^{-1})	$\delta^{18}O$	δD	$\delta^{13}C$ (TDIC)
January 1998 collections						
Lake waters						
CH98-1	Lake Cheleleka	south shore	2.4	7.0	40.6	-2.7
CH98-2	"	east shore	0.2	5.8	33.4	0.7
BAB98-1	Lake Babogoya	margin	na	6.5	38.9	0.7
BAB98-2	"	60m depth	na	6.7	42.5	1.4
BAB98-4A	"	surface - lake centre	0.3	6.7	38.9	0.8
BAB98-3	"	10m depth	na	6.5	39.6	na
B98-1	Lake Bishoftu	margin	0.8	6.9	42.9	2.8
HBM98-1	Lake Hora	marginal (weeds)	2.2	7.2	37.6	7.1
HBM98-2	"	marginal (open water)	2.3	7.1	37.0	6.6
HBM98-3	"	lake bottom (30m)	2.3	7.2	37.6	6.4
HBM98-4	"	20m depth	2.3	7.1	38.4	6.4
HBM98-5	"	10m depth	2.3	7.2	37.4	6.5
HBM98-6	"	suface - lake centre	2.2	7.1	37.8	7.0
HBM98-7	"	margin close to gas bubbles	2.3	6.9	36.6	5.5
KU98-1	Lake Koriftu	margin	0.1	5.4	29.5	-4.4
KU98-2	"	centre	na	5.3	31.4	-4.3
K98-1	Lake Kilotes	margin	0.8	0.2	4.9	na
Groundwaters						
DZ98-1	Kebele well	domestic well	0.60	-0.1	3.9	-6.9
DZ98-2	Management Institue	surface spring	0.6	-2.9	-11.6	-8.9
DZ98-3	Shimbra Meda	ground water pumping station	0.3	-2.8	-13.5	-8.9
DZ98-tap	Royal Hotel	tap water	0.5	-2.9	-13.4	-9.5
CHW98-1	"	ground water	4.5	5.4	30.7	na
CHW98-2	"	ground water (pumped)	4.2	-1.3	-5.0	-6.5
River waters						
MOJO98-1	River Mojo		0.2	-0.3	0.1	-4.7
WR98-2	Wadecha River		0.1	4.2	28.4	-10.6
WT98-1	Wadecha Tributary		0.1	4.1	27.5	-10.8

na = not available

X