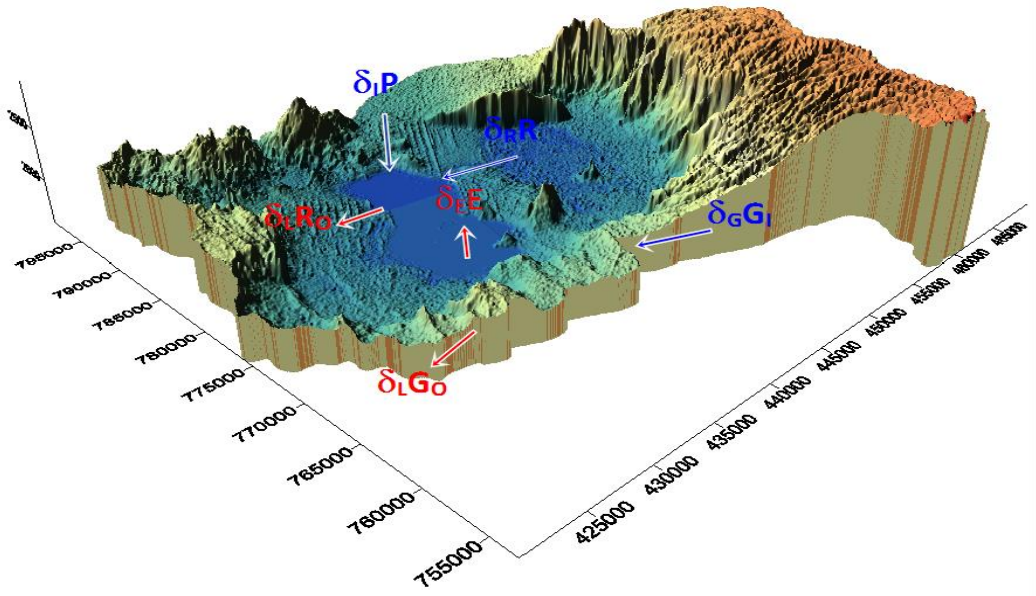
Surface Water-Groundwater Interaction in Hawassa Lake Catchment Using Geochemical and Isotopic Techniques



A THESIS SUBMITTED TO THE SCHOOL OF EARTH SCIENCES IN PARTIAL FULFILLMENTS OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN HYDROGEOLOGY

BY

YEHUALAESHET TADESSE

February 2015

Addis Ababa

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Abstract

Hawassa lake catchment, which is located in the Main Ethiopian Rift, has different ideas about the direction in which the lake and the groundwater interact. Oxygen ($\delta^{18}O$), Hydrogen ($\delta^{2}H$) isotopes and hydrochemical method used to reveal Lake water-groundwater interaction and for determination of a lake water budget. Tritium also revealed the residence time of groundwater in the study area.

Stable isotope study result illustrates that, there is interaction between lake water and groundwater in the Northern and southwestern direction. To support the stable isotope result and to show the general groundwater flow water level measurements used and it show groundwater flow from all around the caldera rim to Lake Hawassa except from the northern side where the ground water flows away from the catchment to Lake Shalla and there is local groundwater flow away from the lake. Along the groundwater flow direction ionic concentration and isotopic enrichment ($\delta^{2}H$and$\delta^{18}O$) increases.

Hydrochemical study result reveals that the area is characterized by three major water types in the area. Main water types in the study area are Na-HCO_3 which is the characteristics of the flow of the caldera followed by Na-Ca-HCO_3 which is the characteristics of the highlands and Ca-Na-HCO_3 which is rare.

Stable isotopes (oxygen-18 and deuterium) exist in water naturally used to quantify the groundwater inflow into the lake and the outflow from the lake. It was found that the average groundwater inflow to Hawassa Lake is 24% out of total inflow to the lake while the average groundwater outflow is 3% out of total outflow from the lake using oxygen-18 and deuterium.

Acronyms

AAU	Addis Ababa University
Cl	chloride
DEM	Digital Elevation Mode
EC	Electrical Conductivity
GSE	Geological Sur vey of Ethiopian
Gnet	net ground-water flow
LMWL	Local Meteoric Water line
m.a.s.l	meter above sea level
MCM	Million cubic meter
MER:	Main Ethiopian Rift
mg/L	milligrams per liter
mL	milliliter
N	nitrogen
Na	sodium
SWL	Static Water Level
TU	Tritium Unit
WFB	Wonji Fault Belt
δ	delta
$\delta^{18}O$	delta oxygen-18
δa	isotopic composition of atmospheric moisture
δD	delta deuterium
δE	isotopic composition of evaporating water
µS/cm	micro Siemens per centimeter
α	water-vapor fractionation factor
ε	Total enrichment factor
Δε	kinetic enrichment factor

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1. Introduction

1.2 Background

In the water cycle, knowing about groundwater-surface water interaction is crucial for the sustainable water resource use. As the effective tracers in water cycle research, environmental isotope and hydrochemistry can reveal the interrelationships between surface water and groundwater effectively.

Lake Hawassa catchment is located in Main Ethiopian Rift Valley of central part of Ethiopia. The region is rich in its natural resources, where water resource is the significant. Beside their use for irrigation, the Lake in this region is habitat for a great variety of fishes, birds, and wild animals, which direct tourist traffic to this area. Natural processes and artificial activities by humans knowingly or unknowingly have created a major problem on the natural resources as well as the ecosystem among which Climatic change, Lake level fluctuation/change, Land degradation, Deforestation and Pollution are some of them. The effects might not be seen at present but manifested on a long run which affects the future condition of the area.

In this research Surface water ground water interaction of the Study area has been studied using hydrochemistry and Isotopes hydrology method. This method is used to understand the mechanism of recharge, interconnections between underground and surface water, the residence time of the groundwater, estimating water balance of Lake and to know the history of water.

The field surveying and sampling for, Lake, spring, river and well water were conducted for Isotopes such as ^{2}H (deuterium),^{18}O (oxygen 18), ^{3}H (tritium)and water quality were measured at the laboratory of Institute of Environmental Assessment and Water Research (IDAEA) of the Spanish Council of Scientific Research (CSIC) at Barcelona, Spain Laboratory.

1.3 Statement of the Problem

Lake Hawassa has important roles for irrigation, habitat for a great variety of fishes, birds, and wild animals .Also the population of Hawassa town put pressure on the safe exploitation of groundwater. In the past, many lands which were covered with forests have been cleared and put under new settlement due to urbanization process. There is intensified surface cover degradation and changes of ecosystem.

Previous works conducted in this area try to reveal the lake water interaction with the groundwater. Some of those studs tell that the lake water interaction is only in north direction while the others tell the interaction is in the southwest direction.

This study will help to understand the clear direction in which the lake water interact with the groundwater and calculate the amount of water that goes out from the lake and inflow to the lake from the groundwater.

1.4 Objective of the study

1.4.1 General objective

The main objective of this research work is to study ground water- Surface water interaction in Lake Hawassa catchment. This will provide a clear idea about how much water goes out from the lake in to the groundwater and the amount of water that flow into the lake. The study also determines the major direction where the lake water interacts with the groundwater.

1.4.2 Specific objective

In addition to the main objective the research work is expected to address the following specific objectives.

- To evaluate the source and mechanism of ground water recharge and flow direction.
- To investigate groundwater connection to modern day infiltration from rainfall.
- To determine the residence time of the groundwater.
- To Estimate the water balance of the Lake (groundwater inflow into the lake and outflow out from the lake).
- To provide conceptual hydrogeochemical model of the area.

1.5 Previous Works and Related Literatures

I. Isotope Enabled Lake Water Balance in Rift Valley Lakes

Hydrochemical and environmental isotope methods together with field hydrologic investigation provide a reasonable result in calculating of water balance of groundwater (Winter, 1978; Dincer 1968; Kebede et.al, 2002). Such few works have been conducted in the rift valley lakes.

(Kebede et.al, 2002) have conducted a lake-groundwater relationship in Bishoftu crater lakes using oxygen isotope balance method. Accordingly, the mean oxygen isotopic composition of Lake Hora, Babigaya and Bishoftu were +7.2‰, +6.5‰ and +6.9‰, respectively. The groundwater samples were isotopically enriched showing that they are mixed with surface water sources (lakes, swamps and reservoirs). The lakes were found to be well mixed and less affected by seasonal variations except slight stratifications in the wet season. The isotopic enrichment of most wells were associated with evaporation from longer residence time (6-10 years). Two of lakes (Kilole and Kuriftu) were with comparatively depleted isotope value and this was suggested to be resulted from fleshing from depleted river water and less residence time. The water budget of the three lakes studied in this work shows evaporation is major outflow (100%, 83% and 92% for Hora, Babigaya and Bishoftu, respectively) whereas direct precipitation and groundwater inflow was the most important sources of groundwater inflow sources. Generally, it has been concluded that the bishoftu crater lakes aquifer are recharged by rainfall immediately in the wet season which is considered to be the source of depleted water. On the other hand, the seepage from surface water bodies was the main sources of enriched water. Additionally, the test on the sensitivity of the parameters shows that the lakes oxygen isotope composition is more sensitive to humidity and isotopic composition of ambient vapor than isotopic composition of inflow.

More importantly, (Ayenew & Gebreegziabher 2006) has modeled the water balance of Hawassa using spreadsheet model simulation. The result of this model shows that the most important water balance components that govern the lake level fluctuations are evaporation, rainfall, and runoff which calculated to be 131, 106, and 83 million cubic meter annual fluxes respectively. This model also agrees with the presence of underground outflow in the subsurface system and it has been found to be 43 million cubic meter. It has justified this idea by presenting the result of

the model by running with only surface water balance components (in the absence of groundwater) there is a progressive separation between observed and calculated lake levels. The calculated levels implying that the lake should accumulate more storage than is actually observed. This separation could not be pinned down to systematic errors in surface runoff, precipitation and evaporation measurements. Therefore, this excess water (43 million cubic meters) is an indication of subterranean outlet of water. In exception to all other rift valley lakes, the fresh nature of the closed lake Hawassa is explained in terms of groundwater outflow (Lamb et al. 2002).

Looking for the time series records of the water balance components the discharge record shows an increasing trend indicating increase in the runoff. This is due to the extensive deforestation of vegetation in the catchment (transformed in to cultivated land) and siltation of swamps during the past three decades. This has been also confirmed by the transformation of Lake Shalo to a grass covered swamp by siltation from the sediment coming from bear upland.

Another, a steady state water balance for Lake Hawassa has been developed by (Telford, 1998). In this work, as in other works, it has been noted that evaporation is the main loss for the lake which accounts for 93% of the outgoing water while precipitation most important source of incoming water, accounting for nearly 56%.

II. Regional groundwater flow and Rift valley aquifers

The groundwater system of the rift valley aquifers is affected by extremely complex interrelated factors. Intensity and attitude of the rift faults and the volcanic stratigraphy and its relation with the various water bodies are believed to be the major governing factors as been explained in Ayenew.et.al (2008). Characteristically, the rift aquifers are often laterally discontinuous due to the disruption in the continuity in lithology caused by faults forming the rift, these large deeper regional faults cause to the presence of large preferential groundwater movement from the highland to the intermountain valley large aquifers; that makes the adjacent highlands of valleys to be the dominant source of recharge to the rift mostly in shallow groundwater inflow Ayenew.et.al (2008). Generally, the dominant source of recharge to the rift valley aquifers comes from groundwater inflow from the mountains bounding the rift and the regional groundwater flow direction is from the plateau to the rift valley aquifers substantiation by the increase in groundwater total salt content and change in groundwater chemistry from Ca–Mg HCO3 type in

the plateau to Na–HCO3–SO4–Cl type in the rift centre (Darling et al. 1996; Gizaw 1996; Ayenew 2005; Kebede et.al, (2007)).

A hydrogeological survey carried out in the basin by (Alemayehu, 2007) shows that fractured ignimbrites and the overlying loose volcano-lacustrine sediments are the two major water-bearing units and generally the work revealed two aquifer groups. The first group is Shallow aquifers which are composed of volcano lacustrine sediments, pumice flows and basaltic lava flows that cover the eastern and western sides of the basin with an average depth ranging from 30 to 50m. Generally, these aquifers are under confined and semi-confined conditions and the sediments have medium to high transmissivity values (WWDSE, 2001). Deep aquifers were in the second group. These aquifers are composed of acidic lava flows and ignimbrites. These show moderate low to high degree of jointing that induces secondary porosity and low to high (0.1 to 80 m/day) permeability ranges (Geremew, 2000; Chernet, 1982) reported to high. Mostly these aquifers are semi-confined because these are intercalated with clays (Tessema, 2003).

III. Tectonic Evolution of East African Rift System

The east African rift system is a part of major tectonic structure resulting from diverging lithosphere movement began about 25-30 million years ago (tertiary time), (Elias, 1984). During the uplifting of the Ethiopian Plateau a long sequence of rigid tectonic movements took place. These movements produced, in a recent but unknown age, a great number of step faults which originated the present Ethiopian Rift Valley. These faults usually stretch parallel to each other with NNE-SSW or NE-SW direction. Only few and short secondary NW-SE faults occur.

All these faults seem to be normal faults with only a few localized examples of horizontal displacement of few tens of meters. This tectonics is still active as it is indicated by the faults affecting even the most recent volcanic products. Another tectonic feature of the Rift Valley is the presence of some depressions that occupied by lakes (G.M. Dia Pola, 1972). East African rift system is known by continental extension. It is believed that there will be new oceanic crust on the breakage of Nubian plate and Somalian plate. An interesting feature marking the evolution of continental rift is that, at a general scale, the type of volcanism changes accordingly with the amount of extension, reflecting the involvement and differentiation of various volumes of magma (latin and Waters, 1991; Metcalf and Smith, 1995). The age of rift can be calculated from

the investigation of magma composition of EARS (East African Rift System) with the amount of extension (B. Abebe et al 2007).

IV. Groundwater and Surface Water Interaction of Lake Hawassa

Many different works (for example, Telford, 1998; Ayenew, 1998; Tessema, 2003) have shown that the groundwater in the aquifers of lake Hawassa interacts with all surface water features streams, lakes, wetlands found within the caldera. Lake Hawassa, being the lowest elevation point, every droplet of water showered to the caldera will flow down to the lake in one or another way unless otherwise evaporated (W.W.D.S.E 2001). The streams that emanate from the caldera rim ends up either directly into Lake Hawassa or Shalo swamp which feeds Tikurwuha River that in turn recharges Lake Hawassa. On the other way, groundwater flow feed the TikurWuha River that in the same fashion feeds Lake Hawassa. As per (Alemayehu, 2007) and many others previously listed works, major groundwater inflow to the Lake is from southern, eastern and western sides of the basin. The groundwater flow coming from different direction emerges as spring at the shore of the Lake. At the same time, the lake discharges water into the groundwater in the northern side. Moreover, Lake Hawassa catchment also feeds the nearby aquifers mainly to the south and southwestern sides of the Lake. This has been indicated by the increasing depth of groundwater as one move away from the lake; 90 meters difference in groundwater head between lake and caldera rims.

V. Water Resources Characteristics Rift Valley Lakes (MER)

a. Surface water

Unlike the groundwater sources, surface water bodies of the MER are less polluted. They are of low salinity and low F concentration which is a main problem associated with MER groundwater due to the fact that they receive a discharge of thermal springs (Gizaw, 1996). Specific to the lakes, their turbidity is dependent of the amount of runoff entering them.

In general, according to (Chernet,1982), Ziway>Langano>Abayata>Awasa>Shalla is the right increasing order of value of turbidity for the major rift valley lakes. This order is believed to be mainly determined by the amount of runoff drained to the lakes. As per this order Shalla is the highest volume and most saline but less disturbed lake in the region. This lake appears to be sky-blue colored visually probably due to the reflection of precipitated amorphous silica.

The chemistry of the lake waters is very variable. A bit higher concentration values have been observed for the non-fresh lakes namely Abaya, Chamo and Langano. The TDS values of the fresh lakes (Ziway, Awasa and Shallo) are ≤l000 mg/l while those of Abaya, Chamo and Langano fall between 1000 and 2000 mg/l. Chitu, Shalla and Abayata was found to be the most saline and alkaline lakes in the MER having TDS values in the range of 20,000-40,000 mg/l. Different investigations including isotope enabled studies carried out in the lakes of the MER showed that evaporation is the a major determinant phenomena and it is proved to be the main reason for the isotopic enrichment of all lakes (Gizaw, 1996).

b. Groundwater

The mineral content of the surface and groundwater system of the basin is dominated by sodium and bicarbonate. The dominance of sodium could be attributed to the weathering of acidic rocks (Alemayehu, 2007). In (Alemayehu, 2007), the Electrical Conductivity (EC) of Lake Hawassa was about 830 µS/cm, which is much less than the value in groundwater around the Lake; vary between 871 µS/cm at eastern part of the town and 1170 µS/cm in a borehole at the eastern shore of Lake Hawassa. This was associated with anthropogenic impact on the groundwater because if the Lake is fed predominately by groundwater, its EC should have been greater than that of the groundwater as the Lake is exposed to further evaporative concentration than the groundwater.

Thermal waters in MER are fairly dilute with a TDS generally below 5000 mg /l. However, they are enriched in Na, HCO, and F (Gizaw, 1996). The pH lie generally between 7 and 10, except for the deep geothermal waters which are between 6 and 7 and are near-neutral for their temperature (Marshall and Franck, 1981).

VI. Fluoride (in the groundwater)

Arising from the excessive presence of fluoride the water quality of the MER water bodies are judged to be very poor (Reimannet.al, 2003) and causing disease like florosis (Gizaw, 1996). Concentration of fluoride in cold waters of the area reaches 16 mg/l which is derived from the host rock; the Corbetti obsidians contain as much as 2500 mg/l of fluoride (UN Technical Report (1973).

The excessive presence of fluoride in rift valley is a geogenic anomaly related to the peculiar geological framework of the area. The Fluoride enrichment, as one moves from the highlands to

valley center, arises from weathering processes on the acidic volcanic rocks and water–rock/sediment interactions in the thermal system of the caldera that could probably be triggered by the high activity of CO_2 in the valleys (Rangoet.al, 2008; Alemayehu, 2007). Pumice, rhyolite, and associated obsidian of the Chabi and Urji volcanoes are the major crock formations in the area (Alemayehu, 2007). In this the aquifer matrixes are mainly rhyolites consisting of volcanic glass and only rare F-bearing accessory minerals. This glassy materials are the most important sources fluoride store and their weathering products could play a role in increasing the concentration of fluoride. Further, the waters from this phenomenon can go through the process of Base Exchange softening with the clay minerals. This all is evidenced by a positive correlation between F, pH, and Na, and inverse correlation between F and Ca (Mg). Under these conditions, fluoride cannot precipitate as fluorite (CaF2) (Rangoet.al, 2008).

2. Methodology, Materials and Tools

2.1 Methodology

The method used to attain the objective of the research work are, Isotopes of water ($\delta^{18}O$, δD), tritium (^{3}H), and major ion chemistry. These methods are completed though three approaches.

The approaches used to meet the object of the research work are collection of secondary data, measurement of water level with in-situ measurement of water quality parameters (EC, Temperature and P^{H}) and sampling water points in order to fill the data gap followed by analysis, interpretation and report writing.

I. Pre-Field work (secondary data collection)

- ✓ Collection of Lake Level and stream flow records from Ministry of water, Irrigation and energy (1970-2008).
- ✓ Review of previous works which include geological and hydrogeological reports and maps, well completion reports, researches done in the similar geological settings; collection and organization of secondary water points data like, characteristics, geochemical (major ions) and environmental isotopes (^{2}H, ^{18}O and ^{3}H) data of water points like boreholes, rivers, springs and lake from different sources.
- ✓ Gathering meteorological data (Rainfall humidity, Temperature, Pan Evaporation and Wind Speed) from Meteorological Agency of Ethiopia.

II. Field work (sampling and in-situ measurement)

After review of previous works, field work is conducted to fill data gap by sampling the representative water points along the traverses made.

Field water sample analyses for both physico-chemical and environmental isotope analysis with in-situ measured parameters like electrical conductivity, total dissolved solids and temperature. Additionally, name of the site, the location (UTME and UTMN and Elevation) have been registered for reference.

The sampling kits which are used for water sample collection are 0.5ml PVC bottles for Cation and anion, 0.5ml of polyethylene (PE) bottles for Deuterium ($\delta^{2}H$) and Oxygen 18 ($\delta^{18}O$)

analysis, 0.5 liter PVC bottles for Tritium (δ^3H) analysis. After completing the sampling process the samples were sent to Spain for laboratory work. The deuterium and oxygen 18 samples were analyzed using Liquid water isotope analyzer model DLT-100 whereas the tritium analysis was counted using scintillation counter. Geochemical analyses carried using basic Titration methods.

a) Geochemical methods

Geochemical analysis of water samples is significant to know mixes and interconnections between water from different source (Underground, Surface waters and aquifers) and the geochemical processes takes place in the study area.

Geochemical analysis was at the Analytical Laboratory of the Institute of Environmental Assessment and Water Research (IDAEA) of the Spanish Council of Scientific Research (CSIC) at Barcelona, Spain Laboratory.

In-situ water quality testing was done for Temperature, pH, and Electrical Conductivity. These were carried out using portable digital pH and EC meters.

Relevant common soft wares were used for mapping, analyzing and for interpretation of data. From the results obtained appropriate maps are constructed. After having the laboratory result of cation and anion, graphical and statistical analyses methods were applied to identify different groups of hydrochemical facies in the study area. To know whether there is an error in the laboratory analysis Reaction error analysis, plots of error percentage and laboratory versus field electrical conductivity were used.

b) Isotopic methods

Stable isotopes are used to Estimating water balance of Lakes (groundwater inflow into the lake and outflow from the lake), Detecting and localizing surface water groundwater interactions, Estimating groundwater recharge rates and groundwater flow velocities and Qualifying recharge mechanisms to groundwater aquifers. In this study it is used to compute the objective mentioned.

Oxygen isotope ($\delta^{18}O$), Deuterium (δ^2H), and Tritium were used in the study area. The composition of Oxygen isotope ($\delta^{18}O$) and Deuterium (δ^2H) in the water is expressed in comparison with the isotopic compositions of Ocean water and is expressed in per mil (‰) deviation from the standard mean ocean water (SMOW) (Craig, 1961).

The deviations of deuterium (δ^2H), oxygen (δ^{18}O) is expressed as:

$$\delta^2\text{H }‰ = \frac{(2\text{H/H})\text{ sample} - (2\text{H/H})\text{smow X } 1000}{(2H/H)_{Smow}}$$

Where δ^2H‰=deuterium in per mil, ^{1}H= hydrogen

Similarly, the deviation of δ^{18}O

$$\delta^{18}\text{O }‰ = \frac{(18O/16O)\text{ sample} - (18O/16O)\text{ smow X } 1000}{18O/16O}$$

Where δ^{18}O‰= oxygen 18 in per mil, ^{16}O= oxygen 16,

The stable isotopic method is used assuming that the isotopic signature does not change unless it is affected by fractionation processes. The water that underwent this process shows a change in its isotopic signature.

III. Data analysis

- ✓ Oxygen isotope and hydrogen isotope balance method to compute groundwater inflow into the lake and out flow from the lake.
- ✓ Analysis of the water samples using Aquachem 4.0 software to determine different water type.
- ✓ Interpretation of the above data based on the geochemical principles and isotope hydrology to support the geochemical findings.
- ✓ Report writing by integrating all the gathered information.

2.2 Materials and Tools

The materials used during the research work include:

- Geological and hydrogeological map
- DEM, GARMIN GPS-72, EC meter, pH meter and bottles for collection of representative water samples.
- Computer software's like Global mapper-11, ArcGIS-10.1, Aquachem-4 and surfer-10.

2.3 Structure of the Thesis

The report contains seven parts of which part one and two gives a clear idea about the research work incorporating the objective of the research, methods and materials used to meet the objective of the research work. Part three describes detail view of the study area including location, physiography, climate condition and surface hydrology. Part four contain the explanation of the geology and hydrogeology of the lake catchment area. Part five is about the hydrochemistry while part six describe about the isotope hydrology. Part seven and eight contains conclusion and reference. Finally, Data which were used with this different part of the thesis are included in the appendix.

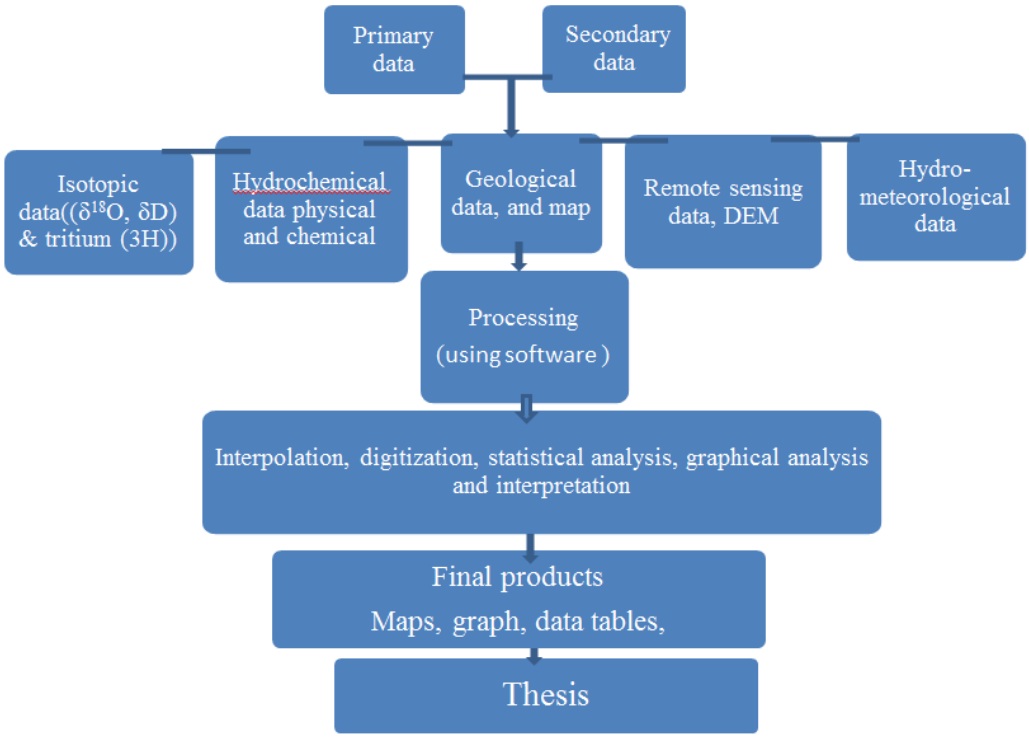

Figure 2-1: Flow chart showing the general structure of the thesis work

3. General overview of the study area

3.1 Location

The Study Area (Figure 3.1) is located in the Main Ethiopian Rift system within the coordinate system of UTM: 416635-472252E and 746325-801643N, Zone 37, Northern Hemisphere. It is about 275 kilometers south of Addis Ababa. The elevation in the study area generally ranges in between 1573 to 2947 meters above sea level (m.a.s.l).

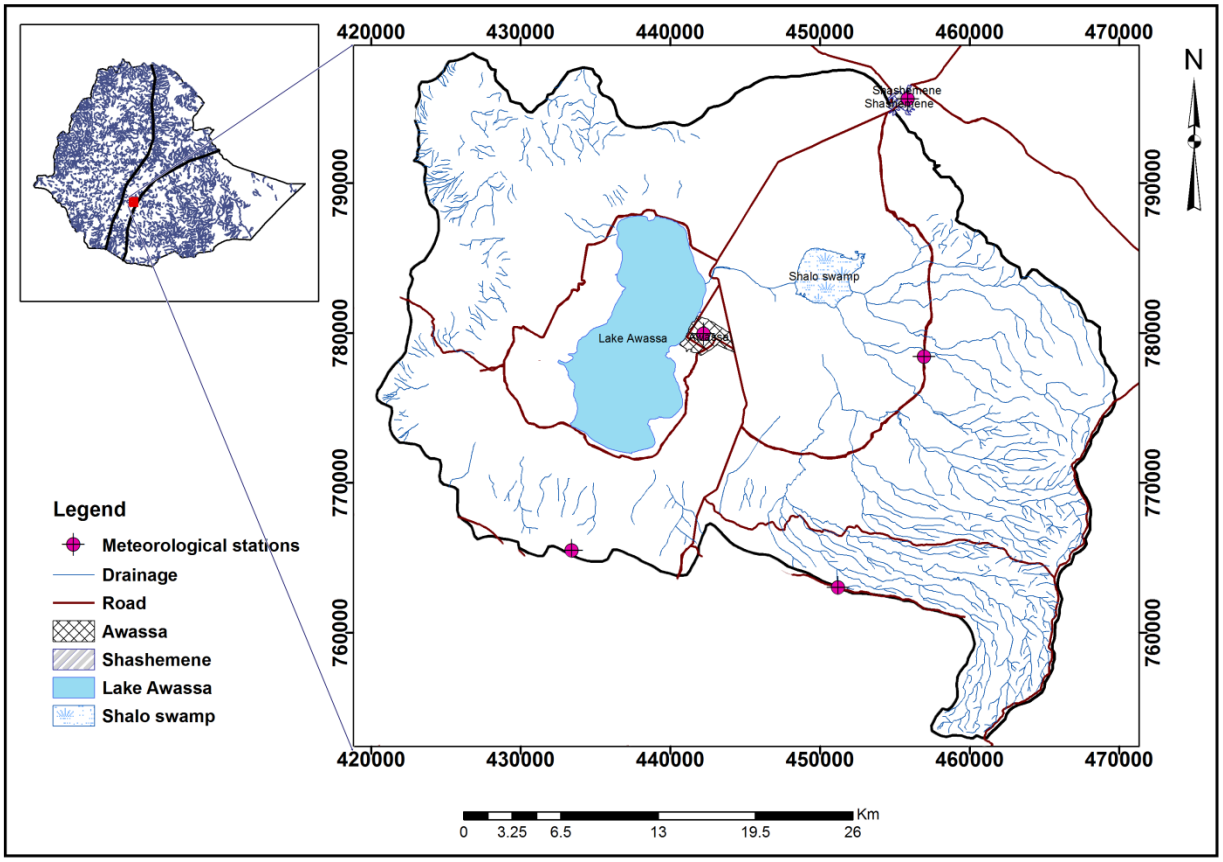

Figure 3-1: Location Map of study area

Lake Hawassa catchment occupies an area 1367.26km^{2}from the total space of the catchment the lake occupies an area of 98 km^2.

The study area can be accessed through an asphalt road connecting Addis Ababa to Moyala, which is a border town on the way to Kenya. The catchment can be accessed in different direction using quite a lot of weathered roads.

3.2 Physiography and Drainage pattern

3.2.1 Topography

The study area is part of the lake regions of the central sector of Main Ethiopian rift, which is occupied by a chain of lakes. It is a caldera lake without surface outlet, which is a closed basin, formed by a volcano-tectonic depression with a 40-50km diameter. The depression is bounded by the remnants of the caldera wall, where steep slopes and faulted blocks characterize them.

The eastern rim of the caldera whose average throw is about 500m and its maximum elevation reaches 2900m which is the maximum in the catchment and it is coincided with the eastern escarpment of the Main Ethiopian rift, (Figure 3.1). The catchment area comprises escarpments, ridges, and plateau, undulating to rolling and dissected plains, depressions swamps, and Lake Hawassa. The floor of the caldera is characterized by flat land containing Lake Hawassa having the lowest elevation in the catchment at 1573m.a.s.l. in the area. The southern and western walls of the caldera form an arc of a circle, which is truncated by several NNE-SSW/N-S trending faults. The northern part is bounded by Corbetti caldera, which is a nested caldera within Hawassa caldera having elevated recent volcanic complexes such as Mt. Chebi and Urji with maximum elevation of 2200m.a.s.l. Water bodies, swampy areas and small volcanic hills characterize the floor of the depression, such as Lake Hawassa and Shallo Swap.

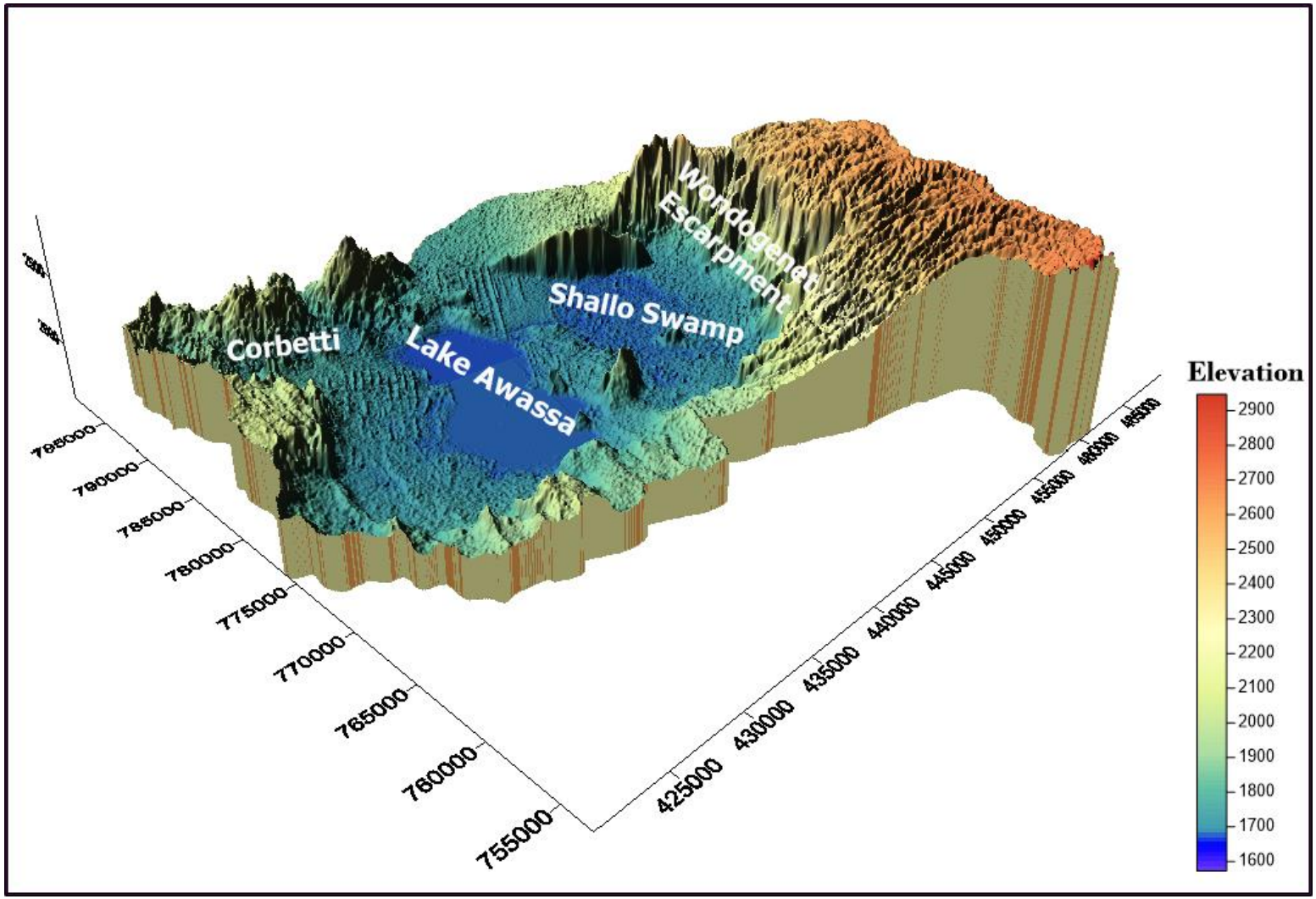

Figure 3-2: Digital Elevation Model showing the topography of the area in m.a.s.l.

3.2.2 Drainage

Factor like topography, land cover, geology including tectonic structures govern the drainage system. In area where the underlying geology is impervious, and topography is steep, dense drainage systems could develop whereas area with porous materials and flat topography produce low drainage density as large volume of water is lost to subsurface through porous materials.

A number of streams are found in the study area (Figure 3.3); they flow toward Lake Hawassa, which is the main water body of the study area. Tikur Woha River is the only perennial stream which flows throughout the year in the basin, and which joins the Hawassa Lake. In addition to Lake Hawassa Shallo swamp is situated in Hawassa caldera.

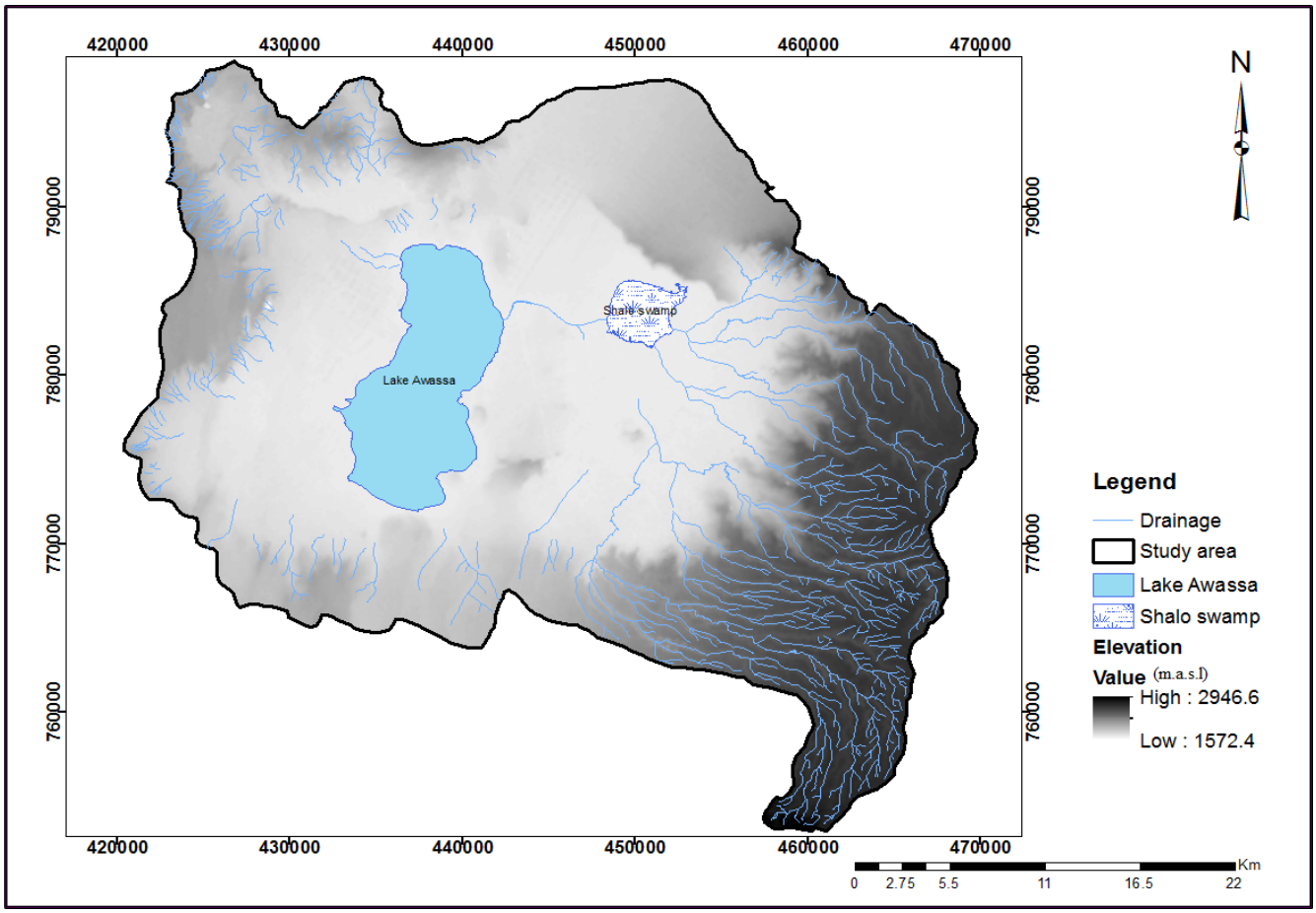

Figure3-3: Surface water body of Lake Hawassa Basin

3.3 Climate and Hydrology

3.3.1 Arial Depth of Precipitation

The climate of the study area is characterized by as sub-humid climate; with extended period of wet season (March-October). Two rainy seasons have been practiced: the main rainy season often extending from July to September and a small extended rainy season from March to May (Figure 3.4). Data from five Stations (Yirba, Hawassa, Hasawia, Wendogenet and Shashemene) are used in order to describe spatial and temporal variations of rainfall in the study area.

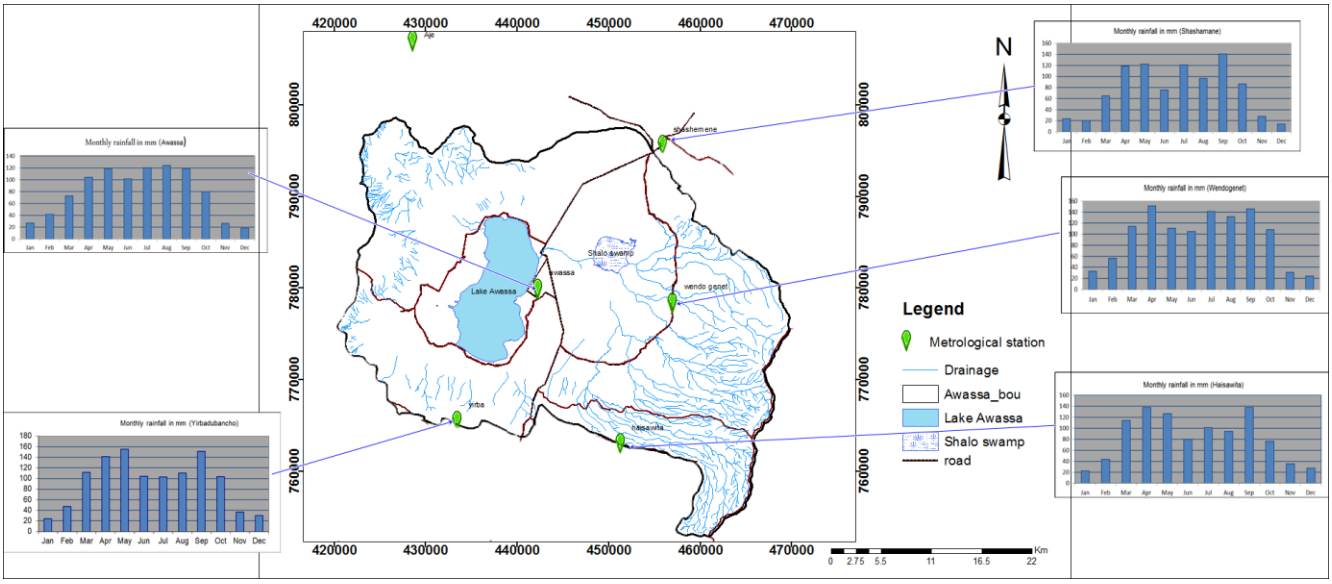

Figure 3-4: Mean monthly rain fall (mm) (1972- 2003).

The moisture for precipitation in the area originates from southwest equatorial air stream, which moves northwards with Inter-Tropical Convergence Zone (ITCZ). Precipitation in the Hawassa station typically ranges between 19 to128 mm per month.

To see spatial variation of precipitation in the study those five metrological stations are used; where two of them (Hawassa and Wendogenet) are located within the study area and three of them (Yirba, Hasawia, and Shashemene) are near the catchment boundary. Hence study area is characterized by flat and elevated topography with sparsely distributed stations, orographic effect can create vastly different microclimates over small distances to measure the rainfall; that can influence the distribution of rainfall by Orographic effect. The average areal depth of precipitation over the catchment has been determined using Isohyetal methods, which can give

good results, because it allows the influence of physiographic parameters like Altitude, slope and exposure to rain bearing winds to be taken into account (Fetter, 1994).

Based on the facts mentioned above, isohytal map (Figure3.5) was created using ArcGIS 10.1 computer code by locating on a base map all rainfall stations, rainfall amount and then draw isohyets(lines of equal rainfall) by proportioning the distances between adjacent gauges according to differences in catchment and then estimate the mean precipitation for the area corresponding to each isohyets and fraction of catchment area under each isohyets, Finally multiply by the mean precipitation for that area and sum to get the catchment average (Table 1). Thus the annual mean rainfall for the area is 1028mm.

Table 3-1: Long-term mean monthly precipitations and altitude in the catchment

Station No.	Name	UTME	UTMN	Elevation, m.a.s.l	Mean Annual Precipitation, mm
1	Yirba	433423	765478	2000	1122
2	Hawassa	442235	779921	1750	953
3	Shashemene	455869	795581	1950	920
4	Haisawita	451228	763012	2240	997
5	Wendo genet	456960	778399	1800	1151

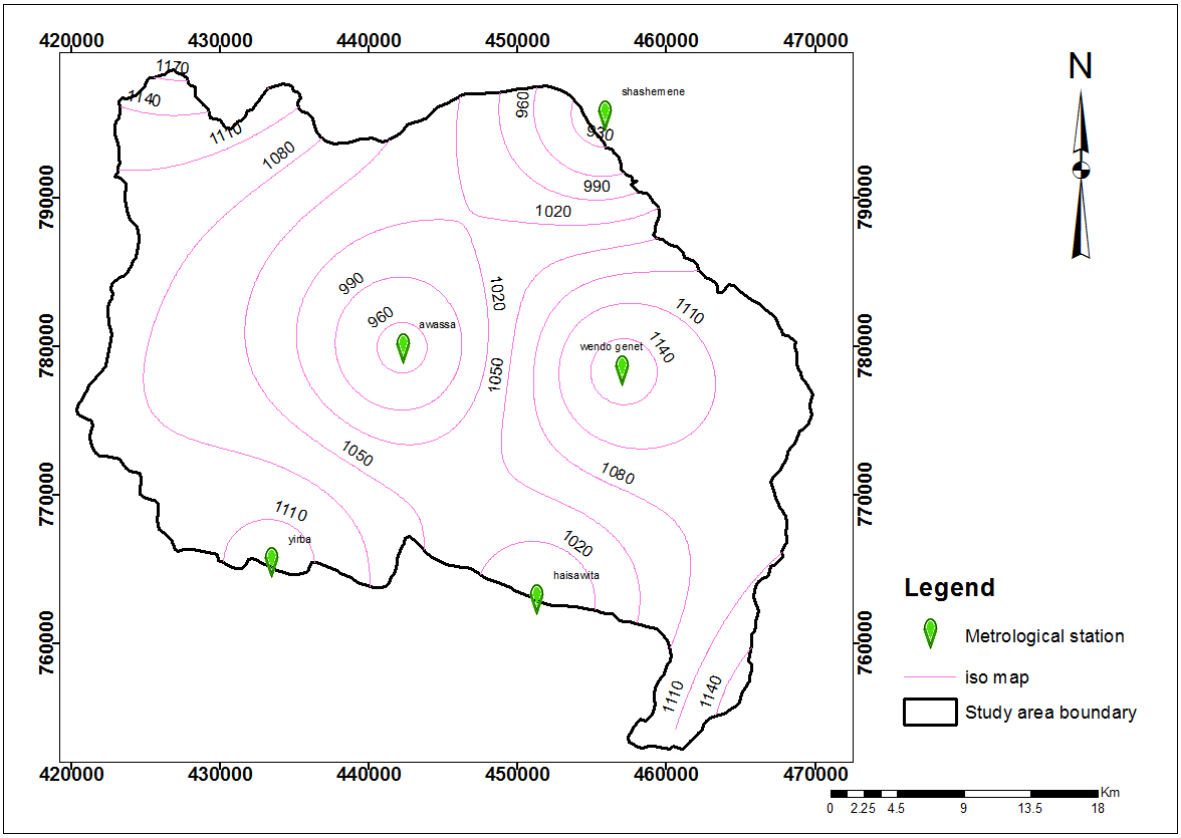

Figure 3-5: Annual isohytal rainfall map of the area

At Hawassa station, Relative Humidity (RH) has been measured, since 1972. The RH records show the mean monthly minimum of 69.8% to be in December, and a maximum of 91.1% in May. From the long-term temperature data of the study area ranges from 10.01^0C observed in November and31.25^0C (max) in March. In the study area, temperature values have been collected since 1972.

Long-term pan evaporation data at Hawassa Station is used and it was recorded using class-A pan. Since evaporation from a natural body of water is usually at a lower rate because the body of water does not have metal sides that get hot with the sun, and while light penetration in a pan is essentially uniform, light penetration in natural bodies of water will decrease as depth increases. There multiplying the pan evaporation by 0.8 (pan coefficient) is used in order to correct the various effects during evaporation from the pan and convert the pan evaporation in to potential evaporation. High evaporation occurs during dry months, reaching about 157mm/month, while during the summer time decreases due to relatively increased humidity (Figure 3.6).

Table 3-2: mean monthly evaporation from pan and from lake

Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann.
Pan evap.	196	181	198	162	164	155	131	137	132	155	183	190	
Lake evap.	157	145	159	130	131	124	105	110	105	124	147	152	1589

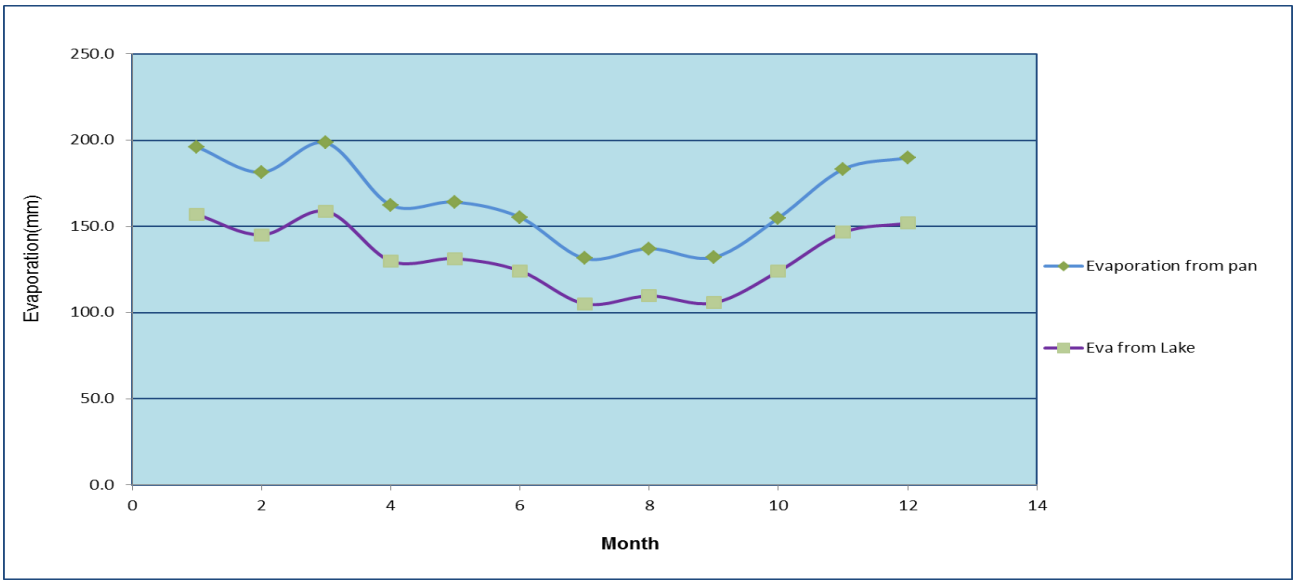

Figure 3-6: Pan and Lake Evaporation value (mm) (1986-2008)

3.3.2 Surface hydrology

In the study area the main water body is Lake Hawassa which lies at an altitude of 1680m.a.s.l in the floor of the caldera. It occupies about 98Km^2 of the total study area (1367.26 km^2).

Water level records at Lake Hawassa have been collected for the period of 1970 to 2008. (Figure 3.7). The lake level is changed starting from 1975 and 1979. However, from 1995 to 1998 it increased enormously. According to (Tessema, 2003), the major causes for the lake level rise are due to is the Surface waters input: since Lake Hawassa is at lower elevation, all surface water enters to the lake without any outlet. Groundwater flow direction is also in the direction of lake except from the north side. The other cause of Lake level change is Siltation from the western part of the catchment.

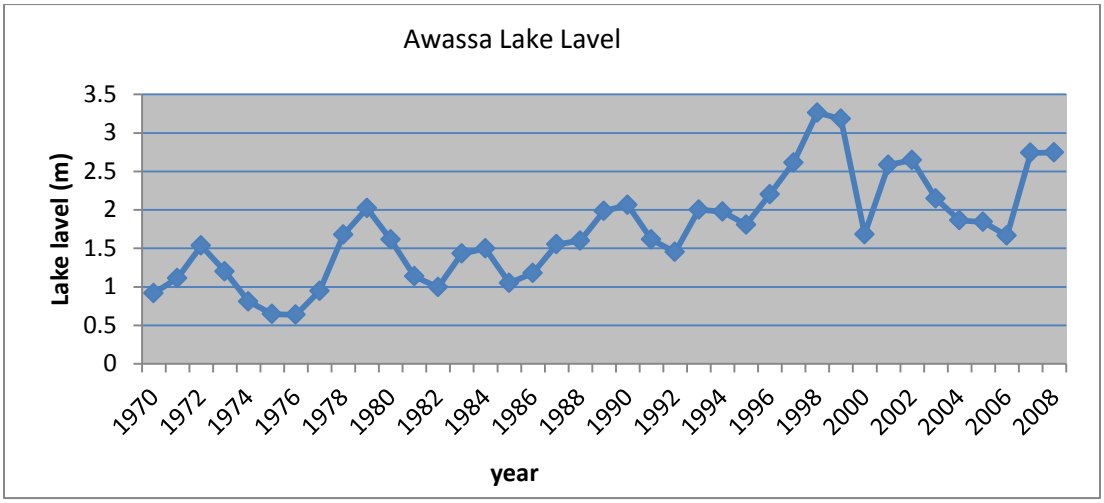

Figure3-7 Lake level records (m) (1970-2008)

Tikurwoha River is the only perennial and gauged stream, which flows into Lake Hawassa. The available monthly flow data starting from 1980 to 2006 at Dato gauging station have been used (Figure 3.8). There is another gauging station downstream of this near lake Hawassa (at the bridge), but this one is affected by backwater flow from the lake during peak flood years. Therefore, only the data from the upstream station, at Dato, can be used for accurate interpretations.

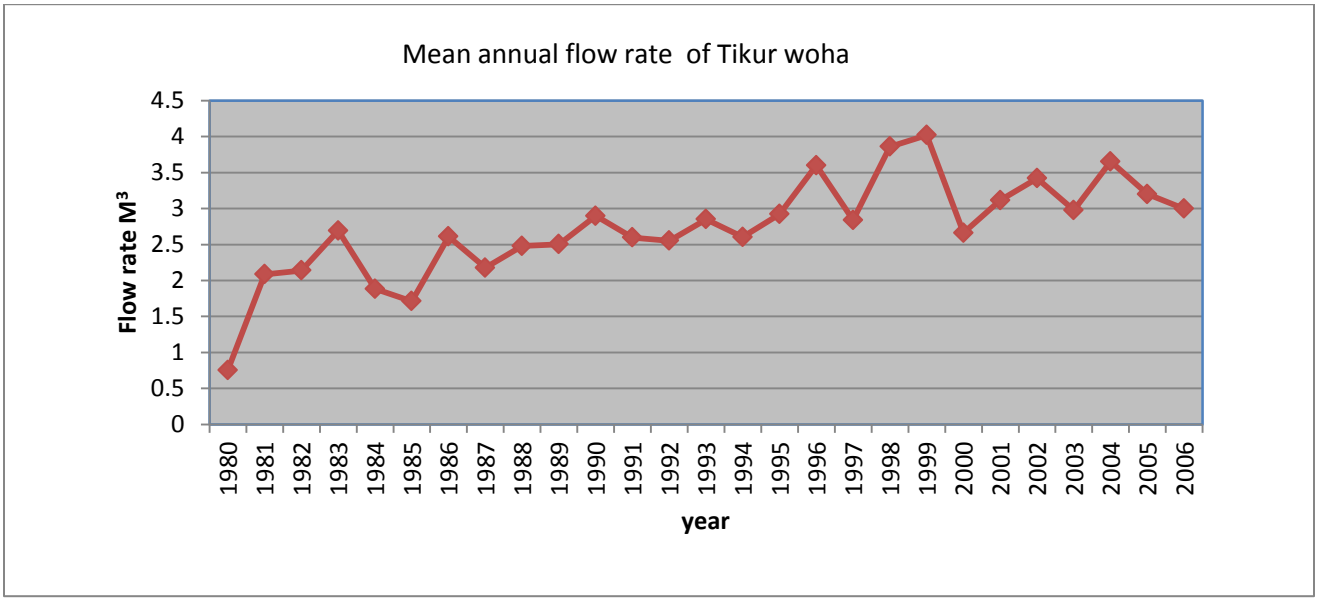

Figure3-8Tikurwoha River flow rate (M^3/yr) (1980-2006)

4. Geology and Hydrogeology

4.1 Regional Geology

The East African Rift System (EARS) is one the most remarkable phenomena of the earth crust (Figure 4.1). It is an elongated large prominent landmark on Earth with a subsided valley flanked by elevated plateau. The rift extend from Jordan southwestern Asia southward through eastern Africa to Mozambique (GIRD, 2007)

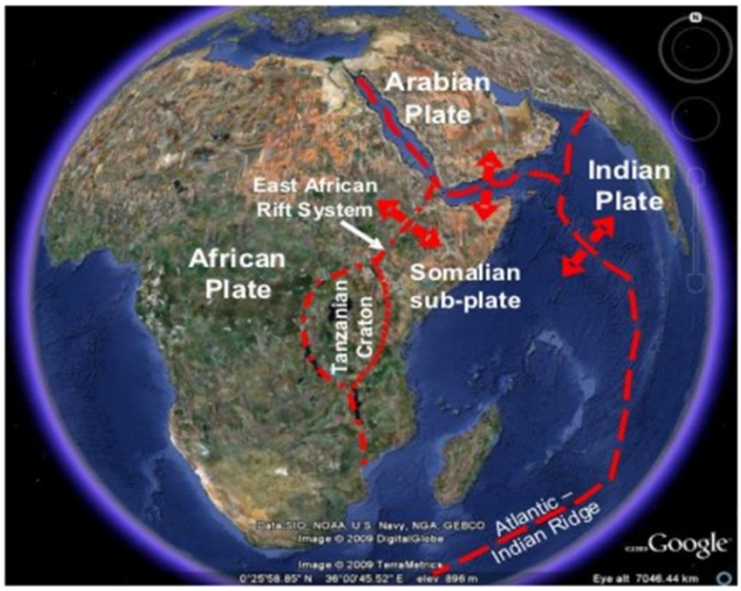

Figure 4-1: Regional plate tectonic setting and the East African Rift System (EARS).
Red arrows show approximate direction of opening of the Rift System.
(Source, http://www.see.leeds.ac.uk/afar/websitepages/structurepages/mer.htm)

The Ethiopian Rift System (ERS), which is part of the EARS and runs throughout Ethiopia in NE-SW direction, is sub-divided into three sectors (Figure 4.2): the Southern Ethiopian Rift (SER), the Main Ethiopian Rift (MER) and Afar Rift.

The MER is the northern segment of the Great East African rift system running NNE-SSW direction. It extends from Lake Abe, Afar-triple junction and dies out southward in to Lake Turkana and Lake Stifane rifts south of Lake Chamo. It is 80km wide and 700km long, bordered by the North Western plateau to the west and the South Eastern plateau to the east.

It is a complex region whose formation is a product of interplay of tectonic, magmatic and sedimentary processes that have operated over long period of time, and which contains a chain of elongated lakes.

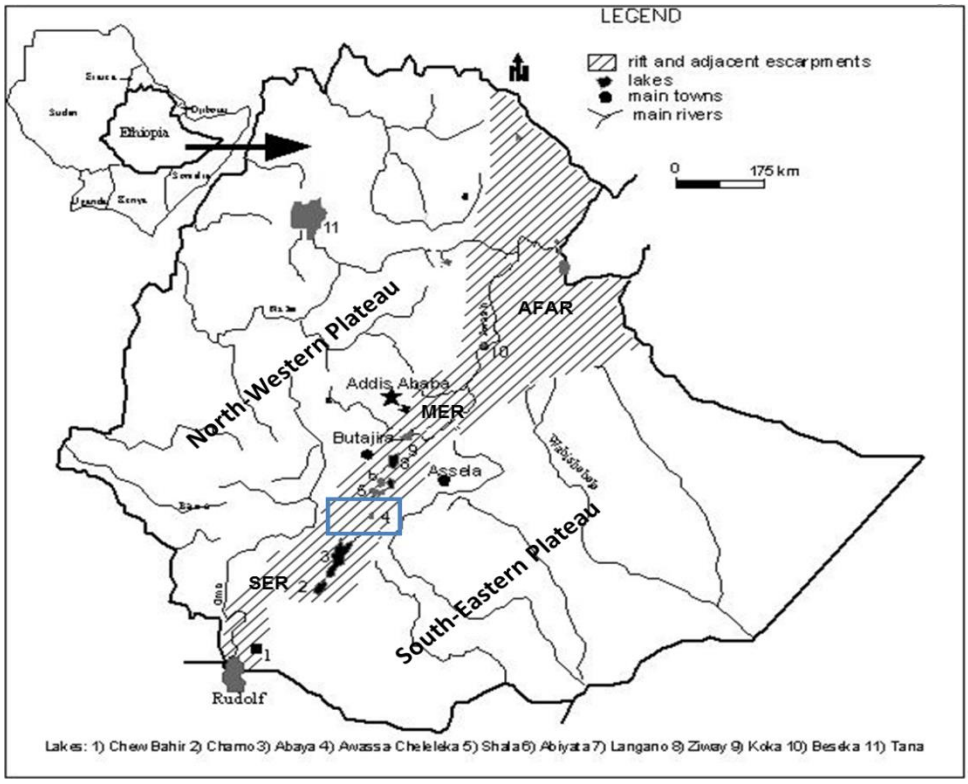

Figure 4-2: The Ethiopian Rift System (ERS)

And its three sectors: Southern Ethiopian Rift (SER), the Main Ethiopian Rift (MER) and Afar Rift. Location of the Study Area (blue square), the Hawassa Lake basin, within the MER

The major geological formation in MER recognized in Oligocene, middle Miocene, late Miocene, early-middle Pleistocene and Holocene (Tessema, 2003).

The oldest volcanic rocks, which are the plateau trap series are exposed on the western escarpment and consists of about 1000m of basaltic lava flows, with interbedded ignimbritic beds, overlaid by massive rhyolites and intervening tuffs and basalts (Di Paola, 1972; Merla et al., 1979; Woldegebriel et al., 1990). Radiometric age of the basalts ranges from 40-25Ma and the rhyolites 37-27Ma (MOWE, 2012; Merla et al., 1979; Woldegebriel et al., 1990andGIRD, 2007.

The eastern plateau is constituted by Pliocene to early Pleistocene (4.6-1.6Ma) shield volcanoes such as Chillalo, Kecha and Badda). It is characterized by trachayte with subordinate basalts and mugearites (MOWE, 2012; Di Paola, 1972; Merla et al., 1979; Woldegebriel et al., 1990andGIRD, 2007) and Miocene phonolites.

Most parts of the floor of the MER are covered by silicic pyroclastic materials, mainly per alkaline rhyolitic ignimbrites, interlayered with basalts and tuffs associated with unwelded pumice (GIRD, 2007). They are early to middle Pliocene. Alkaline and Per alkaline rhyolitic lava flows associated with pumice and ash represent the late silicic volcanic events (Di Paola, 1972 and GIRD, 2007)where they were erupted from late Pliocene to middle Pleistocene, and in some places outcrop as remnants of large caldera.

A more recent volcanic rock occur along the Wonji Fault Belt, which is made up of basaltic lava flows, associated with Hayaloclastites and Scoria cones (Di paola, 1972 and GIRD, 2007). It is very recent and localized, with a radiometric age of 0.13Ma (MOWE, 2012; Tessema, 2003) (Woldegebriel et al.). The Bora Bericco complex, the Aluto volcano, Ficke, and Corbetti calderas are the youngest volcanoes & calderas in the region started to be active from middle Pleistocene (about 0.25Ma) (Di Paola, 1972; Woldegebriel et al., 1990and GIRD, 2007). They are made up of rhyolitic lava flows, unwelded pumice flows & falls and ashes with obsidian, the obsidian flow represent the final product of the volcanic activity. Obsidian flows and pumices were dated 2000yBP.

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

4.2 Local geology

The studied area, as a part of the central sector of the Main Ethiopian rift (MER), exhibits the same nature and history of development of the MER. It is the result of Cenozoic volcano-

tectonic and sedimentation processes. Below are the generalized geological units classified in order to use for interpretation purposes. The description is given starting from the oldest. (Tessema, 2003).

i. Basalts of the plateau trap series (Late Miocene)

These are the most ancient rocks of the area, which are found on the eastern and southeastern part of the caldera wall where the caldera wall overlaps with the eastern escarpment. These rocks are geochronologically grouped under Gurage basalts (Woldegebriel et al., 1990) and consist of fine-grained mugearites overlain by thick welded tuff dominated by collapsed pumice clasts. The basalt is aphanitic, black, and columnarly jointed with spheroidal weathering at the surface. These rocks are assumed to be the foundations where the mega Hawassa caldera was constructed with age of 9.8Ma (Woldegebriel, 1987; Woldegebriel et al., 1990).

ii. Old Alkaline and Peralkaline silicic rocks (Late Pliocene-middle Pleistocene)

This unit constitutes the rift pyroclastics and the old rhyolitic lava flows that includes unwelded to moderately welded tuff, pumaceous pyroclastics, ignimbrites, and ignimbrites & tuffs. It covers large parts of the periphery of the caldera where it is widely distributed on the eastern wall of the caldera. The large part of the eastern caldera wall and south of Lake Hawassa is covered by ignimbrites underlying moderately welded coarse tuff of this unit.

This unit is also exposed in southern and southwestern with Pyroclastic deposits lava rock fragments units and northwestern parts part of the area in which the northeastern is particularly covered by ignimbrites and tuffs of this unit, more than 200m thickness (Zemenu Geremew, 2000) and with age range of 3.7-1.6Ma (Woldegebriel, 1987). The rhyolitic ridges at Wendogenet, with age 2.45Ma (Woldegebriel, 1987) and the rhyolitic necks on the floor of the caldera south east of lake Hawassa are also included in this unit, having vertical sheeting and flow folding structures.

iii. Recent Basaltic lava flows, Hayaloclastites and Scoria cones (recent Pleistocene)

This unit contains Basaltic lava flows associated with scoria cones and Hayaloclastites, forming smaller scattered relief on the floor of the caldera with thickness of a few dozen

meters. The Scoria is mainly associated with scoraceous basaltic flows, exposed east of Lake Hawassa such as Mt. Tumura. Its color range from dark brown to reddish brown whereas the individual grains range from lapilli to bomb size. The Hayaloclastites are yellowish to brown in color, mainly containing fine glassy material with large blocks of basaltic, rhyolitic & ignimbritic rock fragments.

Recent Acidic volcanics (< 1.6Ma)

This unit is the youngest volcanic product in the studied area, consisting of unwelded pumice flows, pumice falls, ashes, welded fine tuff and rhyolites with associated obsidians & pitchstones. This unit is exposed north & North West of lake Hawassa around Corbetti volcano. The pyroclastic deposits, welded & unwelded tuff deposits of the eastern and western caldera wall and the product of Chebbi volcano (Mt. Chebbi & Urji) containing pumice and the rhyolite beds associated with obsidian and pitchstones are some of them.

iv. Volcano-lacustrine deposits (Pleistocene to recent)

This unit is the only sedimentary formation in the area covering almost all parts of the floor of the catchment, deposited as a result of the recession of the lake. These sediments are volcanic in origin and covered by alluvium along river beds. Their thickness estimated to be 30-50m, but it reaches 100m (on south east of L. Hawassa observed from well logs of boreholes) when they are covered by relatively thick alluvium. These lacustrine deposits have variable lithology which is related with their mode of origin, i.e. they are either quiescent lake deposits, water deposited volcanic ejecta or coarse sediments intruded in to the lake by flood events. From well logs observation they are mixed with sediments, locally interbedded with volcano-clastics and rock fragments of rhyolites, ignimbrites, basalts & tuff and the grain size of the sediments ranges from fine to medium sand but increases with depth.

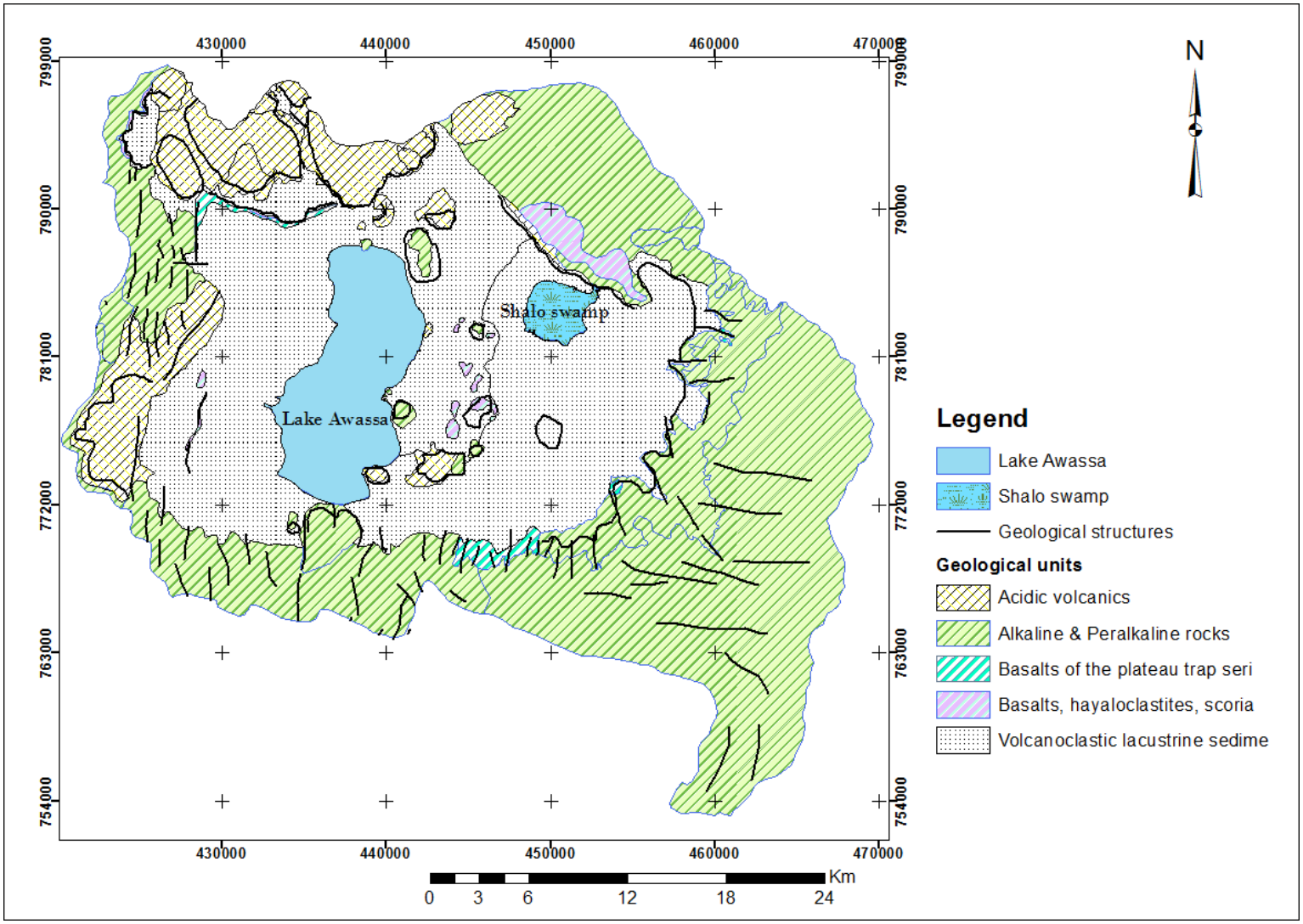

Figure 4-3: Geological units of the Study Area (Adopted from Tessema, 2003)

4.3 Geological Structure

In the Study Area there are a number of rift system faults with north and northeast trend along which the longest axis of Lake Hawassa is oriented (Yemane, 2004). The faults are expansions (normal faults) forming step faults. They are mainly dominant to the south and south west of the lake (Figure 4.5).

The pyroclastic fall deposit is generally affected by NS-NNE/SSW faults exhibiting series of elongated-closed-parallel basins and elevated blocks. The fault scarps are highly subjected to accelerated erosion and mass wasting.

Recent ground cracks are formed in Muleti, southwest of Lake Hawassa. The cracks approximately strike NNE-SSW, which could convey water from the Muleti sub-catchment to Lake Hawassa when intercepted by east-west running faults.

The volcanic collapse structure (caldera) forms nearly circular structure around Lake Hawassa basin. The collapse shifts some of the MER fault systems showing that the collapse has taken place subsequent to the rifting. In the Hawassa caldera a line of young faults affect the rift floor. These faults shattered the floor in to several relatively small horst and grabens. Lakes or swamps occupy the more depressed areas, (Tessema, 2003).

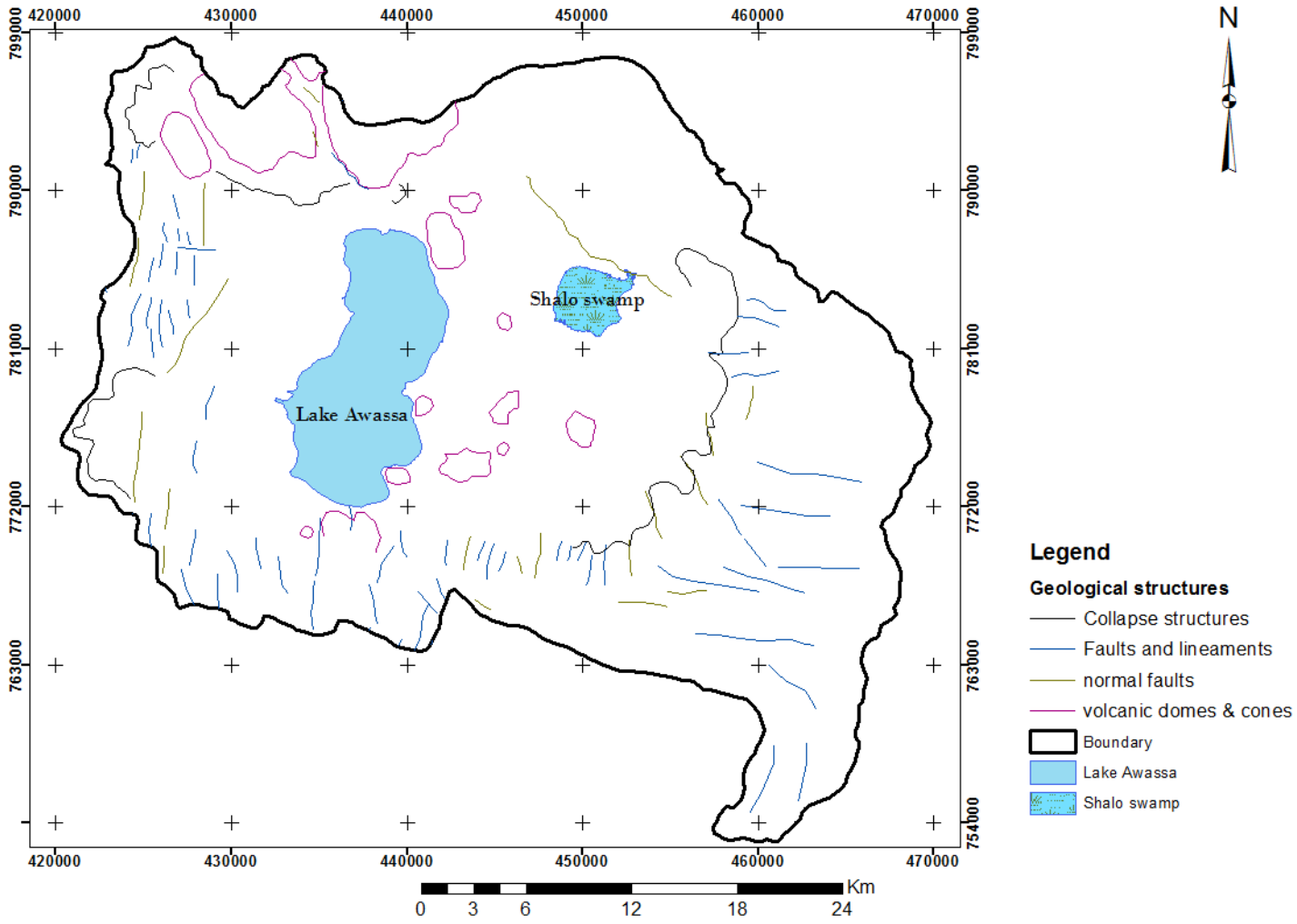

Figure 4-4: structural geology of the study area(Adopted from Tessema, 2003)

4.4 Hydrogeological units

The main two aquifer types in the study area are Fractured and jointed ignimbrites and the overlying volcano-lacustrine sediments. Ignimbrites are also the major water bearing formation of the geothermal fluid in the region (Tessema, 2003). Existing water points are not evenly distributed to characterize different hydrogeological units in the study area. Therefor in water bearing property of rocks and recharge source also considered in addition to hydraulic parameters (k and T) (Tessema, 2003).

High Potential Aquifers: In the Hawassa caldera, east of wondogenet escarpment, is classified as very high potential aquifer. Sand, Pumice and coarse tuff are the permeable water-bearing formations in this area. Borehole in the study area shows that the water-bearing formations separated by diatomaceous clay.

Considerable amount of recharge to groundwater is taking place from overland flow and direct precipitation. Perennial streams, from the Easter highlands and perennial springs that come from the wondogenet escarpment are other source of ground water recharge of this zone.

***High to Moderate Potential aquifers*:** This zone is found in Hawassa-Corbetti caldera; highly permeable sediment and un-welded coarse tuff constitute the potential aquifers of this zone. Unlike to the Wondogenet escarpment, there are no either springs or perennial streams on this part of the catchment. The area receives quite significant amount or recharge from Shemena escarpment and direct rainfall, during rainy season (May to October).

Recharge in this area is limited in time and amount, so the zone was rated as second because of its lesser recharge when compared the first one. More than one aquifers intercalated with clay aquitards with semi-confined condition are common.

Water from lacustrine aquifers is slightly saline, because of evaporative enrichment in the shallow water table, and contains high fluoride; whereas the deep ignimbritic aquifers discharge relatively good quality water.

***Moderate Potential Aquifers*:** Fractured Ignimbrite is the main unit of this aquifer. It is buried deeply under sediments in Hawassa caldera. In this area there is numerous good quality perennial

springs emanate from this unit. The escarpment of Wondogent, east of Lake Hawassa is zone of numerous springs. Most of them are good quality cold springs and some are thermal springs (60-70 0C)

In terms of water quality this is the best zone in the entire study area. Most of these springs are used as drinking water supplies for small villages and towns in the surroundings. Other units falling under this group are: tuffs, basalts, scoria, and recent alluvium.

Low to Moderate Potential Aquifers: Welded tuff is the main unit of this water baring formation. The eastern highland, adjacent to the rift margin categorized under this aquifer units. Even the area receives high amount of rainfall it generated high amount of runoff because of its hilly topography of the area, and the infiltration is very low. High amount of rainfall goes to Hawassa caldera with very small proportion of water left for infiltration.

Low Potential Aquifers: This unit is coved with thin layer of top clay soil and volcanic ash which has low permeability. Infiltration is obstructed by this low permeable layer, therefore the recharge amount is very low, and as a result water table is very deep and poor quality.

Very Low Potential Aquifer: This area receives less amount of precipitation compare to others and the major units in this group are pumice, tuff and other pyroclastics, have high permeability, but without confining layer, a condition which leads to deep water table.

Aquicludes: This zone is characterized by hilly topography that favors high runoff and low recharge to groundwater. Hydro-structures such as joints and fissures are poorly developed; hence runoff is favored over infiltration. Generally acts as an aquiclude. Typical lithologic units grouped under this class are acidic volcanic rocks, namely: Rhyolite, Trachyte, and Obsidians.

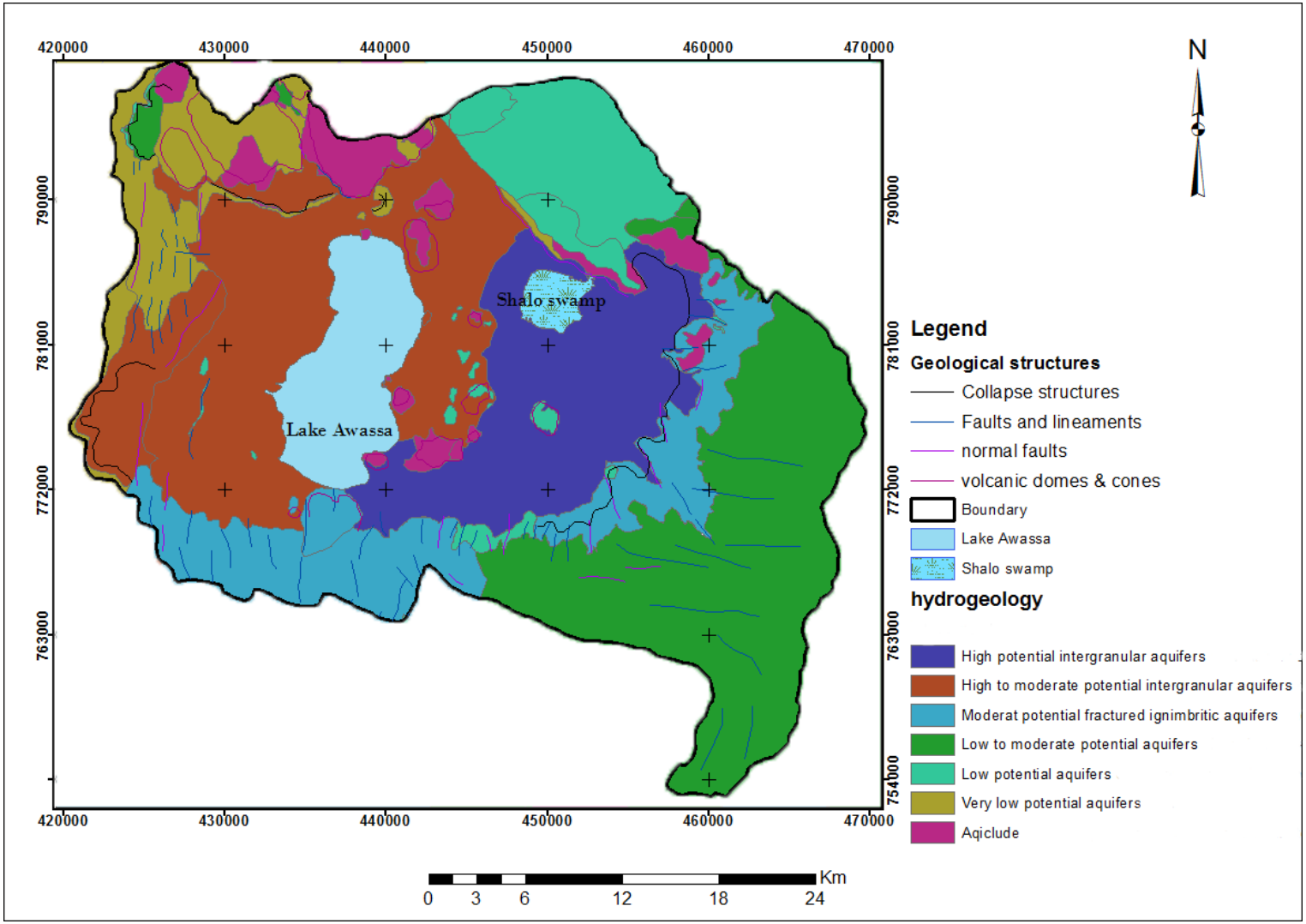

Figure 4-5: Hydrogeological units of the Study Area (Adopted from Tessema, 2003)

5. Result and Discussion

5.1 Hydrogeochemistry

General

The Geochemistry of Lake Hawassa catchment has been studied by Tessema in 2003, Major ion chemistry, isotope and water balance approach was followed to understand the flow and hydrochemical evolution of the study area. According to the study Sodium bicarbonate is the dominant water type in the study area. It also identified that the water bearing formation for both best and poor quality. Ignimbrite have the best quality water for all purposes while lacustrine aquifer have high fluoride and TDS with high potential of water bearing capacity.

Other study concerned about the origin of high bicarbonate and fluoride concentrations in waters of the Main Ethiopian Rift Valley, East African Rift system by (Gizaw, 1996) revealed that the main cause for the bicarbonate in the area is the high rate of carbon dioxide outgassing. In the closed-basin lakes of the region evaporative concentration is responsible for the high salinity, alkalinity and fluoride.

Additional studies in the Main Ethiopian Rift by (Rangoet.al, 2008), revealed the source and enrichment mechanism of fluoride and hydrochemical faces of surface and groundwater in the highlands and within the rift valley. Groundwater and surface water from the highlands, typically characterized by low total dissolved solids (TDS) and Ca (Mg)–HCO3 hydrochemical faces, do not show high F content. The consequent interaction of these waters with the various rocks of the rift valley induces a general increase of the TDS, and a variation of the chemical signature towards Na–HCO3compositions, with a parallel enrichment of F. Main interacting matrixes are rhyolites consisting of volcanic glass and only rare F-bearing accessory minerals (such as alkali amphibole). The glassy material is extremely reactive, and its weathering products (i.e. fluvio/volcano-lacustrine sediments) further concentrate the fluoride. The interaction of these ‘‘weathered/reworked’’ volcanic products with water and carbon dioxide at high pH causes the release of fluoride into the interacting water.

The main enrichment mechanism that explains the high F content of the local groundwater is that during the interaction of water with the matrix, Ca–Mg uptake by the aquifer matrix, with release of Na into the groundwater.

5.1.1 Data Availability and quality

i. Data Availability

After review and collecting of existing data it was possible to identify easily where to collect and conduct field measurements like EC, PH and temperature. Twenty-six newly collected samples and 103 previous data of isotopes and hydrochemical data from lake, borehole, springs, rivers and dug wells are used to represent the study area.

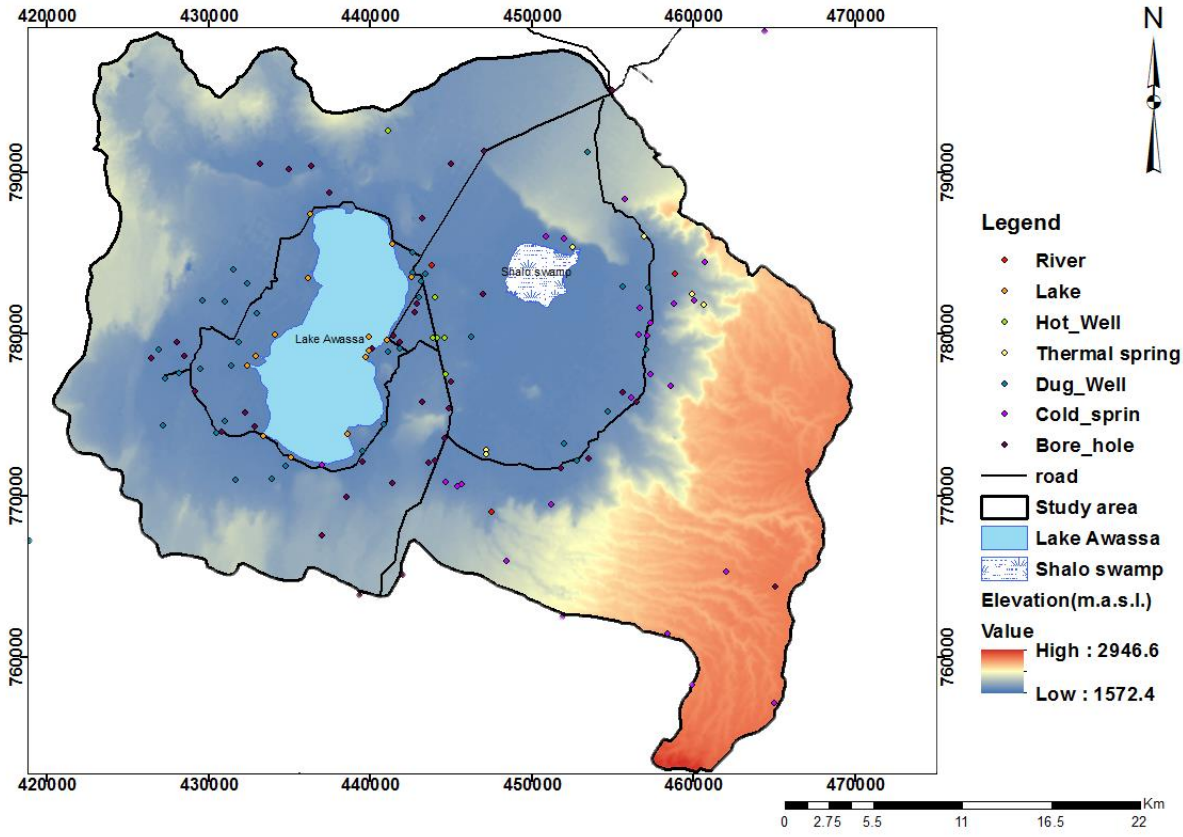

Figure 5-1: Hydrochemical and isotope ($\delta^{18}O$and $\delta^{2}H$) data availability map

Whereas BH is bore hole, CS is cold spring, DW is dug well, HW is hot well, LK is lake, RV is river and TS thermal spring.

During field work of water sample collection, initially sample bottles wash out two times before taking sample. Surface water (river, streams and lake) and groundwater samples were collected.

When groundwater removed from its source parameters like temperature, PH, EC and alkalinity of water undergo changes due to aeration, oxidation and degassing or absorption of atmospheric

carbon dioxide (CO2). This reaction process cause other activities such as, degassing of CO2 could make precipitation of carbonates and oxidation of some element (Hem, 1989). To reduce such problems in-situ measurement at the field has been taken for those parameters immediately after sampling (Table 4).

pH: The hydrogen-ion activity in an aqueous solution is controlled by interrelated chemical reactions that produce or consume hydrogen ions. It is controlled by the presence of gaseous and dissolved carbondioxide from sources (Bicarbonate and carbonate ions) and its value in between 6.5 and 8.5 is potable based on WHO standards. The study area has a minimum of 5.25 and 9.39 higher. Generally it is progressively increases towards northern and north east direction of the study area.

Electrical conductivity: is the degree of salinization of groundwater which is a widely used method for categorizing groundwater. Equally, a measurement of the EC of a solution will also give a relative indication of the amount of dissolved salts. The more salts that are dissolved in the water thus the higher electric conductivity.

Table 5-1: Field measured parameters of water

TDS		EC, µS/cm		Temp, oC		pH	
Low	High	Low	High	Low	High	Low	High
28.8	2238	48	3730	20.7	69.15	5.26	9.39

ii. Data quality

Water samples were collected and analyzed for the parameters like, major cations (Na+, K+, Ca2+ and Mg2+) and major Anions (Cl^-,F^-, NO_3^-,CO^{3-} , HCO_3^{2-},SO_4^{2-}).

After the samples were analyzed in Institute of Environmental Assessment and Water Research (IDAEA) of the Spanish Council of Scientific Research (CSIC) at Barcelona, Spain Laboratory, the data were tested for charge balance error (Freeze and Cherry, 1979)prior to the interpretation of the data. The charge balance was calculated using the following formula:

$$Charge\ Balance\ error(\%) = \frac{\sum \text{cation} - \sum \text{anion}}{\sum \textbf{ca}\text{tion} + \sum \text{anion}} \text{X } 100$$

Whereas the sum of anions and cations are in milli equivalent per liter

The Charge balance error of 15 samples from both primary and secondary data was above 5. The rest of the data (118) have charge balance errors below 5% which is an acceptable analysis error.

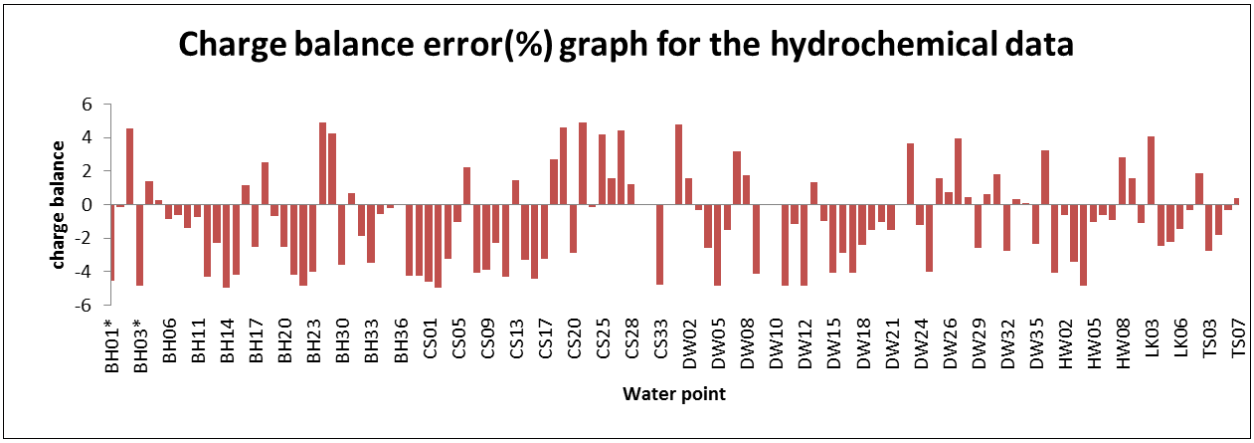

Figure 5-2: Charge balance error graph of hydrochemical data

Major cation and anion concentration observed in the Lake Hawassa catchment show different conditions. There is variation in the concentration of major caion and anion.

The dominant cation is sodium followed by calcium; whereas the dominant anion is bicarbonate with minor chloride and sulfate that occur in thermal waters. Figure5.3 a piper tri-linear diagram of different water bodies, cold boreholes, geothermal wells, dug wells, cold springs, and Lake. From this plot classification is accomplished based on the presence of dominant cations and anions.

Main water types in the study area are Na-HCO3 (Sodium Bicarbonate type) followed by Na-Ca-HCO3 (Sodium-Calcium Bicarbonate type) and Ca-Na-HCO3 (Calcium -Sodium Bicarbonate type).

Na-HCO3 (Sodium Bicarbonate type)

Na-Ca-HCO3 (Sodium-Calcium Bicarbonate type)

Ca-Na-HCO3 (Calcium -Sodium Bicarbonate type).

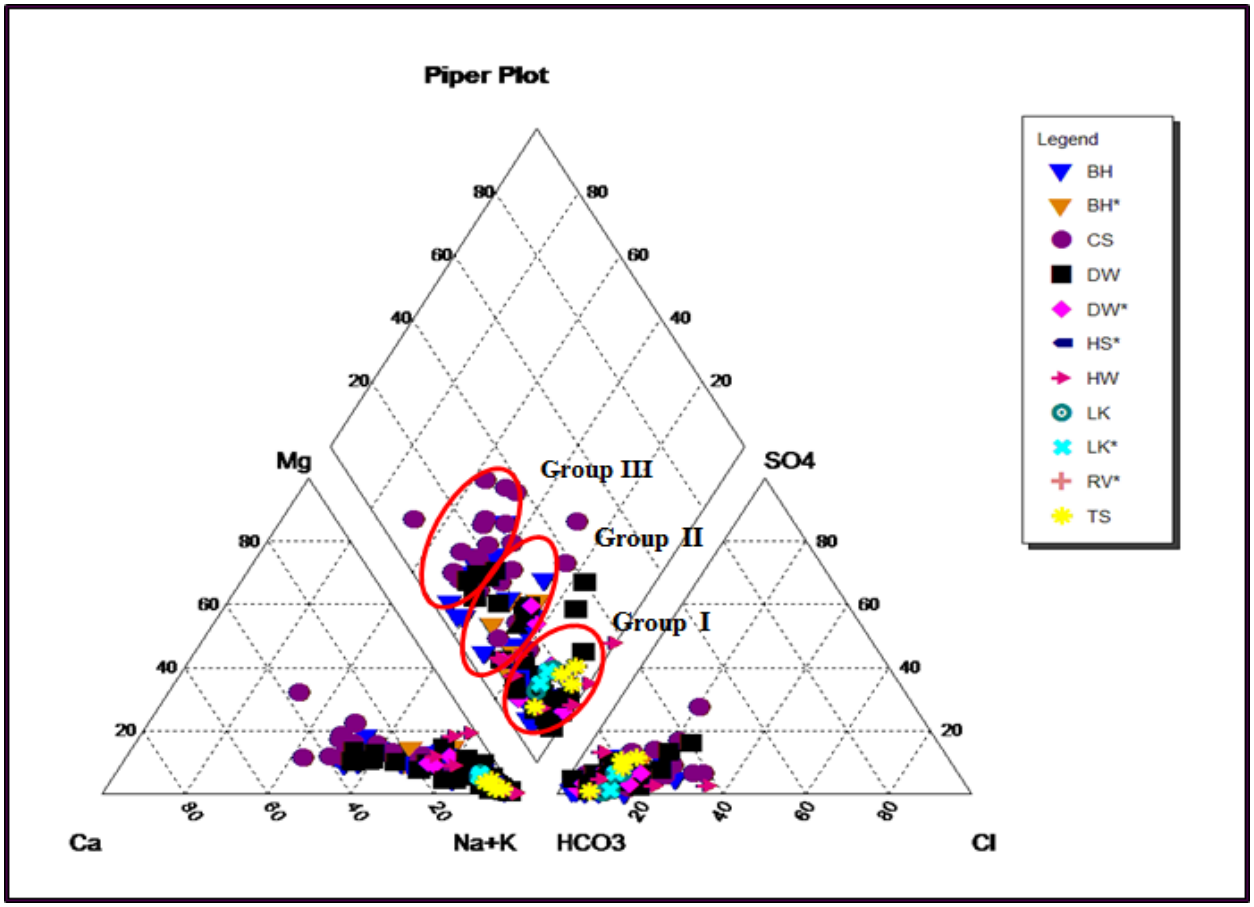

Figure 5-3: Piper plot for hydrochemical data

Whereas BH-is borehole, CS is cold spring, DW is dug well, HS is hot spring, HW is hot well, LK is lake, RV is river, TS is thermal spring. Samples with * represent primary samples.

Group I: - with in this group the major cation is Sodium and Bicarbonate is the major anion. So the water samples in this group are Sodium Bicarbonate (Na-HCO3) type. Both surface and ground water of the floor of the caldera such as: Tikur Wuha River, dug wells around the lake, cold bore holes and hot spring and geothermal wells around Corbetti is characterized by this type of water.

Group II: - Sodium and calcium are dominant cations while Bicarbonate is the major anion. The water type is Sodium-calcium Bicarbonate (Na-Ca-HCO3) type. It is the characters of Dug wells, cold springs and bore holes which are found at the foot of Easter caldera. In the South and South Waster hills there are Dug wells and Cold Springs which are also characterized by this water type.

Group III:- The major cations in this group are calcium followed by Sodium and Bicarbonate is the major anion with in this group. It is the characteristics of cold spring at the eastern escarpment and highland. It is the characteristics of cold springs of the eastern escarpment (Wondogent escarpment) and highlands.

5.1.2 Spatial hydrochemical patterns

1. Electrical conductivity (EC) and TDS

Using the newly collected samples and old data, the GIS map plot was used and shows the distribution of electrical conductivity in the catchment.

Electrical conductivity is the degree of salinization of groundwater which is a widely used method for categorizing groundwater. Likewise, a measurement of the EC of a solution will also give a relative indication of the amount of dissolved salts. The more salts that are dissolved in the water thus the higher electric conductivity.

Spatial distribution map of EC and TDS shows almost the same pattern. The electrical conductivity and TDS increases as one goes to Lake Hawassa. EC value in the cold springs in the eastern highland of the catchment is low (< 100 µS/cm) while the foot of the escarpment and southeastern highlands have EC value 100 µS/cm to 700 µS/cm. In general, Ground waters located within in floor of the caldera have higher EC (>1000 µS/cm), which shows the ground water flow from the highland area into the floor of the caldera (Figure 5.4).

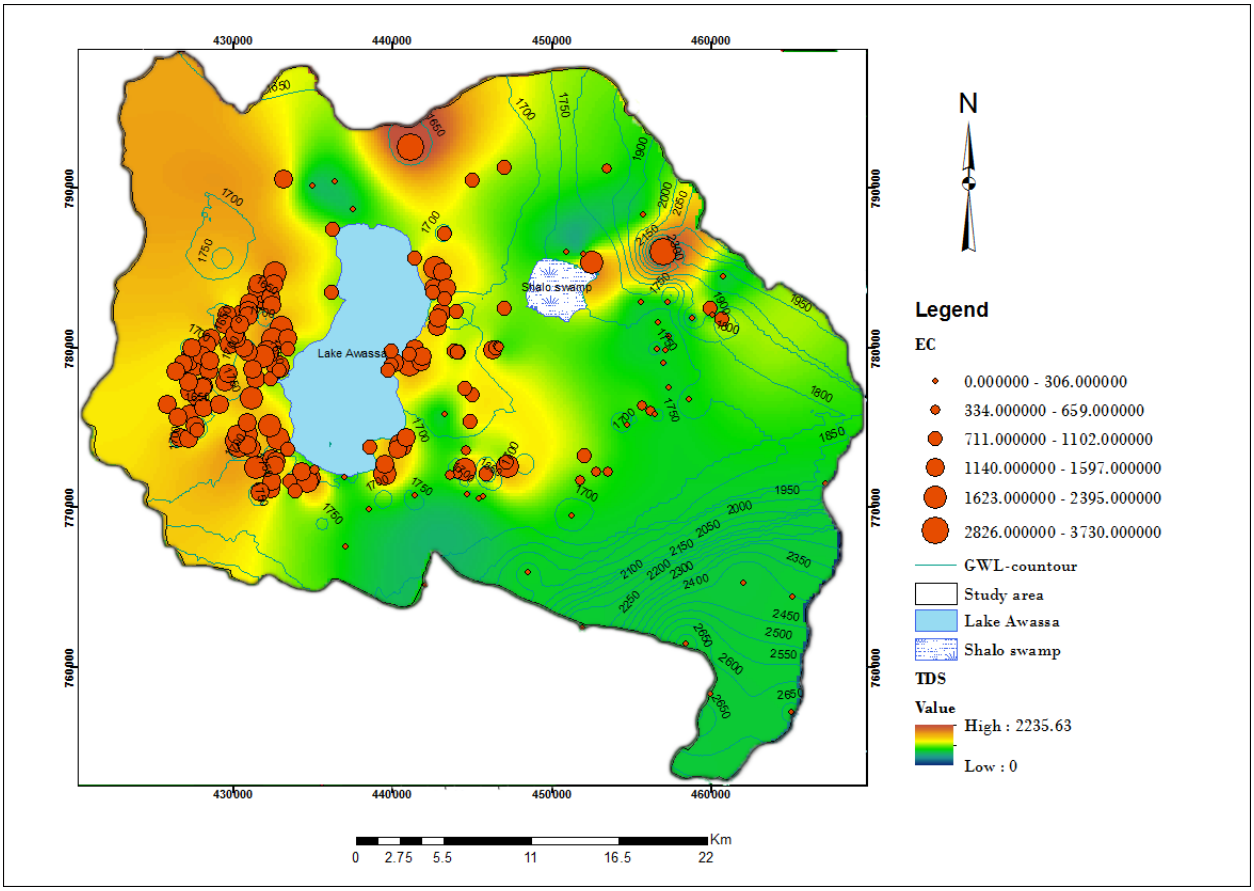

Figure 5-4: Spatial distribution map for TDS and EC

Temperature measurement for 23 water points has been taken. The lowest temperature was recorded at Abba Tusho cold spring (20.7^{o}C) and the highest was recorded at Wondogent thermal spring (69.15^{o}C).

2. Fluoride

Fluoride concentration in potable water is permissible below 1.5mg/l and 3mg/l according to WHO and MOWE standards however, excessive amount results a number of adverse effect like dental fluorosis (WHO, 2004).

The concentration of dissolved-fluoride in the water can be controlled by several potential soluble inions. The main enrichment mechanism that explains the high F content of the local groundwater is that during the interaction of water with the matrix, Ca–Mg uptake by the aquifer matrix, with release of Na into the groundwater (Rangoet.al, 2008; Alemayehu, 2007) in the study area it is also visible that high fluoride concentrations are more likely to occur in area

where calcium concentration is low. The lower fluoride value 0.07 mg/l is found in highlands at the Easter and Southeaster part of the study area from cold springs and the higher value46 to 58 mg/l is found in rift floor (lowlands) and in Northern part of the study area from hot wells. The high fluoride values are from thermal effect and from fluoride bring formation. In general the high fluoride concentration of the area is from weathering processes on the acidic volcanic rocks and water–rock/sediment interactions in the thermal system of the caldera that could probably be triggered by the high activity of CO_2 (Rangoet.al, 2008; Alemayehu, 2007).

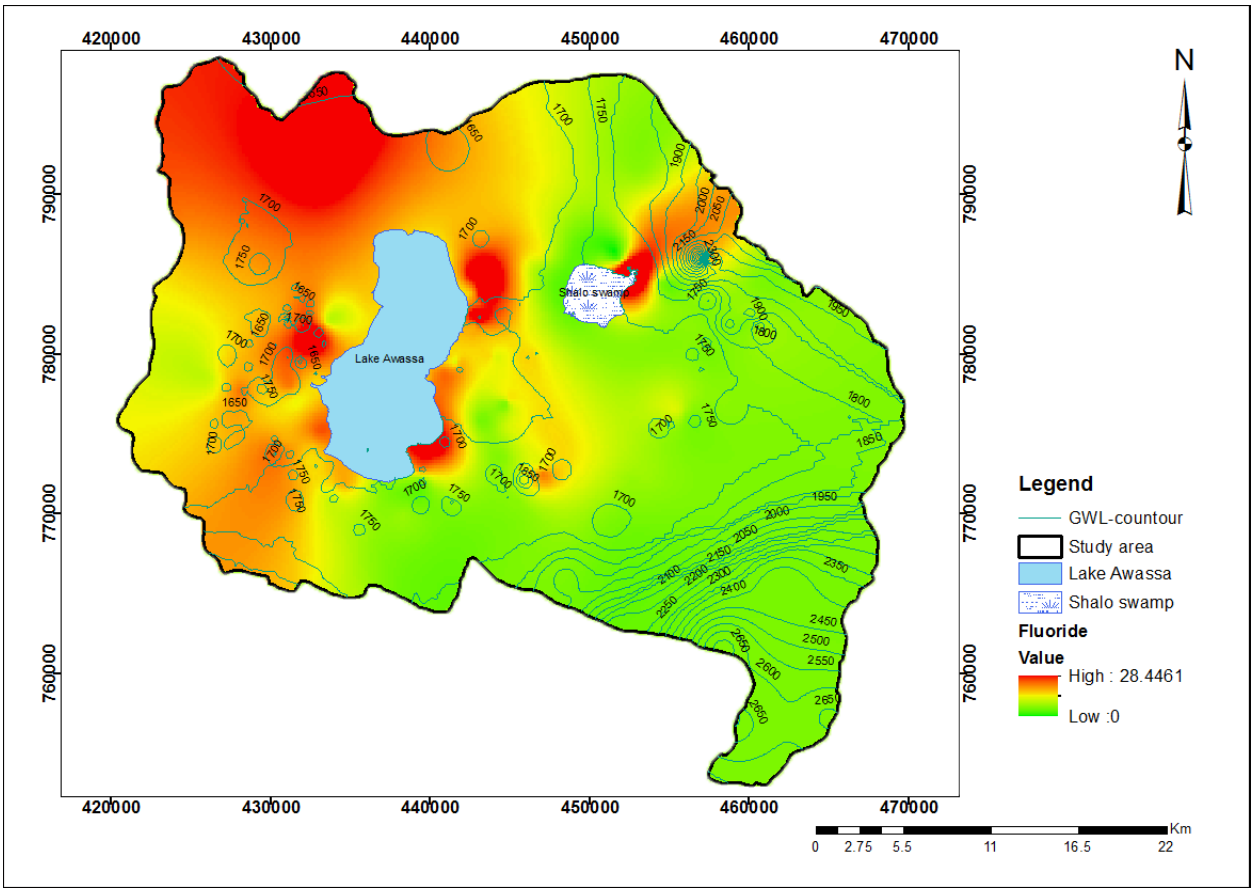

Figure 5-5: Spatial distribution map for Floride

3. Calcium and Sodium

The spatial distribution of major cation Calcium (Ca2+) concentration in the study area is high in the floor of the caldera at the eastern part of the Lake. The maximum amount of Calcium is 87.5 mg/l which is observe on the floor of the caldera at the southern part of Lake Hawassa. As one goes from the elevated high area to the rift floor of the caldera concentration of Ca^{2+} decreases whereas, concentration of Na+ progressively increases contrariwise to Ca^{2+} (Figure5.6 and5.7).

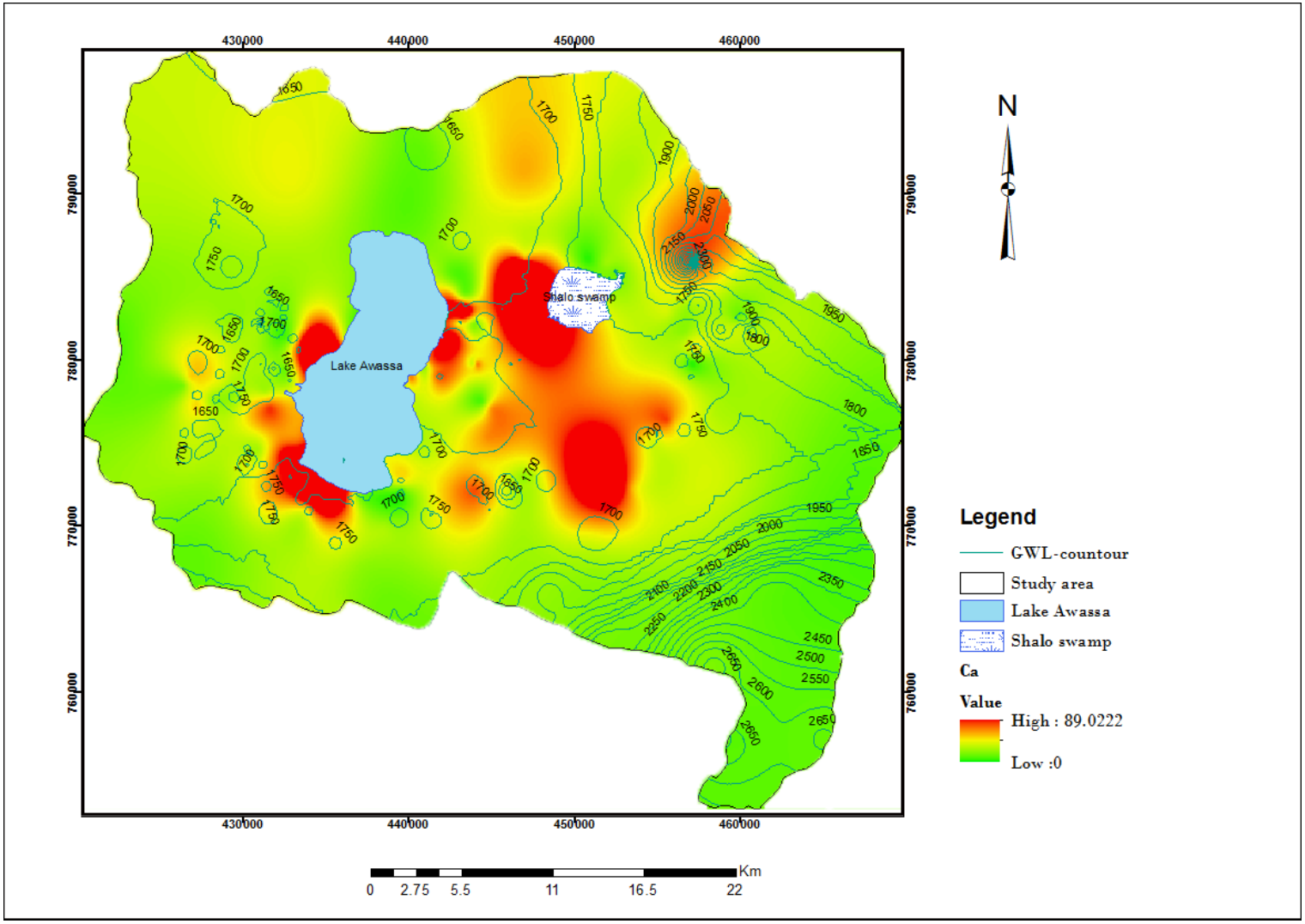

Figure 5-6: Spatial distribution map for Floride

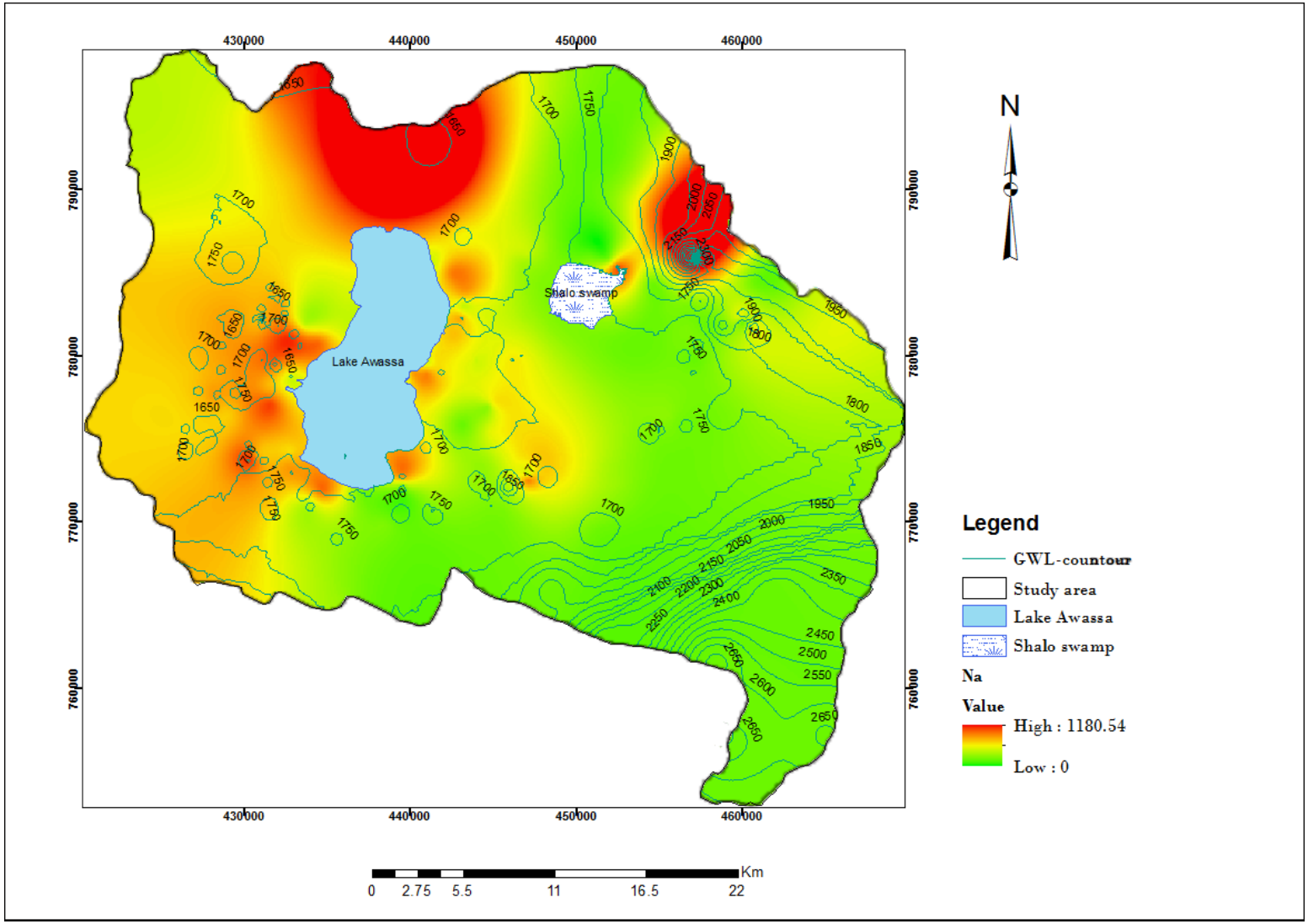

Figure 5-7: Spatial distribution map for Sodium

In general hydrochemistry of the study area classify in to three based on its water type. (1) Water samples with Ca-Na-HCO3 this type of water is rare in the study area. It is the characteristics of cold springs of the eastern escarpment (wondogent escarpment) and highlands with low TDS and EC value. (2) Na-Ca-HCO3 water type which have intermediate TDS and EC with respect to the area with Ca-Na-HCO3 water type. Dug wells, Bore holes, cols springs which are located at the foot of eastern escarpment and caldera rims, rivers that drains the eastern escarpment, dug wells and cold springs are characterized by this type of water. (3) Na-HCO3 water type. Both surface and ground water of the floor of the caldera such as: Tikur Wuha River, dug wells around the lake, cold bore holes and hot spring and geothermal wells around Corbetti is characterized by this type of water. TDS and EC valueis high in this area with relative to previous two groups. However, Lake Hawassa have EC < 800 μS/cm.

5.2 Isotope Hydrology

Stable and radioactive environmental isotopes used to study hydrological systems, and proved information to understanding groundwater systems. Environmental stable isotopes of δD& $\delta^{18}O$ are used as ideal tracers for the physical movement of water. Stable isotopes of δD and $\delta^{18}O$ give information about the origin, recharge-discharge processes, and flow directions. As water moves in to the ground it begins to record information on the history of its recharge source and properties mainly from rainfall solutes as well as isotopic ratios in the water molecule and the chemical composition follows progressive changes from recharge areas/sources toward areas of discharges where establishing distinctive chemicals characteristics. These processes are time and space dependent, the chemical changes as well as isotopic variations may be used to provide information on the flow paths.

Data collected from previous work and samples from field (26) have been used for this study.

The isotopic composition of water is expressed in comparison with the isotopic compositions of Ocean water and is expressed in per mil (‰) deviation from the standard mean ocean water (SMOW) (Craig, 1961).

The local meteoric water line was created using IAEA data of Hawassa station from GNIP isotopic data base web site (http://isohis.iaea.org/Database). Isotopic composition of these precipitations data ($\delta^{18}O$ (‰) against $\delta^{2}H$ (‰)) are plotted and resulted with a linear trend represented by the equation $\delta^{2}H$ (‰) = 7. $5\delta^{18}O$ (‰) +13.3 is known as the local meteoric water line (LMWL).

The isotopic data were plotted for different water bodies along with the LMWL, such as rainfall at Hawassa, hot springs, cold boreholes, geothermal wells, dug wells, cold springs, lake and river (Figure 6.1).

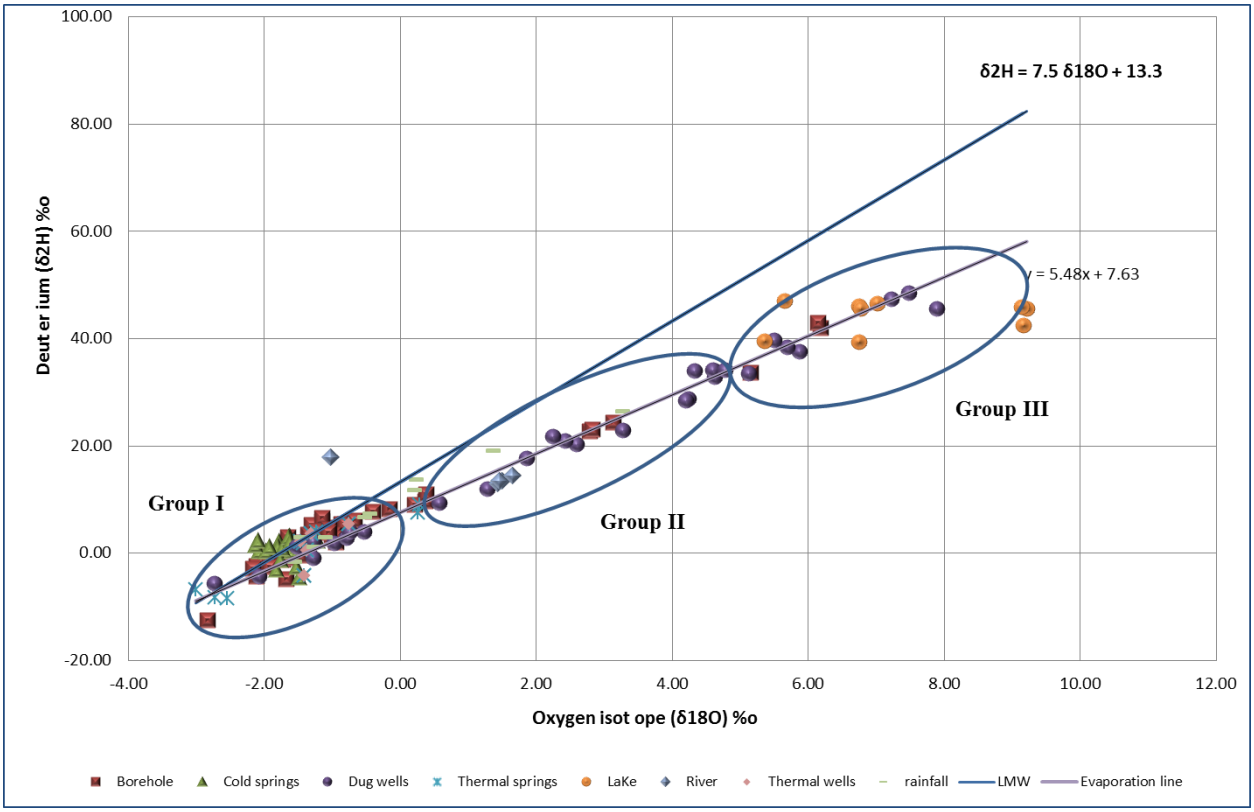

Figure 5-8 Deuterium Vs. Oxygen-18 for different water body samples.

Group I

In this group the isotope concentration of water samples are depleted. Thermal springs from wondogent escarpment, all cold springs, all thermal wells, most of bore holes and dug wells located at the foot of eastern caldera wall & highland are found within this group. The isotopic concentration of this group is close-fitting with the LML. It reveals that shallow circulation of ground water. Fast circulation of water in this area can be the role of faults and the steep elevation of the area.

Group II

This group represent sample found in the intermediate plotting position which shows relative enrichment. Unlike rain water samples within this group are far from LMWL. Dug wells found near the eastern shore of the lake Hawassa, thermal spring which is sampled from Shallo spring, some of boreholes found near Lake Hawassa to the west and North West of Lake Hawassa toward corbetti caldera included with this group. It shows characteristics of mixing with the evaporated Lake Hawassa and meteoric water. Two rain fall samples are also included with this

group, hence rain fall samples are collected in different seasons, and the variation can be due to seasonal effect.

Group III

Samples with in this group are highly enriched with heaviest isotope of $\delta^{18}O$ and $\delta^{2}H$. Lake Hawassa, some Dug wells from the west and northwest side of the lake and boreholes are found near Lake Hawassa to the west and North West of Lake Hawassa toward corbetti caldera are set with in this group. Isotopic composition of samples indicates it is in the state of evaporation relative to the present day precipitation.

The result illustrates that the ground water system is recharged from the combination of direct/diffuse recharge, from highlands that bounds the study area through fractures and indirect recharge from Lake Hawassa.$\delta^{18}O$ and $\delta^{2}H$ result reveals that there are two types of groundwater circulation in the study area. Local, shallow and fast circulating groundwater, which is characterized by depleted isotopic composition (group I).Thermal springs from wondogent escarpment, all cold springs, bore holes and dug wells located at northeastern, southeastern and the foot of eastern caldera wall &highland feed by this type of flow. Streams that originate from eastern escarpment are also part of this kind of flow and join Shallo Swap at the end.

The second is intermediate, relatively slow and deep circulating groundwater which is characterized by intermediate enrichment of isotopic composition (Grou II). This flow feed Dug wells, thermal spring and boreholes found at the floor of the caldera including Tikur Wuha River.

From the spatial distribution of isotope concentration (δ18O‰) it is clear to see in which direction the lake water interact with the groundwater (figer 6.2). The major groundwater flow is in the northern direction while the is also interction of lake water in the southweaster dirction.

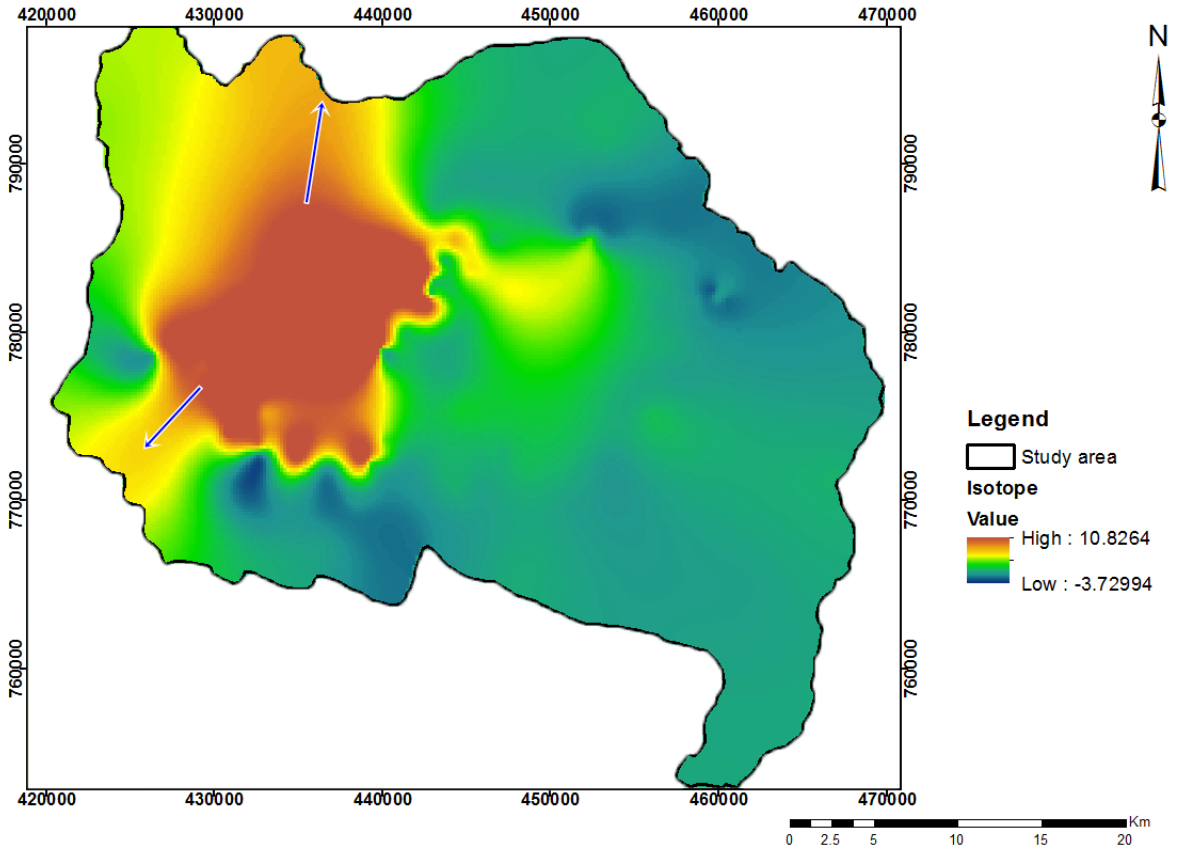

Figure 5-9: spatial distribution of isotope (δ18O‰)

Static water level samples from secondary and primary data (123 SWL data) used to identify the groundwater flow direction. According static water level value, the groundwater flow towards the Lake except in the northern direction where the ground water flows outside of the catchment. However, local ground water flow direction in the southwestern part of the lake show there is groundwater flow way from the lake. Also Isotopic ($\delta^{18}O$) concentration of groundwater along the groundwater flow direction and in the Northern and Southwestern side of the lake shows isotopic enrichment (figure 6.2).

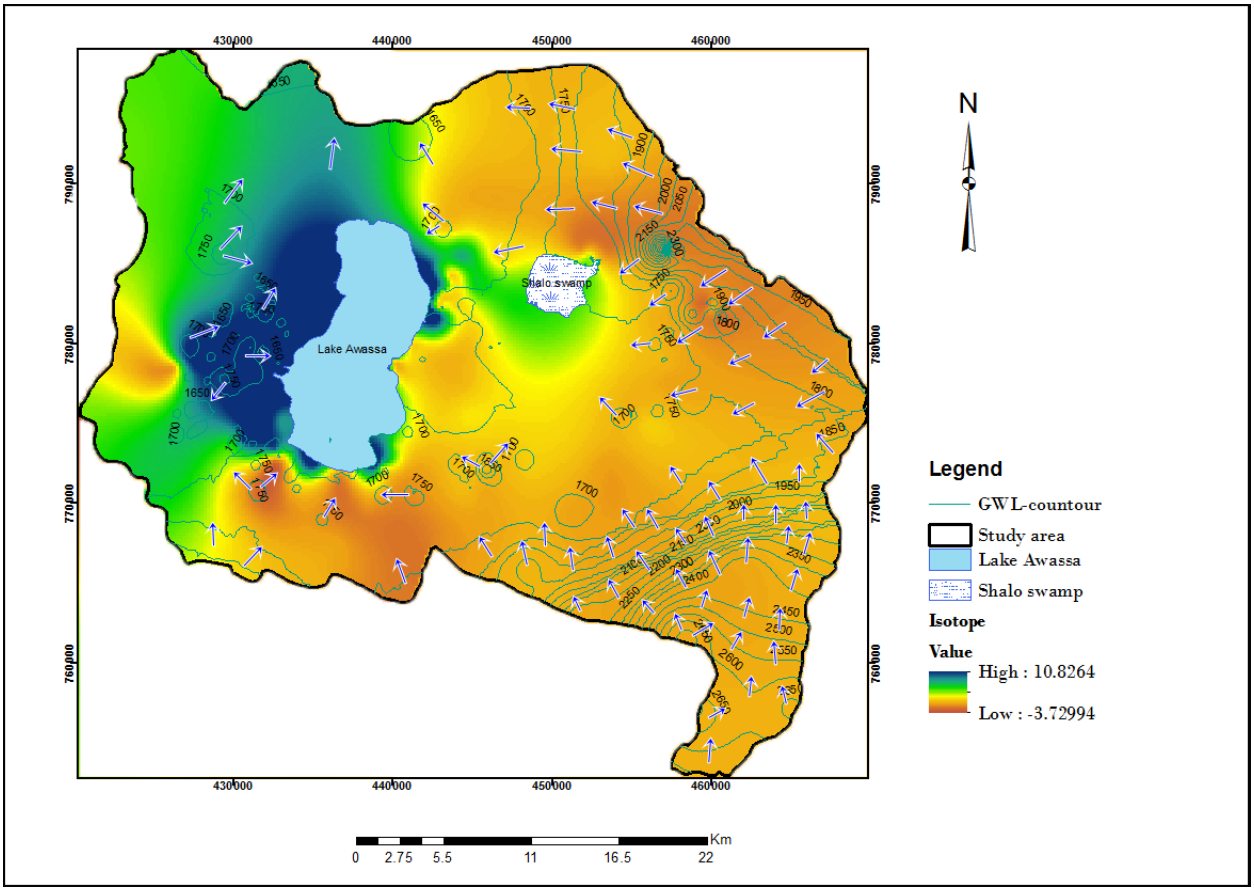

Figure 5-10: grownwater flow direction and isotope concetration (δ18O‰) along the flowdiration.

5.2.1 Lake Isotope budget

One needs to consider all the hydrologic components of the lake and its surroundings In order to determine the water balance of a lake. Based on conventional water balance method, measurements from extensive piezometer networks required to estimate the groundwater contribution.

Hence stable isotopes are part of hydrological cycle and part of the water they can be easily used. Isotope enabled lake water balance method is used to determine groundwater inflow and outflow independently. Stable isotopes have been used for the study of lakes by many investigators.

Theory

The main inflows to the lakes are precipitation to the lake, P; run off, R; and groundwater inflow, Gi. The main outflows from the lakes are groundwater outflow, Go; and evaporation from the lake surface, E. However the lake is closed lake with no surface out flow then, surface outflow, Ro; from the lake is zero.

The precipitation, surface inflow and evaporation are measured at the site, while the groundwater inflow and outflow can be found by the residual of the water budget equation. The general water budget relationship for a lake is:

$$\boldsymbol{P + R + Gi - E - Go = \frac{d}{dt}(V)}$$ **.....Equation 1**

Whereas P, R, and E are precipitation, run off and evaporation respectively, Gi and Go are groundwater inflow and out flow. V is the volume of water in the lake.

An additional equation can be written by considering the isotope composition of the water budget elements expressed in delta notation in units per mil (‰) and since a small and shallow lake is rather well mixed, one can assume that the isotopic compositions of groundwater out flow (δGo) outflows are the same as those of the lake (δL):$\delta Go = \delta L$.

The isotopic mass balance equation becomes,

$$\boldsymbol{P\delta_P + R\delta_R + Gi\delta_i - E\delta_E - Go\delta_L = \frac{d}{dt}(V\delta_L)}$$ **(Pearson and coplen, 1978; Kebede, 2002) .....Equation 2**

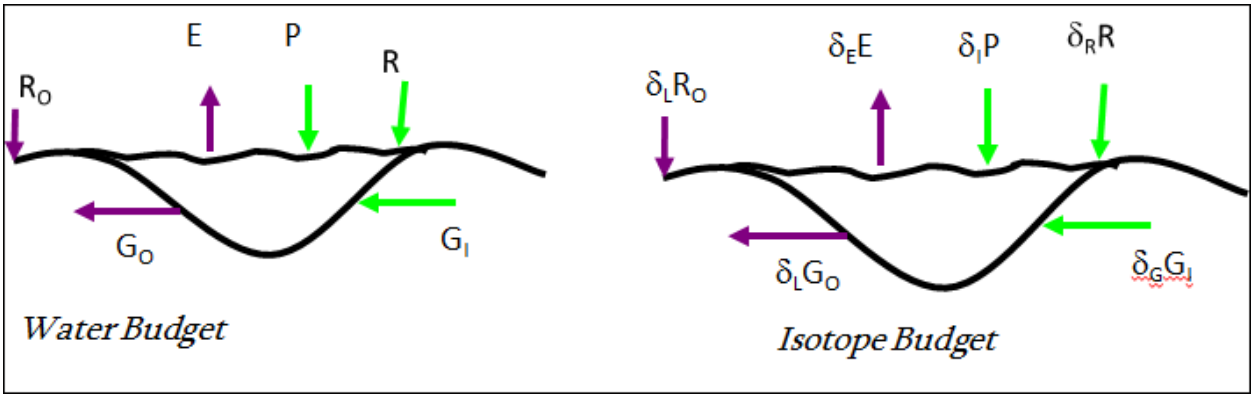

Figure 5-11: isotope contents associated with respective water flux

Combing equations 1 & 2: The groundwater inflow rate, Gi, can be solved as follows

$$\boldsymbol{Gi} = [\boldsymbol{P}(\mathbf{1}+\boldsymbol{k})(\boldsymbol{\delta_L}-\boldsymbol{\delta_P})+\boldsymbol{E}(\boldsymbol{\delta_E}-\boldsymbol{\delta_L})]/[\boldsymbol{\delta_{gi}}-\boldsymbol{\delta_L}] \quad \text{.....Equation 3}$$

However, δ_E is unknown in equation 4. According to Craig and Gordon's (1965) relation:

$$\boldsymbol{\delta_E} = \left[[\boldsymbol{\alpha^*\delta_L} - \boldsymbol{h\delta_A} - \varepsilon] \Big/ [\mathbf{1} - \boldsymbol{h} + \mathbf{10^{-3}}\boldsymbol{\Delta}\varepsilon] \right] \quad \text{.....Equation 4}$$

Where α^* is the equilibrium isotopic fraction factor at kinetic temperature of the evaporating surface ($1/\alpha^*$ and α is equal to 1.0098 for $\delta^{18}O$ at 25^oc, h is the relative humidity normalized to water surface temperature, δ_A is the isotopic composition of local atmospheric vapor, It is practically impossible to measure this parameter (δ_A) in the field. Researchers Kebede et al., 2002; and (Gonfiantini et al., 1973; Kebede, 2002) estimated δ_A for Ethiopia lakes using Lake Hora and Afera as terminal index lake respectively. The 'index lake method' is a suitable method to indirectly infer δ_A and h. By assuming that there is no remarkable variation in δ_A over the region, the δ_A obtained from the index terminal lake can then be used to derive the δE for other lakes under a similar climatic condition.

ε is the fractionation factor, and $\Delta\varepsilon$ is the diffusion controlled or kinetic fractionation factor. The total fractionation factor (ε) is the sum of equilibrium (ε^*) and kinetic fractionation factor ($\Delta\varepsilon$):

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

$$\Delta\varepsilon = (1-h)\left[\frac{\rho_A}{\sum\rho}\left(\frac{\rho_{i,A}}{\rho_A}-1\right)+\frac{\rho_B}{\sum\rho}\left(\frac{\rho_{i,B}}{\rho_B}-1\right)\right] \text{(Craig and Gordon (1965))}$$

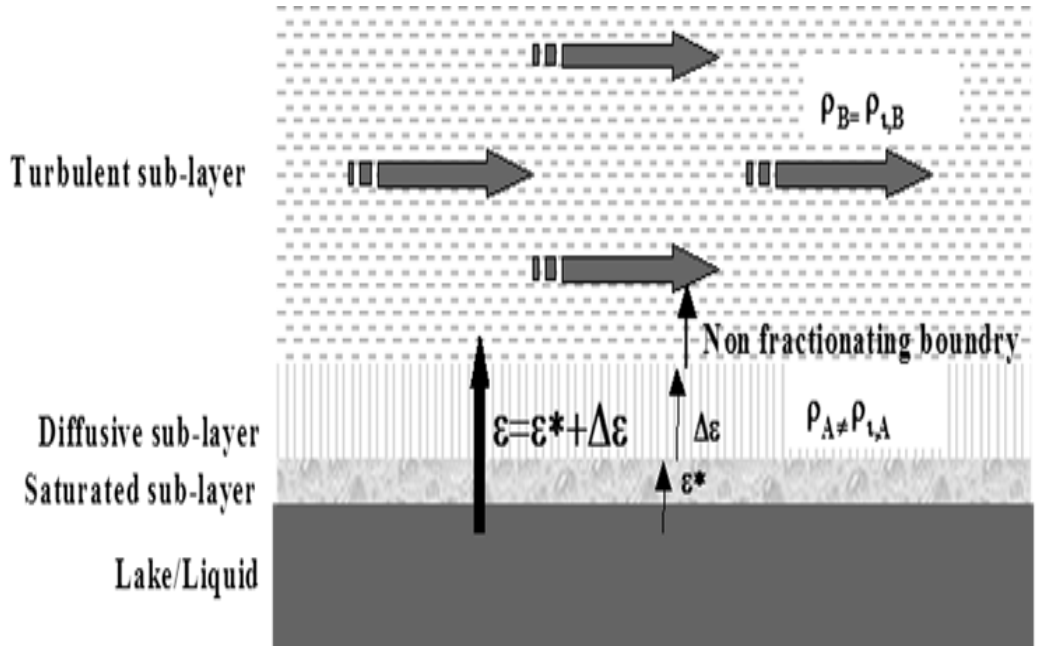

Figure 5-12: A simplified representation of the Craig and Gordon evaporation model.

Where the terms in the bracket (ρ) are the transport resistance of the isotopic species in the diffusive sub-layer "A" and in the turbulent sub layer "B". However the turbulent sub-layer is not fractionating$\left(\frac{\rho_{i,B}}{\rho_B} - \mathbf{1}\right)$ is equals zero.The transport resistance in the diffusive sub layer$\left(\frac{\rho_{i,A}}{\rho_A} - \mathbf{1}\right)$is obtained from the relative differences between the molecular diffusivities of the normal and isotopic species of water in air and is determined to be CK=14.3‰ for $\delta^{18}O$ and 12.5‰ for δD

Therefor

$$\Delta\varepsilon^{18}O = 14.3 * (1-h)‰$$
$$\Delta\varepsilon^{2}H = 12.5 * (1-h)‰$$

Equations 1-4 can be rearranged as follows for lake in hydrologic steady state but not in isotopic steady state.

$$\frac{d\delta}{dt} = -[(\mathbf{1} + \boldsymbol{mx})\boldsymbol{\delta_L} - \boldsymbol{\delta_I} - \boldsymbol{x\delta^*}]\, {}^{\boldsymbol{I}}/_{\boldsymbol{V}} \quad \text{... ... ...Equation 5}$$

$$\text{Where, } m = \frac{h - \varepsilon/1000}{1 - h + \Delta\varepsilon/1000}$$
$$x = E/I,$$

$\delta^* = (h\delta_A + \varepsilon)/(h - 10^{-3}\varepsilon)$; $\delta^*$is the limiting isotopic composition which is the isotopic enrichment value that would be approached by residual waters of a shrinking water body exposed to evaporation.

For lakes with hydrologic steady state but not in isotopic steady state the solution of equation 5 leads to equation 6.

$$\boldsymbol{\delta_L = \delta_{L_{ss}} - (\delta_{L_{ss}} - \delta_o) exp\left[-(1 + mx)\frac{It}{V}\right]} \text{ ... ...Equation 6}$$

Whereas $\delta_{L_{ss}} = \left[\frac{\delta_I + mx\delta^*}{1+mx}\right]$

Or

$$\frac{\boldsymbol{I}}{\boldsymbol{E}} = \frac{\boldsymbol{h}}{\boldsymbol{1-h}}\left(\frac{\boldsymbol{\delta^* - \delta_{Lss}}}{\boldsymbol{\delta_{Lss} - \delta_I}}\right) \text{.....Equation 7}$$

Where, $I=P+R_I + G_I$, which is total inflow to the lake. δ_I is the initial isotopic composition of the inflow water to lake. It is the intersection between the LEL and the LMWL (($\delta^{18}O_I$= -2.5‰ and δD = -5‰)).δ_A& h is used from (Kebede et al., 2002) which is estimated using Lake Horaas terminal index lake.

Precipitation, runoff and evaporation data are used from metrological records. Evaporation at Hawassa station is used and it was recorded using class A pan, pan coefficient of 0.8 is used in order to correct the various effects during evaporation from the pan. Mean monthly and annual runoff to the lake, precipitation and evaporation both from the lake and pan is summarized (Table 6.1).

Table 5-2: Mean monthly pan and lake evaporation

Months	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Ann.
Mean(pp)	27	41	73	104	118	102	124	128	122	82	27	19	969
Mean(Runoff to the lake)	9	7	8	8	10	11	12	13	15	16	13	11	134
Mean pan evap.	196.2	181.4	198.5	162.4	164.1	155.3	131.4	137.1	132.1	154.9	183.2	189.9	1986.4
Lake evap.	156.9	145.1	158.8	129.9	131.3	124.2	105.1	109.7	105.6	123.9	146.5	151.9	1589.1

5.2.2 Isotopic water budget calculations

In the annual isotope enabled lake water balance method, average isotopic values ($\delta^{18}O_{ave}$& $\delta^{2}H_{ave}$) of Lake Hawassa, annual precipitation, annual evaporation and annual runoff from Tikurwuha river at Dato (Table 6.1) used in the isotopic enabled lake water balance to estimate groundwater inflow and out flow. Both $\delta^{18}O$ & $\delta^{2}H$ based isotope water balance is estimated using equation 7.

Using theδ18Owater budget approach, the annual groundwater out flow from the lake and inflow to the lake is calculated as follow:-

$$\frac{I}{E} = \frac{h}{1-h}\left(\frac{\delta^{*} - \delta_{Lss}}{\delta_{Lss} - \delta_{in}}\right)$$

$$\frac{I}{E} = \frac{0.6}{1-0.6}\left(\frac{13.8 - 7.12}{7.12 - -2.5}\right)$$

$$\frac{I}{E} = 1.041, I = 1.041 * E$$

$$\underline{\boldsymbol{I = 1654.11 \text{ mm/mm area of the lake}}}$$

$$I = R_I + P + G_I, \text{ there for} \qquad 1654 = 134 + 969 + G_I$$

$$\boldsymbol{G_I = 551}$$

$$\mathrm{P} + \mathrm{R}_I + \mathrm{G}_I = \mathrm{E} + \mathrm{G}_o$$

$$G_o = {}^{I}/_{E}$$

$$\boldsymbol{G_o = 65}$$

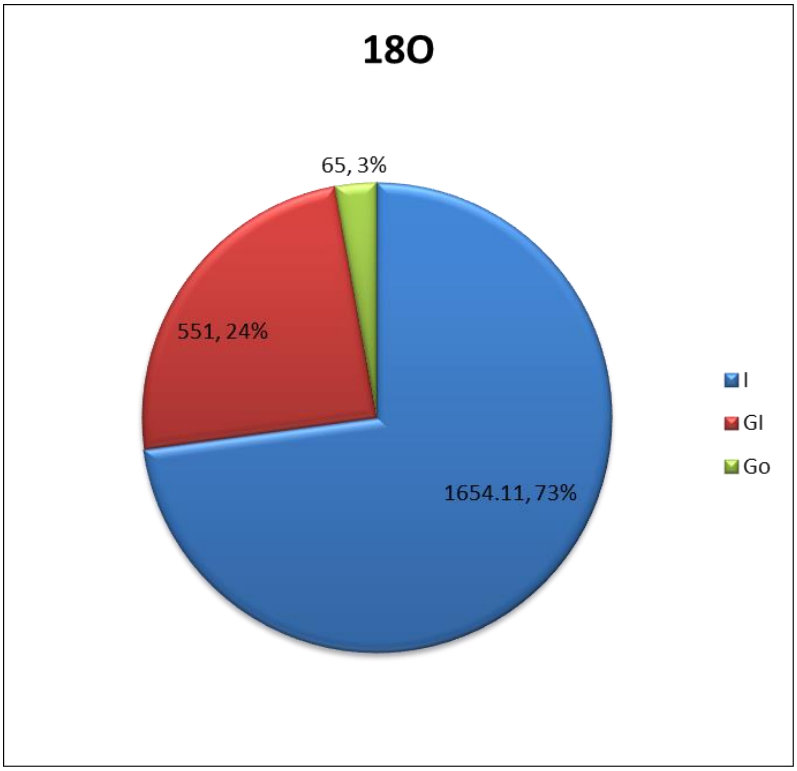

Figure 5-13: Pie diagram showing the distribution of groundwater inflow(I), Outflow (O) and total inflow (I) into the lake using $\delta^{18}O$(‰).

If $\delta^{2}H$ is used instead of $\delta^{18}O$, the annual groundwater inflow to the lake is calculated as follow:-

$$\frac{I}{E} = \frac{h}{1-h}\left(\frac{\delta^* - \delta_{Lss}}{\delta_{Lss} - \delta_{in}}\right)$$

$$\frac{I}{E} = \frac{0.6}{1-0.6}\left(\frac{82 - 46.27}{46.27 - -5}\right)$$

$$\frac{I}{E} = 1.046, \qquad I = 1.046 * E$$

$$\underline{\boldsymbol{I = 1661.48 \text{ mm/mm area of the lake}}}$$

$$I = R_I + P + G_I, \text{ There for } \quad 1661.48 = 134 + 969 + G_I$$

$$\boldsymbol{G_I = 559}$$

$$P + R_I + G_I = E + G_o, \qquad G_o = {}^{I}/_{E}, \qquad G_o = {}^{1661.48}/_{1589}, \quad \boldsymbol{G_o = 72}$$

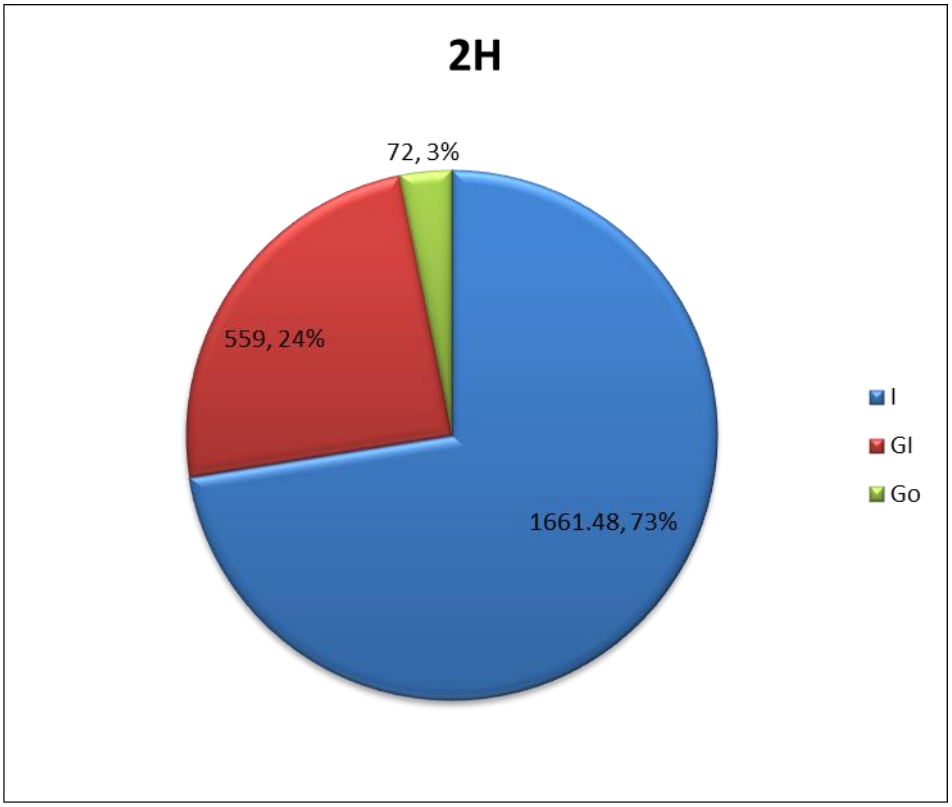

Figure 5-14: Pie diagram showing the distribution of groundwater inflow (I), Outflow (O) and total inflow (I) into the lake using δD(‰)

Using both δD and δ^{18}Otechniques average groundwater out flow from the lake is 3% while the average groundwater inflow is 24%. The dominant outflow and inflow elements are Evaporation and precipitation respectively

Table 5-3: Annual isotope budget of Hawassa Lake using ^{18}O and ^{2}H

Lake	$\delta^{18}O_{ave}$	$\delta^{2}H_{ave}$	E	P	R_I	R_O	I		x or $\left(\frac{E}{I}\right)$		G_I		G_O	
							$\delta^{18}O$	$\delta^{2}H$	$\delta^{18}O$	$\delta^{2}H$	$\delta^{18}O$	$\delta^{2}H$	$\delta^{18}O$	$\delta^{2}H$
Hawassa	7.12	46.27	1589	969	134	0	1654.1	1661.5	0.961	0.957	551 (24%)	559 (24%)	65 (3%)	72 (3%)

Annual isotope budget of Lake Hawassa in mm per unit mm area of the lake, groundwater components are also reported in percentage of total inflow or total water loss.

5.2.3 Tritium (3H)

Since the beginning of atmospheric nuclear testing, large quantities of ^{3}H have been introduced into the atmosphere. In 1954-55, 1958, and 1961-62 large amounts of tritium were released into

the atmosphere. After that Tritium is used as a guide to distinguish between recharge that occurred before atomic weapons testing and more recent recharge.

Tritium is introduced into the hydrologic cycle by both natural and human sources. Atmospheric tritium is formed when cosmic rays bombard nitrogen to yield 3H.This occurs according to the following reaction:

$$^{14}N + n \rightarrow ^{12}C + 3H$$

Where n is a neutron from cosmic radiation. About 3 to 5% of all neutrons in the upper atmosphere react with nitrogen to form 3H.

Tritium concentrations in precipitation have been greatly influenced by atmospheric testing of atomic weapons. Tritium concentration is expressed in units of TU. One TU is a $^{3}H/^{1}H$ ratio equal to 10^{18}atoms of hydrogen. Because most tritium is disseminated in the environment as water, it enters the hydrologic cycle as precipitation and eventually becomes concentrated in levels detectable in groundwater. Tritium atoms then combine with oxygen, forming water that subsequently falls as precipitation.

Because groundwater tritium concentrations reflect atmospheric tritium levels when the water was last in contact with the atmosphere, it can be used to date groundwater recharge. Due to the tritium values vary both spatially and temporally which is not significantly affected by chemical reactions, therefore tritium values in water samples used to know the age of groundwater. Tritium has a half-life of 12.32 years.

Naturally occurring tritium exists in concentrations of about 1-to-5TU prior to atmospheric nuclear bomb testing in the 1950s, tritium's natural average concentrations ranged from approximately 2 to 8 TU. Approximately 1.13 x 109 TU were added in the northern hemisphere from atmospheric nuclear bomb testing with the largest tritium concentrations peaking in 1963. Since cessation of atmospheric nuclear tests, tritium concentrations have dropped to between 12 and 15 TU, although small contributions from nuclear power plants occur (Clark and Fritz,

1997).

Fifteen Water samples were collected during field work and send to Institute of Environmental Assessment and Water Research (IDAEA) of the Spanish Council of Scientific Research (CSIC) at Barcelona for laboratorial analysis.

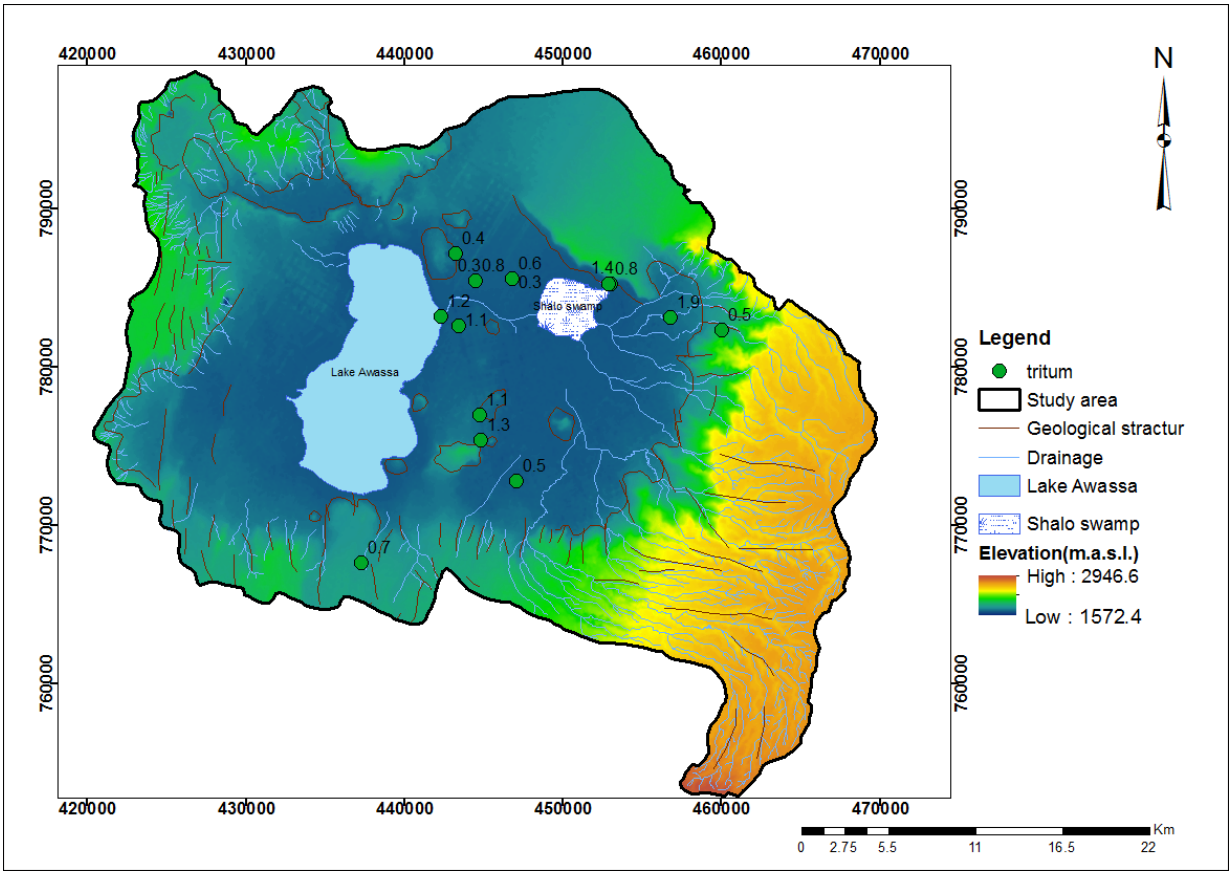

Figure 5-15: Available Tritium data distribution map

Most of the available data were located on the eastern side of the lake (Figure 6.7), the estimation of groundwater residence time using this data only represent limited area only.

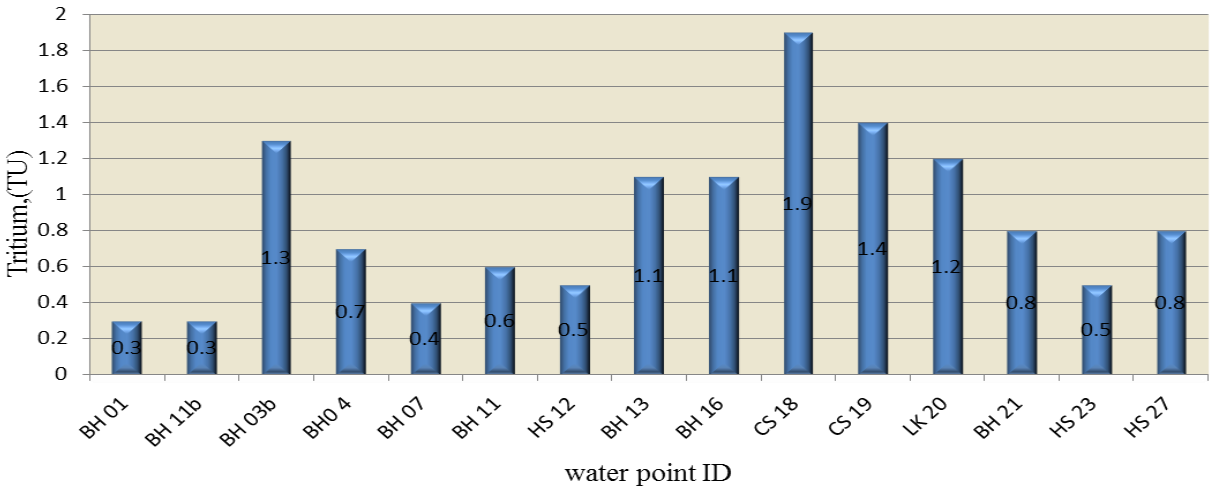

Figure 5-16: Tritium value of the water points

Groundwater age estimation using tritium only provides semi-quantitative, which is based on Mazor (1991) groundwater age classification;

- Water with <0.8 TU indicates a pre-1952 age
- Water with significant tritium concentration in practice >10 TU is of a post -1952 age
- Water with little, but measureable, tritium (0.8-10TU) indicates a mixture of pre-1952 age and post-1952 age.

Most of the water points located in the northeastern part of the lake have tritium value of less than 0.8, which indicate sub modern water (recharged prior to 1950). Out of fifteen water points six water points in the eastern side of the lake have tritium value of 0.8 to 1.9 which indicates a mix of sub modern and modern water. The lower value of tritium (<0.8TU) in boreholes (BH01, BH11b and BH07) which are located in rift floor indicate water that infiltrate pre-1952.

6. Conclusions

Hydrochemical analysis results revealed that there are three water types in the study area. These are: Ca-Na-HCO3, Na-Ca-HCO3 and Na-HCO3 water types.Ca-Na-HCO3 water type is rare in the study area and it is the characteristics of cold springs of the eastern escarpment (wondogent escarpment) and highlands which have low TDS and EC. It is characterized by recharge area waters as an early stage geochemical evolution. Na-Ca-HCO3 water type which is the characteristics of dug wells, Bore holes, cols springs which are located at the foot of eastern escarpment and caldera rims, rivers that drains the eastern escarpment, dug wells and cold springs are characterized by this type of water.Na-HCO3 water type is highly concentrated water types located in the floor of the caldera, with high TDS and EC. It characterizes the discharge zone of the present study area. Thus the hydrochemical analysis result reveals that the groundwater system of the area evolves from Ca-Na-HCO3type to Na-HCO3 water types.

Stable isotope $\delta^{18}O$ and $\delta^{2}H$ results shows there are two types of groundwater flow. Such as:- Local, shallow and fast circulating ground water. This is the characteristic of the eastern escarpment, southeastern and northeastern highlands. It is characterized by low EC and TDS value and with no isotopic fractionation. The other is relatively slow and deep circulating groundwater. It is characterized by high TDS and EC fractionated water which states the strong rock water reaction along flow paths. This flow recharges bore holes and dug wells which are found at floor of the caldera, including Tikur Wuha river and thermal springs around Shallo swamp.

Spatial distribution of stable isotope $\delta^{18}O$ and static water level measurement revealed that flow direction of groundwater is towards the lake except from the northern part of the catchment where lake feed the groundwater outside of the catchment and in the southwestern side the lake the is local water flow away from the lake.

Tritium result identify that the water points in Lake Hawassa catchment have tritium value in between 0.3 to 1.9 showing that they are recharged before 1952 (TU<0.8) and mixture of pre-1952 age and post-1952 age water (0.8-10TU). Thus the tritium value detects that they are recharged both before and after 1952.

Isotope enabled lake water balance revealed the average groundwater inflow to Lake and out flow from Lake Hawassa. The ground inflow is calculated using $\delta^{18}O$ and $\delta^{2}H$, which is to be 24%. While the average groundwater outflow from Lake Hawassa is calculated to be 3% using $\delta^{18}O$ and $\delta^{2}H$. The dominant in flow component to the lake is precipitation, which is 59% of total inflow. While the major out flow component is evaporation which is almost 96 %.

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Annex I: Mean monthly climate data from different stations of the study area

(Source, Ethiopian Metrological agency)

Station	Recorded period	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
		Monthly rain fall data at Hawassa station(mm)											
Hawassa	1972-2013	27.3	39.02	72.98	106.6	120.2	100.8	125.6	120.7	122.9	73.1	33.05	21.85
		Mean monthly sun shine hours data at Hawassa station											
Hawassa	1985-2012	8.6	8.8	7.6	6.8	7.5	6.7	5.0	5.3	5.4	6.3	8.3	8.7
		Mean monthly wind speed data at Awassa station(m/s) at 2m above the ground											
Hawassa	1973-2008	1.0	1.1	1.1	1.1	1.1	1.4	1.2	1.1	1.1	0.8	0.9	1.1
		Mean monthly pan evaporation data at Awassa station(mm)											
Hawassa	1986-2008	196.2	181.4	198.5	162.4	164.1	155.3	131.4	137.1	132.1	154.9	183.2	189.9

Annex II**:** Average Monthly River run off Data (mm)

(Data from EMWE&I, 1980-to-2006 G.C)

Tkur Wuha run off (mm)												
1980	3.0	2.3	2.1	1.9	2.1	2.4	3.4	4.2	5.0	7.0	3.2	1.8
1981	1.4	1.8	4.5	8.0	8.6	7.1	8.4	14.7	18.4	18.6	8.7	5.6
1982	4.3	3.8	4.1	4.9	7.2	7.1	12.6	11.9	14.8	16.7	11.0	9.8
1983	7.0	4.7	4.6	5.2	13.5	16.6	11.2	13.7	16.7	18.4	14.1	10.4
1984	8.4	6.5	5.8	5.2	5.6	7.8	9.4	11.3	12.8	11.6	6.1	5.0
1985	4.3	3.4	3.0	2.1	6.1	9.3	6.7	9.7	15.4	15.2	6.7	4.7
1987	5.2	3.8	5.0	7.7	13.7	14.9	10.6	9.0	12.0	12.2	9.0	7.0
1988	5.9	5.0	5.5	5.3	6.2	7.8	12.1	17.4	18.6	17.9	13.7	10.1
1989	8.9	7.3	7.7	7.6	8.9	12.3	11.2	11.5	13.8	15.9	11.6	9.7
1990	9.2	8.0	12.7	16.8	13.9	10.1	10.0	12.1	12.2	18.4	14.8	8.2
1991	7.2	5.8	5.6	7.8	14.0	8.5	11.7	14.4	15.5	17.2	13.3	10.5
1992	6.8	4.5	4.4	4.8	8.1	9.4	11.0	12.8	18.4	21.8	17.1	10.2
1993	8.0	6.2	5.8	5.3	8.9	13.7	15.8	15.6	16.3	18.4	15.4	14.6
1994	11.0	5.7	5.0	6.2	7.7	9.4	12.5	17.7	18.1	15.0	12.3	11.1
1995	10.0	8.2	5.3	7.2	9.5	11.3	12.6	14.0	15.3	16.4	18.0	19.9
1997	13.5	10.8	11.0	9.6	11.1	11.1	10.7	10.5	10.0	13.3	14.7	16.9
1998	18.1	16.1	13.2	8.0	12.3	17.9	18.6	16.4	16.2	19.7	18.9	19.2
1999	19.0	15.6	17.0	16.3	16.4	14.7	16.9	17.6	17.6	19.3	17.4	15.1
2000	13.2	11.6	5.9	0.0	5.8	11.5	13.6	16.0	16.4	16.0	12.8	12.1
2001	12.1	8.1	8.1	10.4	13.3	14.9	13.9	13.6	13.9	16.4	17.1	15.7
2002	14.5	11.8	12.4	12.7	14.5	15.5	14.5	13.5	13.9	16.4	17.1	15.7
2005	4.5	4.2	12.3	11.7	13.6	15.3	15.9	17.6	18.7	18.7	15.3	14.3
2006	14.1	12.4	12.3	8.7	8.6	8.2	9.7	12.0	14.3	18.2	17.6	15.2

Annex III: Lake Hawassa Level data (m)

(Data from EMWE&I, 1970-to-2008 G.C)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1970	0.8	0.7	0.7	0.7	0.7	0.7	0.7	0.8	1.1	1.4	1.4	1.3
1971	1.1	1.0	0.8	0.8	0.8	0.9	1.1	1.2	1.3	1.5	1.6	1.5
1972	1.4	1.3	1.3	1.2	1.4	1.4	1.5	1.6	1.8	2.0	1.9	1.7
1973	1.6	1.4	1.2	1.1	1.0	1.0	1.0	1.2	1.3	1.3	1.2	1.1
1974	0.9	0.8	0.7	0.7	0.6	0.6	-	-	-	1.1	1.0	0.9
1975	0.7	0.6	0.4	0.4	0.3	0.3	0.3	0.6	0.9	1.1	1.1	1.0
1976	0.8	0.7	0.6	0.5	0.4	0.4	0.4	0.6	0.7	0.9	0.9	0.9
1977	0.8	0.8	0.6	0.6	0.6	0.7	0.8	0.9	1.0	1.3	1.6	1.7
1978	1.6	1.5	1.4	1.4	1.4	1.4	1.5	1.6	1.9	2.2	2.2	2.1
1979	2.0	2.0	1.9	1.9	1.9	1.9	1.9	2.0	2.1	2.3	2.3	2.1
1980	2.0	1.9	1.8	1.6	1.6	1.6	1.5	1.5	1.5	1.6	1.5	1.3
1981	1.2	1.0	0.9	1.0	1.0	1.0	1.0	1.1	1.3	1.5	1.4	1.3
1982	1.2	1.0	1.0	0.9	0.8	0.8	0.9	0.9	1.0	1.1	1.2	1.2
1983	1.1	1.0	0.9	0.8	1.0	1.3	1.4	1.5	1.8	2.1	2.2	2.1
1984	2.0	1.8	1.6	1.5	1.4	1.4	1.4	1.4	1.5	1.5	1.4	1.2
1985	1.1	0.9	0.7	0.7	0.9	0.9	1.0	1.1	1.2	1.3	1.5	1.4
1986	1.1	0.9	0.8	0.8	0.8	0.9	1.1	1.3	1.5	1.7	1.7	1.6
1987	1.4	1.2	1.2	1.2	1.2	1.6	1.7	1.7	1.8	1.9	1.9	1.7
1988	1.6	1.4	1.3	1.2	1.2	1.2	1.2	1.5	1.9	2.2	2.4	2.2
1989	2.1	2.0	1.8	1.8	1.8	1.9	2.0	2.0	2.0	2.2	2.2	2.1
1990	2.0	2.0	2.0	2.1	2.1	2.1	2.1	2.1	2.1	2.2	2.1	1.9
1991	1.8	1.7	1.6	1.6	1.6	1.6	1.6	1.6	1.7	1.7	1.6	1.5
1992	1.3	1.3	1.2	1.1	-	-	1.1	1.2	1.5	1.8	2.0	2.0
1993	1.9	1.9	1.8	1.7	1.8	1.9	2.0	2.0	2.1	2.2	2.3	2.2
1994	2.1	1.9	1.8	1.7	1.7	1.7	1.8	2.1	2.3	2.4	2.3	2.1
1995	2.0	1.8	1.7	1.7	1.7	1.7	1.7	1.7	1.9	2.0	1.9	1.8

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1996	1.7	1.6	1.5	1.5	1.6	1.9	2.3	2.5	2.8	3.1	3.1	2.9
1997	2.7	2.6	2.4	2.4	2.4	2.4	2.5	2.6	2.6	2.8	3.0	3.1
1998	3.1	3.1	3.1	3.1	3.1	3.1	3.1	3.2	3.3	3.6	3.8	3.7
1999	3.5	3.4	3.3	3.2	3.1	3.0	3.0	3.0	3.1	3.2	3.3	3.2
2000	-	-	-	-	2.6	2.5	2.4	2.4	2.4	2.6	2.7	2.6
2001	2.5	2.3	2.2	2.2	2.3	2.4	2.5	2.6	2.8	3.0	3.1	3.0
2002	2.9	2.7	2.6	2.6	2.6	2.6	2.6	2.6	2.7	2.7	2.6	2.5
2003	2.4	2.2	2.1	2.0	2.1	2.1	2.1	-	-	-	-	-
2004	-	-	-	-	1.9	1.8	1.7	1.8	1.9	2.0	2.0	1.9
2005	1.7	1.6	1.6	1.5	1.6	1.8	1.9	2.0	2.0	2.2	2.2	2.0
2006	1.6	1.5	1.4	1.4	-	-	1.9	2.0	2.3	2.5	2.7	2.7
2007	2.5	2.5	2.3	2.3	2.3	2.5	2.6	2.8	3.1	3.4	3.4	3.2
2008	3.0	2.9	2.7	2.5	2.5	2.5	2.6	2.7	2.9	3.0	-	-

Annex IV**:** Hydrochemical data of water points in the study area

units (all in mg/l). Except EC, µs/cm, T-Temperature ^{o}C, Alk-Alkalinity.

ID	Data Source	UTME	UTMN	Na	K	Ca2+	Mg2+	Cl	NO3	CO3	HCO3	AlK
BH01*	Primary data	444859	775359	187.8	15.8	17.7	19.5	21.5	0.0	0.0	683.2	479.0
BH03*	Primary data	444859	775359	190.2	17.2	29.0	17.9	69.8	25.8	0.0	585.6	480.4
BH04*	Primary data	437318	767643	34.9	5.5	15.3	5.1	1.6	1.9	0.0	287.7	236.0
BH06*	Primary data	447018	786149	289.2	20.5	31.6	9.2	41.6	0.3	0.0	1061.4	870.8
BH07*	Primary data	443250	787150	231.2	16.5	28.9	8.0	25.2	0.0	0.0	1004.1	823.8
BH11*	Primary data	*446796*	*785559*	223.7	13.7	13.2	7.7	53.1	1.5	0.0	927.2	760.7
BH13*	Primary data	444763	776932	106.4	8.5	14.4	12.2	24.0	5.0	0.0	835.7	685.6
BH16*	Primary data	443450	782566	292.6	14.4	10.4	1.1	29.9	6.0	0.0	1189.5	975.9
BH17*	Primary data	440120	778876	252.1	17.6	19.8	12.5	51.5	0.0	0.0	457.5	375.3
BH21*	Primary data	*444521*	*785432*	184.7	15.4	18.3	19.8	19.8	0.0	0.0	884.5	725.6
BH22*	Primary data	441805	779461	255.5	18.5	28.4	24.2	52.0	24.2	0.0	933.3	765.7
BH30*	Primary data	444306	777777	162.5	13.6	27.9	20.9	28.4	1.3	0.0	793.0	650.6
CS18*	Primary data	456837	783125	22.1	9.3	7.6	2.3	6.7	8.6	0.0	201.3	165.1
CS19*	Primary data	453032	785244	26.7	5.9	9.2	2.0	7.3	15.5	0.0	192.2	157.6
DW02*	Primary data	432768	772663	458.9	33.3	13.9	5.5	58.7	0.0	0.0	1820.8	1493.8
DW05*	Primary data	432293	775143	179.2	14.6	6.6	1.5	75.0	71.5	0.0	1104.1	-
DW08*	Primary data	433072	775116	304.8	44.5	29.0	11.4	27.7	23.3	0.0	1082.6	888.1
DW10*	Primary data	432674	773396	350.0	40.7	42.8	29.4	148.4	14.0	0.0	1172.0	961.5
DW14*	Primary data	454591	784463	114.7	9.0	18.4	3.9	14.2	11.4	0.0	610.0	500.4
DW24*	Primary data	431677	777136	472.3	32.3	34.0	14.5	164.7	28.1	0.0	1430.3	1173.4
DW25*	Primary data	433725	781971	380.2	12.6	8.2	2.5	56.6	4.9	60.0	1067.5	975.9
DW26*	Primary data	*432627*	*779410*	290.8	22.4	32.6	23.3	164.1	8.9	0.0	1220.0	1000.9
DW28*	Primary data	434465	780844	283.4	35.4	16.0	8.0	67.6	5.6	0.0	1098.0	900.8
HS12*	Primary data	460028	782322	173.5	42.0	11.2	3.6	20.5	0.0	0.0	808.3	905.8
HS23*	Primary data	447095	772805	219.4	17.5	12.7	6.5	35.5	0.0	0.0	683.2	663.1
HS27*	Primary data	452926	785196	392.8	27.2	2.5	0.3	83.0	2.8	0.0	1030.9	560.5

ID	Data Source	UTME	UTMN	Na	K	Ca2+	Mg2+	Cl	NO3	CO3	HCO3	AlK
LK09*	Primary data	436263	781285	177.3	30.6	10.0	6.6	32.8	0.0	150.0	579.5	845.7
LK20*	Primary data	442347	783187	163.6	27.9	9.1	5.9	28.2	0.3	180.0	500.2	725.6
LK29*	Primary data	440028	779166	172.6	30.2	9.8	6.5	32.1	0.0	90.0	640.5	710.6
RV15*	Primary data	448696	782565	248.1	19.0	6.6	1.9	40.9	0.0	0.0	73.2	675.6
BH01	GSE, 2003	454990	794978	142.0	18.0	40.2	5.8	59.0	145.4	59.0	275.0	60.1
BH02	GSE, 2003	443247	787145	218.0	9.2	12.0	2.8	26.0	2.2	14.0	548.0	-
BH03	GSE, 2003	442856	781844	285.0	33.0	29.7	20.62	45.2	0.88	0.0	733.0	-
BH04	GSE, 2003	441848	779460	246.0	16.6	30.0	24	43.0	16	0.0	743.0	-
BH05	GSE, 2003	441401	779904	232.0	20.5	30.0	22	44.0	0.21	0.0	716.0	-
BH06	GSE, 2003	444891	775368	192.0	13.5	26.0	16	53.0	7.3	11.0	534.0	-
BH07	GSE, 2003	444574	773563	77.0	7.2	19.0	9	15.0	10.5	16.0	286.0	-
BH08	GSE, 2003	444086	772115	68.0	10.0	32.0	13	40.0	0.84	65.0	255.0	-
BH09	GSE, 2003	439500	772100	430.0	27.3	22.5	14.24	46.7	10.56	0.0	963.7	-
BH10	GSE, 2003	441362	770748	44.0	7.0	10.0	5	4.0	< .04	11.0	236.0	-
BH11	GSE, 2003	438521	769883	32.0	5.6	10.5	4	5.0	1.7	12.0	134.0	-
BH12	GSE, 2003	439293	763859	49.0	3.3	2.2	0.7	3.0	< .03	0.0	156.0	-
BH13	GSE, 2003	436541	763710	28.5	7.2	12.0	4	5.0	0.27	17.0	137.0	-
BH14	GSE, 2003	429989	763353	37.0	6.0	19.0	4	4.0	< .03	0.0	198.0	-
BH15	GSE, 2003	434404	759498	29.0	9.0	9.0	2.2	3.0	< .03	0.0	132.0	-
BH16	GSE, 2003	438015	759244	23.0	7.0	8.0	2	10.0	15.06	0.0	83.0	-
BH17	GSE, 2003	433187	790548	314.0	12.1	16.6	5.8	23.0	< .04	0.0	889.0	-
BH18	GSE, 2003	426416	778488	278.0	12.5	6.0	1.1	23.0	26.9	0.0	662.0	-
BH19	GSE, 2003	447033	791288	148.0	13.4	24.0	9	26.0	0.14	14.0	477.0	-
BH20	GSE, 2003	430824	773951	338.0	25.0	12.3	3.7	63.0	7.53	0.0	856.0	-
BH21	GSE, 2003	455627	776365	54.0	3.0	33.0	5	6.0	< .03	0.0	272.0	-
BH22	GSE, 2003	456448	775840	16.0	9.0	20.0	5	20.0	33.5	35.0	73.0	-
BH23	GSE, 2003	453503	772256	38.0	13.0	23.0	4	22.0	4.43	0.0	177.0	-
BH24	GSE, 2003	467137	771511	13.0	3.0	9.3	2	5.0	2.66	0.0	85.0	-

ID	Data Source	UTME	UTMN	Na	K	Ca2+	Mg2+	Cl	NO3	CO3	HCO3	AlK
BH25	GSE, 2003	465072	764373	9.3	3.3	6.0	1.3	6.0	1.77	0.0	56.0	-
BH27	GSE, 2003	446991	782483	94.0	11.4	64.6	11.97	42.7	5.72	0.0	374.9	-
BH28	GSE, 2003	442779	781335	300.0	32.8	44.1	8.37	48.7	3.52	0.0	757.1	-
BH30	GSE, 2003	445009	777028	208.0	14.0	26.0	18	40.0	5.2	0.0	639.0	-
BH31	GSE, 2003	443231	775814	8.0	6.0	16.0	4	8.0	2.4	5.0	28.0	-
BH32	GSE, 2003	428480	778614	332.0	9.7	16.0	3.3	48.0	1.3	2.0	778.0	-
BH33	GSE, 2003	429138	776451	280.0	12.9	12.0	12	35.0	0.7	5.0	836.0	-
BH34	GSE, 2003	432817	774293	260.0	43.5	48.0	26	156.0	27.5	11.0	707.0	-
BH35	GSE, 2003	440128	779062	312.0	21.0	26.0	16	54.0	0.67	0.0	887.0	-
BH37	GSE, 2003	437181	756601	13.0	4.0	11.0	1.4	5.0	1.77	0.0	95.0	-
BH38	GSE, 2003	430804	755288	22.0	4.0	9.3	3	3.0	0.44	0.0	112.0	-
BH39	GSE, 2003	435598	752687	16.0	5.0	14.3	2.3	10.0	6.65	0.0	109.0	-
BH40	GSE, 2003	431250	752170	15.0	5.0	11.0	2	3.0	0.89	0.0	104.0	-
BH41	GSE, 2003	431299	747854	16.0	7.0	12.4	2.4	7.0	4.43	0.0	105.0	-
CS01	GSE, 2003	456672	781620	34.0	11.0	8.0	3	8.0	< .03	0.0	92.0	-
CS02	GSE, 2003	458776	781867	22.0	5.3	13.0	4	6.0	1.33	0.0	134.0	-
CS03	GSE, 2003	460084	782090	17.0	5.4	12.0	4	8.0	7.97	0.0	99.0	-
CS04	GSE, 2003	457343	777517	18.0	6.1	22.0	3	7.0	3.1	0.0	92.0	-
CS05	GSE, 2003	458592	776758	24.0	8.0	11.0	4	7.0	6.65	0.0	113.0	-
CS06	GSE, 2003	462037	765283	4.0	2.0	3.0	1	3.0	7.09	0.0	20.0	-
CS07	GSE, 2003	451238	769452	14.0	5.3	17.0	9	6.0	9.75	0.0	149.0	-
CS08	GSE, 2003	445646	770671	0.0	0.0	17.6	11.178	7.5	5.28	0.0	12.2	-
CS09	GSE, 2003	445381	770562	27.2	5.9	14.8	7.12	4.0	9.24	0.0	156.2	-
CS10	GSE, 2003	444676	770823	2.3	5.0	14.0	4	5.0	6.3	32.0	124.0	-
CS11	GSE, 2003	436985	771887	35.5	4.7	8.5	3	5.0	1.2	11.0	131.0	-
CS12	GSE, 2003	443002	760888	7.4	6.4	6.0	1.4	6.0	12.85	0.0	49.0	-
CS13	GSE, 2003	448464	765928	12.0	6.3	8.0	2.2	7.0	13.29	0.0	61.0	-
CS14	GSE, 2003	451888	762462	6.1	4.3	3.3	1	3.0	0.89	0.0	40.0	-

ID	Data Source	UTME	UTMN	Na	K	Ca2+	Mg2+	Cl	NO3	CO3	HCO3	AlK
CS15	GSE, 2003	458388	761450	7.0	6.0	6.0	1.3	5.0	11.08	0.0	46.0	-
CS16	GSE, 2003	459946	758292	6.0	5.0	3.0	1	4.0	3.1	0.0	37.0	-
CS17	GSE, 2003	464996	757168	6.0	6.0	4.0	1	6.0	11.52	0.0	32.0	-
CS18	GSE, 2003	451992	785880	25.0	5.0	9.0	3	7.0	10	0.0	81.0	-
CS19	GSE, 2003	457323	780700	22.0	13.0	18.0	3.5	16.0	20.5	38.0	82.0	-
CS20	GSE, 2003	456608	779956	16.0	8.0	7.0	2.2	6.0	0.68	26.0	73.0	-
CS21	GSE, 2003	455746	788356	40.0	7.0	7.0	2	13.0	69.9	26.0	41.0	-
CS22	GSE, 2003	456186	776054	23.0	17.2	20.0	6	25.0	35.1	21.0	93.0	-
CS23	GSE, 2003	461987	787362	16.0	7.0	22.0	4	9.0	58.8	19.0	59.0	-
CS24	GSE, 2003	461555	786954	10.0	2.3	2.3	1	5.0	9.3	19.0	22.0	-
CS25	GSE, 2003	462876	786900	11.4	5.0	13.4	2	10.0	22.2	2.0	50.0	-
CS26	GSE, 2003	460747	784454	12.0	4.0	10.0	1.8	9.0	7.5	11.0	55.0	-
CS27	GSE, 2003	430472	758306	29.0	6.1	6.0	2	19.0	31.01	0.0	63.0	-
CS28	GSE, 2003	464441	798695	17.0	5.0	11.0	2	9.0	11.4	37.0	65.0	-
CS32	GSE, 2003	438672	750022	13.0	6.0	7.0	2	7.0	5.32	0.0	83.0	-
CS33	GSE, 2003	432014	750919	27.5	10.1	4.7	1.5	9.0	0.89	0.0	104.0	-
DW01	GSE, 2003	453439	791221	69.0	14.0	10.4	2	29.0	43.9	35.0	124.0	-
DW02	GSE, 2003	430456	773897	475.0	24.8	15.0	7.5	163.0	61.5	4.0	931.0	-
DW03	GSE, 2003	433918	771026	123.0	10.6	23.0	8	12.0	2.9	7.0	410.0	-
DW04	GSE, 2003	434741	771816	420.0	34.0	87.5	30	161.0	10.6	28.0	1262.0	-
DW05	GSE, 2003	424724	764354	30.0	28.0	24.0	6	15.0	< .03	0.0	218.0	-
DW06	GSE, 2003	441086	778907	375.0	30.0	13.0	23	66.0	0.14	0.0	858.0	-
DW07	GSE, 2003	441823	779103	264.0	17.8	32.0	28	69.0	78	0.0	699.0	-
DW08	GSE, 2003	443037	782227	328.0	9.4	18.0	2	49.0	20	0.0	755.0	-
DW09	GSE, 2003	443282	783063	144.0	29.0	66.0	18	30.0	0.14	0.0	562.0	-
DW10	GSE, 2003	443429	783712	328.0	20.0	12.0	6	30.0	8.2	0.0	775.0	-
DW11	GSE, 2003	442636	785021	398.0	25.0	4.0	2	61.0	0.53	0.0	928.0	-
DW12	GSE, 2003	457004	779044	19.0	10.4	8.0	2	8.0	8.86	0.0	92.0	-

ID	Data Source	UTME	UTMN	Na	K	Ca2+	Mg2+	Cl	NO3	CO3	HCO3	AlK
DW13	GSE, 2003	431531	783983	304.0	10.3	8.0	2.1	37.0	4.7	22.0	713.0	-
DW14	GSE, 2003	432378	783143	338.0	11.2	4.2	0.5	43.0	3.99	0.0	832.0	-
DW15	GSE, 2003	454686	775165	25.0	14.0	15.0	3	7.0	3.99	0.0	140.0	-
DW16	GSE, 2003	431880	779484	417.5	9.9	10.0	1.3	77.0	3.2	18.0	1030.0	-
DW17	GSE, 2003	452000	773211	94.0	15.2	56.0	10	28.0	0.89	0.0	464.0	-
DW18	GSE, 2003	429445	777840	350.0	14.8	8.0	1.2	59.0	4.7	14.0	852.0	-
DW19	GSE, 2003	431402	778053	324.0	10.5	10.8	2.9	48.0	0.44	0.0	834.0	-
DW20	GSE, 2003	428165	777563	352.0	19.8	9.1	3.9	40.0	2.22	0.0	908.0	-
DW21	GSE, 2003	431664	770968	280.0	15.1	20.0	20	39.0	3.5	10.0	859.0	-
DW22	GSE, 2003	439509	772724	354.0	33.0	18.0	6	51.0	2.9	11.0	949.0	-
DW23	GSE, 2003	455612	782890	26.0	11.0	14.0	3	14.0	1.77	0.0	104.0	-
DW24	GSE, 2003	440863	774376	268.0	47.0	12.0	6	38.0	0.19	5.0	748.0	-
DW25	GSE, 2003	446254	779830	236.0	20.0	26.0	10	7.0	14.9	18.0	697.0	-
DW26	GSE, 2003	457255	782872	33.0	9.0	9.0	2	10.0	18.3	39.0	107.0	-
DW27	GSE, 2003	442601	783759	288.0	34.5	30.0	10	103.0	128.1	11.0	574.0	-
DW28	GSE, 2003	430971	782021	310.0	12.9	10.0	3.2	48.0	6.8	23.0	728.0	-
DW29	GSE, 2003	429591	782050	348.0	20.9	8.0	0.8	36.0	2.5	26.0	919.0	-
DW30	GSE, 2003	432993	781279	470.0	29.0	7.5	2	70.0	2.6	0.0	1032.0	-
DW31	GSE, 2003	452744	772218	69.0	30.0	46.0	8	21.0	0.16	39.0	331.0	-
DW32	GSE, 2003	426882	778994	286.0	12.8	20.0	4	37.0	2.8	25.0	795.0	-
DW33	GSE, 2003	427283	777249	292.0	15.4	20.0	4	38.0	4.3	32.0	745.0	-
DW34	GSE, 2003	427174	774333	282.0	15.2	12.0	6	37.0	3.1	21.0	723.0	-
DW35	GSE, 2003	430975	774571	318.0	21.0	10.0	10	39.0	6.1	7.0	900.0	-
DW36	GSE, 2003	418913	767227	69.0	29.0	14.0	2.3	13.0	6.2	0.0	224.0	-
DW47	GSE, 2003	434955	748998	12.0	8.0	12.0	0.6	3.0	2.66	0.0	107.0	-
HW01	GSE, 2003	443985	782246	204.0	7.5	8.0	4	33.0	0.69	0.0	562.0	-
HW02	GSE, 2003	444116	779738	164.0	10.8	28.0	14	24.0	1.1	0.0	554.0	-
HW03	GSE, 2003	444066	779743	150.0	9.0	18.0	9	23.0	0.89	0.0	493.0	-

ID	Data Source	UTME	UTMN	Na	K	Ca2+	Mg2+	Cl	NO3	CO3	HCO3	AlK
HW04	GSE, 2003	444530	777465	178.0	13.5	4.0	24	33.0	2.8	0.0	630.0	-
HW05	GSE, 2003	443874	779764	184.0	11.2	14.0	24	25.0	1	0.0	580.0	-
HW06	GSE, 2003	437301	799860	1125.0	50.0	5.0	0.7	72.0	3	0.0	2440.0	-
HW07	GSE, 2003	431499	799258	1250.0	73.0	3.0	0.2	241.0	7.6	0.0	1421.0	-
HW08	GSE, 2003	441112	792579	1117.0	60.0	4.0	0.4	548.0	3.3	0.0	1708.0	-
LK01	GSE, 2003	439731	778581	152.0	25.0	11.0	6	28.0	1.5	0.0	373.0	-
LK02	GSE, 2003	441388	785594	151.0	25.4	10.0	5	29.0	3.1	0.0	412.0	-
LK03	GSE, 2003	432893	778614	157.0	30.0	10.0	5	32.0	4.9	7.0	364.0	-
LK04	GSE, 2003	436137	783475	158.0	3.1	10.0	5	30.0	5.8	18.0	400.0	-
LK05	GSE, 2003	439907	779806	150.0	23.8	9.0	6	30.0	2.8	0.0	363.0	-
LK06	GSE, 2003	441060	779619	151.0	25.0	10.0	6	33.0	3.3	0.0	414.0	-
TS01	GSE, 2003	452526	785341	450.0	27.0	5.0	0.1	93.0	0 .04	0.0	778.0	-
TS02	GSE, 2003	456965	786018	740.0	40.0	34.0	5	156.0	<0.04	0.0	1553.0	-
TS03	GSE, 2003	459944	782463	182.0	41.0	6.0	3	26.0	0.74	11.0	564.0	-
TS04	GSE, 2003	460642	781786	170.0	42.0	11.0	4	25.0	1.33	0.0	541.0	-
TS05	GSE, 2003	447156	772809	196.0	15.0	8.0	5	38.0	0.19	171.0	467.0	-
TS07	GSE, 2003	447189	772574	380.0	25.0	10.0	3.1	60.0	0.12	44.0	854.0	-
TS08	GSE, 2003	432212	746480	57.0	6.0	4.0	1.4	6.0	0.44	0.0	211.0	-

Id	Data Source	X	Y	Z	DATE	pH	COND	TDS	T
BH01	GSE,2003	454990	794978	1879	Jan-Mar,99	6.9	965.0	579.0	-
BH02	GSE,2003	443247	787145	1751	Jan-Mar,99	7.7	1006.0	603.6	-
BH03	GSE,2003	442856	781844	-	26/10/98	-	1284.0	770.4	-
BH04	GSE,2003	441848	779460	1756	22/10/98	7.7	1215.0	729.0	-
BH05	GSE,2003	441401	779904	1733	26/10/98	7.6	1228.0	736.8	-
BH06	GSE,2003	444891	775368	1736	Jan-Mar,99	7.5	1076.0	645.6	-
BH07	GSE,2003	444574	773563	1658	Jan-Mar,99	7.0	518.0	310.8	-
BH08	GSE,2003	444086	772115	1674	Jan-Mar,99	6.5	587.0	352.2	-
BH09	GSE,2003	439500	772100	-	22/10/98	6.5	1623.0	973.8	-
BH10	GSE,2003	441362	770748	1873	Jan-Mar,99	7.0	285.0	171.0	-
BH11	GSE,2003	438521	769883	1887	Jan-Mar,99	6.8	239.0	143.4	-
BH12	GSE,2003	439293	763859	1891	Jan-Mar,99	6.9	227.0	136.2	-
BH13	GSE,2003	436541	763710	1970	Jan-Mar,99	6.5	233.0	139.8	-
BH14	GSE,2003	429989	763353	1957	Jan-Mar,99	6.7	306.0	183.6	-
BH15	GSE,2003	434404	759498	1871	Jan-Mar,99	6.4	217.0	130.2	-
BH16	GSE,2003	438015	759244	2288	Jan-Mar,99	6.1	188.0	112.8	-
BH17	GSE,2003	433187	790548	1720	Jan-Mar,99	7.8	1380.0	828.0	-
BH18	GSE,2003	426416	778488	1805	Jan-Mar,99	8.0	1228.0	736.8	-
BH19	GSE,2003	447033	791288	1751	Jan-Mar,99	7.7	811.0	486.6	-
BH20	GSE,2003	430824	773951	1732	Jan-Mar,99	7.8	1493.0	895.8	-
BH21	GSE,2003	455627	776365	1749	Jan-Mar,99	7.8	432.0	259.2	-
BH22	GSE,2003	456448	775840	1779	Jan-Mar,99	6.0	241.0	144.6	-
BH23	GSE,2003	453503	772256	1679	Jan-Mar,99	6.5	369.0	221.4	-
BH24	GSE,2003	467137	771511	2696	Jan-Mar,99	6.2	131.0	78.6	-
BH25	GSE,2003	465072	764373	2772	Jan-Mar,99	6.2	94.0	56.4	-
BH26	GSE,2003	445000	790500	1740	23/01/01	-	1054.0	632.4	-
BH27	GSE,2003	446991	782483	1751	19/10/98	-	760.0	456.0	-
BH28	GSE,2003	442779	781335	1732	19/10/98	-	1310.0	786.0	-

Id	Data Source	X	Y	Z	DATE	pH	COND	TDS	T
BH30	GSE,2003	445009	777028	1730	19/10/98	7.6	1091.0	654.6	-
BH31	GSE,2003	443231	775814	1750	Jan-Mar,99	6.6	118.0	70.8	-
BH32	GSE,2003	428480	778614	1779	Jan-Mar,99	7.7	1507.0	904.2	-
BH33	GSE,2003	429138	776451	1703	Jan-Mar,99	7.6	1302.0	781.2	-
BH34	GSE,2003	432817	774293	1771	Jan-Mar,99	7.4	1684.0	1010.4	-
BH35	GSE,2003	440128	779062	1906	Jan-Mar,99	7.6	1400.0	840.0	-
BH36	GSE,2003	437015	767515	1856	Jan-Mar,99	-	276.0	165.6	-
BH37	GSE,2003	437181	756601	1826	Jan-Mar,99	6.2	148.0	88.8	-
BH38	GSE,2003	430804	755288	1787	Jan-Mar,99	6.3	179.0	107.4	-
BH39	GSE,2003	435598	752687	1654	Jan-Mar,99	6.2	193.0	115.8	-
BH40	GSE,2003	431250	752170	1800	Jan-Mar,99	6.3	163.0	97.8	-
BH41	GSE,2003	431299	747854	1637	Jan-Mar,99	6.4	181.0	108.6	-
BH42	GSE,2003	432260	775132	1725	Jan-Mar,99	7.9	1666.0	999.6	-
BH43	GSE,2003	451782	771715	1807	Jan-Mar,99	6.4	508.0	304.8	-
BH44	GSE,2003	443604	772002	1714	Jan-Mar,99	7.2	463.0	277.8	-
BH45	GSE,2003	442048	765113	1954	Jan-Mar,99	6.1	207.0	124.2	-
BH46	GSE,2003	436390	762120	1981	Jan-Mar,99	6.2	229.0	137.4	-
BH50	GSE,2003	428005	779498	1709	Jan-Mar,99	7.8	1288.0	772.8	-
CS01	GSE,2003	456672	781620	1702	Jan-Mar,99	6.3	234.0	140.4	-
CS02	GSE,2003	458776	781867	1925	Jan-Mar,99	7.8	212.0	127.2	-
CS03	GSE,2003	460084	782090	1797	Jan-Mar,99	6.3	191.0	114.6	-
CS04	GSE,2003	457343	777517	1717	28/01/99	6.2	164.0	98.4	-
CS05	GSE,2003	458592	776758	1781	21/10/98	6.3	208.0	124.8	-
CS06	GSE,2003	462037	765283	2436	28/01/99	5.3	48.0	28.8	-
CS07	GSE,2003	451238	769452	1667	21/10/98	6.6	242.0	145.2	-
CS08	GSE,2003	445646	770671	1740	28/01/99	6.8	274.0	164.4	-
CS09	GSE,2003	445381	770562	1740	21/10/98	-	235.0	141.0	-
CS10	GSE,2003	444676	770823	1729	Jan-Mar,99	6.4	218.0	130.8	-

Id	Data Source	X	Y	Z	DATE	pH	COND	TDS	T
CS11	GSE,2003	436985	771887	1710	Jan-Mar,99	6.8	228.0	136.8	-
CS12	GSE,2003	443002	760888	1859	Jan-Mar,99	5.8	107.0	64.2	-
CS13	GSE,2003	448464	765928	1918	Jan-Mar,99	5.8	142.0	85.2	-
CS14	GSE,2003	451888	762462	2195	Jan-Mar,99	5.9	68.0	40.8	-
CS15	GSE,2003	458388	761450	2672	Jan-Mar,99	5.3	98.0	58.8	-
CS16	GSE,2003	459946	758292	2626	Jan-Mar,99	5.7	65.0	39.0	-
CS17	GSE,2003	464996	757168	2657	Jan-Mar,99	5.7	79.0	47.4	-
CS18	GSE,2003	451992	785880	1730	Jan-Mar,99	6.2	181.0	108.6	-
CS19	GSE,2003	457323	780700	1678	Jan-Mar,99	6.0	275.0	165.0	-
CS20	GSE,2003	456608	779956	1785	Jan-Mar,99	6.3	143.0	85.8	-
CS21	GSE,2003	455746	788356	1906	Jan-Mar,99	6.0	264.0	158.4	-
CS22	GSE,2003	456186	776054	1639	Jan-Mar,99	6.3	334.0	200.4	-
CS23	GSE,2003	461987	787362	2200	Jan-Mar,99	6.0	254.0	152.4	-
CS24	GSE,2003	461555	786954	2180	Jan-Mar,99	6.1	76.0	45.6	-
CS25	GSE,2003	462876	786900	2075	Jan-Mar,99	5.6	157.0	94.2	-
CS26	GSE,2003	460747	784454	1642	Jan-Mar,99	6.4	135.0	81.0	-
CS27	GSE,2003	430472	758306	2101	Jan-Mar,99	5.8	205.0	123.0	-
CS28	GSE,2003	464441	798695	2000	Jan-Mar,99	6.1	163.0	97.8	-
CS29	GSE,2003	457122	779857	1704	Jan-Mar,99	6.0	162.0	97.2	-
CS30	GSE,2003	450872	786000	1787	Jan-Mar,99	6.2	175.0	105.0	-
Cs31	GSE,2003	458852	757314	2729	Jan-Mar,99	-	100.0	60.0	-
CS32	GSE,2003	438672	750022	1842	Jan-Mar,99	5.9	127.0	76.2	-
CS33	GSE,2003	432014	750919	1720	Jan-Mar,99	6.1	185.0	111.0	-
CS34	GSE,2003	462973	788008	e	Jan-Mar,99	5.6	125.0	75.0	-
DW01	GSE,2003	453439	791221	1810	Jan-Mar,99	6.5	436.0	261.6	-
DW02	GSE,2003	430456	773897	1820	Jan-Mar,99	7.7	2186.0	1311.6	-
DW03	GSE,2003	433918	771026	1812	Jan-Mar,99	7.6	711.0	426.6	-
DW04	GSE,2003	434741	771816	1641	Jan-Mar,99	-	2395.0	1437.0	-

Id	Data Source	X	Y	Z	DATE	pH	COND	TDS	T
DW05	GSE,2003	424724	764354	1978	Jan-Mar,99	6.4	387.0	232.2	-
DW06	GSE,2003	441086	778907	1906	Jan-Mar,99	7.8	1654.0	992.4	-
DW07	GSE,2003	441823	779103	1721	Jan-Mar,99	7.9	1438.0	862.8	-
DW08	GSE,2003	443037	782227	1779	Jan-Mar,99	7.8	1318.0	790.8	-
DW09	GSE,2003	443282	783063	1747	Jan-Mar,99	7.4	1039.0	623.4	-
DW10	GSE,2003	443429	783712	1705	Jan-Mar,99	8.0	1389.0	833.4	-
DW100	GSE,2003	432711	772903	1789	Jan-Mar,99	-	1502.0	901.2	-
DW101	GSE,2003	431403	772484	1808	Jan-Mar,99	-	1698.0	1018.8	-
DW102	GSE,2003	432624	772601	1725	Jan-Mar,99	-	1349.0	809.4	-
DW103	GSE,2003	432372	771160	1758	Jan-Mar,99	-	1438.0	862.8	-
DW104	GSE,2003	432412	771608	1789	Jan-Mar,99	7.5	1416.0	849.6	-
DW11	GSE,2003	442636	785021	1785	Jan-Mar,99	8.1	1632.0	979.2	-
DW12	GSE,2003	457004	779044	1717	Jan-Mar,99	6.3	182.0	109.2	-
DW13	GSE,2003	431531	783983	1797	Jan-Mar,99	7.9	1308.0	784.8	-
DW14	GSE,2003	432378	783143	1790	Jan-Mar,99	8.1	1416.0	849.6	-
DW15	GSE,2003	454686	775165	1778	Jan-Mar,99	6.5	254.0	152.4	-
DW16	GSE,2003	431880	779484	1584	Jan-Mar,99	7.9	1763.0	1057.8	-
DW17	GSE,2003	452000	773211	1686	Jan-Mar,99	6.7	784.0	470.4	-
DW18	GSE,2003	429445	777840	1819	Jan-Mar,99	7.8	1514.0	908.4	-
DW19	GSE,2003	431402	778053	1728	Jan-Mar,99	7.9	1403.0	841.8	-
DW20	GSE,2003	428165	777563	1757	Jan-Mar,99	7.8	1463.0	877.8	-
DW21	GSE,2003	431664	770968	1849	Jan-Mar,99	7.7	1406.0	843.6	-
DW22	GSE,2003	439509	772724	1830	Jan-Mar,99	7.7	1597.0	958.2	-
DW23	GSE,2003	455612	782890	1742	Jan-Mar,99	6.2	211.0	126.6	-
DW24	GSE,2003	440863	774376	1654	Jan-Mar,99	-	1299.0	779.4	-
DW25	GSE,2003	446254	779830	1654	Jan-Mar,99	7.6	1140.0	684.0	-
DW26	GSE,2003	457255	782872	1678	Jan-Mar,99	6.2	240.0	144.0	-
DW27	GSE,2003	442601	783759	1741	Jan-Mar,99	7.5	1558.0	934.8	-

Id	Data Source	X	Y	Z	DATE	pH	COND	TDS	T
DW28	GSE,2003	430971	782021	1821	Jan-Mar,99	8.2	1373.0	823.8	-
DW29	GSE,2003	429591	782050	1672	Jan-Mar,99	7.7	1447.0	868.2	-
DW30	GSE,2003	432993	781279	1634	Jan-Mar,99	8.1	2033.0	1219.8	-
DW31	GSE,2003	452744	772218	1740	Jan-Mar,99	6.8	613.0	367.8	-
DW32	GSE,2003	426882	778994	1697	Jan-Mar,99	7.6	1317.0	790.2	-
DW33	GSE,2003	427283	777249	1683	Jan-Mar,99	7.8	1379.0	827.4	-
DW34	GSE,2003	427174	774333	1667	Jan-Mar,99	7.9	1313.0	787.8	-
DW35	GSE,2003	430975	774571	1712	Jan-Mar,99	7.9	1445.0	867.0	-
DW36	GSE,2003	418913	767227	2037	Jan-Mar,99	6.7	412.0	247.2	-
DW37	GSE,2003	440309	773630	1739	Jan-Mar,99	-	1580.0	948.0	-
DW38	GSE,2003	443109	784770	1683	26/05/99	7.5	1397.0	838.2	-
DW39	GSE,2003	431993	783459	1654	Jan-Mar,99	8.3	1674.0	1004.4	-
DW40	GSE,2003	433423	780608	1701	Jan-Mar,99	7.3	1345.0	807.0	-
DW41	GSE,2003	427183	779130	1723	Jan-Mar,99	7.5	1338.0	802.8	-
DW42	GSE,2003	430913	773875	1664	Jan-Mar,99	-	1427.0	856.2	-
DW43	GSE,2003	444548	772363	1713	Jan-Mar,99	-	1731.0	1038.6	-
DW44	GSE,2003	433570	771611	1695	Jan-Mar,99	-	1102.0	661.2	-
DW45	GSE,2003	434311	772260	1691	Jan-Mar,99	-	1432.0	859.2	-
DW46	GSE,2003	434660	771641	1800	Jan-Mar,99	-	1851.0	1110.6	-
DW47	GSE,2003	434955	748998	1834	Jan-Mar,99	6.4	150.0	90.0	-
DW48	GSE,2003	444150	772378	1679	Jan-Mar,99	-	-	390.6	-
DW49	GSE,2003	440552	773898	1722	Jan-Mar,99	-	1845.0	1107.0	-
DW50	GSE,2003	446491	779985	1739	Jan-Mar,99	7.4	948.0	568.8	-
DW51	GSE,2003	446613	780138	1689	Jan-Mar,99	6.8	601.0	360.6	-
DW52	GSE,2003	446680	780045	1776	Jan-Mar,99	6.4	538.0	322.8	-
DW53	GSE,2003	432620	784668	1750	Jan-Mar,99	8.3	1879.0	1127.4	-
DW54	GSE,2003	432536	784018	1734	Jan-Mar,99	8.0	1408.0	844.8	-
DW55	GSE,2003	431477	783714	1680	Jan-Mar,99	8.4	1535.0	921.0	-

Id	Data Source	X	Y	Z	DATE	pH	COND	TDS	T
DW56	GSE,2003	432075	783018	1692	Jan-Mar,99	8.7	1830.0	1098.0	-
DW57	GSE,2003	432406	782659	1653	Jan-Mar,99	8.0	1392.0	835.2	-
DW58	GSE,2003	430998	782774	1791	Jan-Mar,99	8.0	1400.0	840.0	-
DW59	GSE,2003	430956	782315	1553	Jan-Mar,99	8.3	1379.0	827.4	-
DW60	GSE,2003	430529	782142	1675	Jan-Mar,99	8.1	1509.0	905.4	-
DW61	GSE,2003	430731	782009	1707	Jan-Mar,99	8.3	1528.0	916.8	-
DW62	GSE,2003	430375	781765	1733	Jan-Mar,99	7.8	-	-	-
DW63	GSE,2003	430410	781467	1747	Jan-Mar,99	7.7	1258.0	754.8	-
DW64	GSE,2003	429478	781478	1681	Jan-Mar,99	7.6	1298.0	778.8	-
DW65	GSE,2003	428612	780588	1686	Jan-Mar,99	7.5	1300.0	780.0	-
DW66	GSE,2003	428306	780169	1715	Jan-Mar,99	7.6	1296.0	777.6	-
DW67	GSE,2003	430088	780825	1704	Jan-Mar,99	7.6	1264.0	758.4	-
DW68	GSE,2003	430198	780570	1675	Jan-Mar,99	8.0	1268.0	760.8	-
DW69	GSE,2003	429758	780199	1733	Jan-Mar,99	8.0	1501.0	900.6	-
DW70	GSE,2003	430696	780007	1740	Jan-Mar,99	7.9	1336.0	801.6	-
DW71	GSE,2003	430965	779740	1778	Jan-Mar,99	7.9	1382.0	829.2	-
DW72	GSE,2003	432145	779754	1692	Jan-Mar,99	8.2	1805.0	1083.0	-
DW73	GSE,2003	432521	780543	1698	Jan-Mar,99	8.1	1941.0	1164.6	-
DW74	GSE,2003	427432	779971	1781	Jan-Mar,99	7.7	1277.0	766.2	-
DW75	GSE,2003	427268	779411	1772	Jan-Mar,99	7.7	1369.0	821.4	-
DW76	GSE,2003	427541	778898	1685	Jan-Mar,99	7.6	1877.0	1126.2	-
DW77	GSE,2003	428560	779178	1665	Jan-Mar,99	7.8	1270.0	762.0	-
DW78	GSE,2003	429692	778408	1713	Jan-Mar,99	7.7	1348.0	808.8	-
DW79	GSE,2003	431200	778623	1767	Jan-Mar,99	7.5	1335.0	801.0	-
DW80	GSE,2003	432798	778773	1714	Jan-Mar,99	7.6	2170.0	1302.0	-
DW81	GSE,2003	431168	776853	1696	Jan-Mar,99	7.7	1733.0	1039.8	-
DW82	GSE,2003	427218	777861	1760	Jan-Mar,99	7.9	1270.0	762.0	-
DW83	GSE,2003	428100	777504	1689	Jan-Mar,99	7.8	1370.0	822.0	-

Id	Data Source	X	Y	Z	DATE	pH	COND	TDS	T
DW84	GSE,2003	427711	776890	1691	Jan-Mar,99	-	1486.0	891.6	-
DW85	GSE,2003	428121	776214	1667	Jan-Mar,99	-	1310.0	786.0	-
DW86	GSE,2003	425860	776414	1703	Jan-Mar,99	-	1254.0	752.4	-
DW87	GSE,2003	426522	775674	1779	Jan-Mar,99	7.7	1251.0	750.6	-
DW88	GSE,2003	427246	775828	1638	Jan-Mar,99	-	1312.0	787.2	-
DW89	GSE,2003	427624	775138	1720	Jan-Mar,99	-	1290.0	774.0	-
DW90	GSE,2003	427735	774855	1667	Jan-Mar,99	-	1073.0	643.8	-
DW91	GSE,2003	426694	774354	1813	Jan-Mar,99	-	1482.0	889.2	-
DW92	GSE,2003	430850	775335	1708	Jan-Mar,99	-	1348.0	808.8	-
DW93	GSE,2003	430246	774579	1637	Jan-Mar,99	-	1397.0	838.2	-
DW94	GSE,2003	430235	774200	1784	Jan-Mar,99	-	1905.0	1143.0	-
DW95	GSE,2003	430321	773839	1716	Jan-Mar,99	-	1963.0	1177.8	-
DW96	GSE,2003	445875	772111	1907	Jan-Mar,99	-	955.0	573.0	-
DW97	GSE,2003	430831	773955	1746	Jan-Mar,99	-	1450.0	870.0	-
DW98	GSE,2003	431131	773715	1630	Jan-Mar,99	-	1481.0	888.6	-
DW99	GSE,2003	432440	773051	1726	Jan-Mar,99	-	1594.0	956.4	-
HW01	GSE,2003	443985	782246	1727	Jan-Mar,99	7.8	907.0	544.2	-
HW02	GSE,2003	444116	779738	1712	Jan-Mar,99	7.7	872.0	523.2	-
HW03	GSE,2003	444066	779743	1779	Jan-Mar,99	7.6	792.0	475.2	-
HW04	GSE,2003	444530	777465	1754	Jan-Mar,99	7.1	1025.0	615.0	-
HW05	GSE,2003	443874	779764	1711	Jan-Mar,99	7.9	931.0	558.6	-
HW06	GSE,2003	437301	799860	1750	17/02/87	8.0	3730.0	2238.0	-
HW07	GSE,2003	431499	799258	1783	23/06/87	9.4	3410.0	2046.0	-
HW08	GSE,2003	441112	792579	1797	23/06/87	8.0	3040.0	1824.0	-
LK01	GSE,2003	439731	778581	1686	Jan-Mar,99	9.0	778.0	466.8	-
LK02	GSE,2003	441388	785594	1683	Jan-Mar,99	9.0	789.0	473.4	-
LK03	GSE,2003	432893	778614	1747	Jan-Mar,99	8.8	807.0	484.2	-
LK04	GSE,2003	436137	783475	1728	Jan-Mar,99	8.6	800.0	480.0	-

Id	Data Source	X	Y	Z	DATE	pH	COND	TDS	T
LK05	GSE,2003	439907	779806	1763	Jan-Mar,99	9.0	787.0	472.2	-
LK06	GSE,2003	441060	779619	1761	Jan-Mar,99	8.8	776.0	465.6	-
LK07	GSE,2003	432362	778049	1695	17/02/87	8.6	809.0	485.4	-
LK12	GSE,2003	442552	783488	0	23/06/87	8.7	801.0	480.6	-
LK13	GSE,2003	439922	778929	1708	23/06/87	8.9	828.0	496.8	-
LK14	GSE,2003	435118	772381	1664	23/06/88	8.6	659.0	395.4	-
LK15	GSE,2003	433408	779920	1698	Jan-Mar,99	-	798.0	478.8	-
LK16	GSE,2003	436266	787404	1624	Jan-Mar,99	8.7	785.0	471.0	-
LK17	GSE,2003	438572	773780	1752	Jan-Mar,99	-	787.0	472.2	-
LK18	GSE,2003	433403	773660	1793	Jan-Mar,99	-	967.0	580.2	-
TS01	GSE,2003	452526	785341	1733	Jan-Mar,99	8.8	1964.0	1178.4	-
TS02	GSE,2003	456965	786018	2532	Jan-Mar,99	6.4	2826.0	1695.6	-
TS03	GSE,2003	459944	782463	1929	Jan-Mar,99	7.7	965.0	579.0	-
TS04	GSE,2003	460642	781786	1710	Jan-Mar,99	8.0	903.0	541.8	-
TS05	GSE,2003	447156	772809	1707	Jan-Mar,99	5.8	970.0	582.0	-
TS07	GSE,2003	447189	772574	1724	Jan-Mar,99	6.8	1708.0	1024.8	-
TS08	GSE,2003	432212	746480	1893	Mar-14	6.9	286.0	171.6	-
DW02*	Primary data	432768	772663	1712	Mar-14	8.2	2170.0	-	-
DW24*	Primary data	431677	777136	1717	Mar-14	7.9	2150.0	-	-
DW05*	Primary data	432293	775143	1736	Mar-14	7.9	1877.0	-	-
DW10*	Primary data	432674	773396	1701	Mar-14	7.7	1876.0	-	-
HS27*	Primary data	452926	785196	1708	Mar-14	8.0	1818.0	-	67.5
DW26*	Primary data	432627	779410	1720	Mar-14	8.0	1755.0	-	-
DW25*	Primary data	433725	781971	1715	Mar-14	8.6	1714.0	-	-
BH07*	Primary data	443250	787150	1713	Mar-14	7.3	1620.0	-	-
BH16*	Primary data	443450	782566	1720	Mar-14	8.0	1513.0	-	26.5
DW08*	Primary data	433072	775116	1707	Mar-14	7.9	1499.0	-	-
DW28*	Primary data	434465	780844	1711	Mar-14	8.0	1460.0	-	-

Id	Data Source	X	Y	Z	DATE	pH	COND	TDS	T
BH17*	Primary data	440120	778876	1711	Mar-14	7.7	1450.0	-	27.1
RV*	Primary data	445387	783611	1704	Mar-14	8.0	1432.0	-	33.0
BH22*	Primary data	441805	779461	1702	Mar-14	7.6	1373.0	-	30.8
BH06*	Primary data	447018	786149	1734	Mar-14	7.3	1324.0	-	30.8
RV15*	Primary data	448696	782565	1700	Mar-14	7.8	1191.0	-	28.3
BH03*	Primary data	444859	775359	1754	Mar-14	7.4	1121.0	-	25.3
HS23*	Primary data	447095	772805	1730	Mar-14	6.3	1088.0	-	52.0
BH11*	Primary data	446796	785559	1734	Mar-14	7.8	1057.0	-	33.5
BH*	Primary data	446796	785559	1734	Mar-14	7.9	1036.0	-	34.5
BH13*	Primary data	444763	776932	1798	Mar-14	7.5	1008.0	-	30.2
BH21*	Primary data	444521	785432	1712	Mar-14	7.8	987.0	-	28.9
BH01*	Primary data	444521	785432	1712	Mar-14	7.8	977.0	-	29.1
BH30*	Primary data	444306	777777	1768	Mar-14	7.3	975.0	-	31.4
HS12*	Primary data	460028	782322	1718	Mar-14	7.3	896.0	-	69.2
LK20*	Primary data	442347	783187	1697	Mar-14	9.0	885.0	-	23.6
LK09*	Primary data	436263	781285	1699	Mar-14	8.9	882.0	-	24.2
LK29*	Primary data	440028	779166	1698	Mar-14	8.9	882.0	-	23.9
DW14*	Primary data	454591	784463	-	Mar-14	7.3	630.0	-	26.4
BH04*	Primary data	437318	767643	1863	Mar-14	7.2	274.0	-	-
CS*	Primary data	456914	783082	1754	Mar-14	6.3	218.0	-	20.7
CS19*	Primary data	453032	785244	1725	Mar-14	6.5	202.0	-	32.6
CS18*	Primary data	456837	783125	1732	Mar-14	6.5	201.0	-	21.3

Annex V: Environmental Isotope Data (δD, δ^{18}Oand ^{3}H)

Id	X	Y	Date	Data Source	δD(‰)	δ^{18}O(‰)
BH01*	444521	785432	May, 2014,	Primary data	22.69	2.78
BH11*	446796	785559	May, 2014,	Primary data	3.25	-1.01
BH16*	443450	782566	May, 2014,	Primary data	8.21	-0.16
BH17*	440120	778876	May, 2014,	Primary data	9.74	0.36
BH21*	444521	785432	May, 2014,	Primary data	23.08	2.82
BH22*	441805	779461	May, 2014,	Primary data	5.35	-0.87
BH03*	444859	775359	May, 2014,	Primary data	5.39	-0.82
BH04*	437318	767643	May, 2014,	Primary data	-2.39	-2.12
BH06*	447018	786149	May, 2014,	Primary data	6.10	-0.68
CS18*	456837	783125	May, 2014,	Primary data	3.12	-1.52
CS19*	453032	785244	May, 2014,	Primary data	0.45	-1.93
DW10*	432674	773396	May, 2014,	Primary data	28.79	4.23
DW02*	432768	772663	May, 2014,	Primary data	-5.75	-2.74
DW24*	431677	777136	May, 2014,	Primary data	45.50	7.88
DW05*	432293	775143	May, 2014,	Primary data	37.63	5.87
DW08*	433072	775116	May, 2014,	Primary data	22.87	3.28
TS23*	447095	772805	May, 2014,	Primary data	3.94	-1.23
TS27*	452926	785196	May, 2014,	Primary data	7.49	0.26
LK20*	442347	783187	May, 2014,	Primary data	51.90	9.16
LK29*	440028	779166	May, 2014,	Primary data	52.49	9.22
LK09*	436263	781285	May, 2014,	Primary data	52.90	9.14
RV15*	448696	782565	May, 2014,	Primary data	12.94	1.43
RV01*	448219	782372	May, 2014,	Primary data	13.48	1.50
RV02*	447693	782316	May, 2014,	Primary data	13.46	1.45
RV03*	445279	783718	-	Primary data	14.37	1.65
BH01	454990	794978	-	GSE, 2003	0.7	-1.64
BH02	443247	787145	-	GSE, 2003	3.5	-0.99

Id	X	Y	Date	Data Source	δD(‰)	$\delta^{18}O$(‰)
BH03	442856	781844	-	GSE, 2003	41.9	6.18
BH04	441848	779460	-	GSE, 2003	2.83	-0.98
BH05	441401	779904	-	GSE, 2003	2.05	-0.95
BH06	444891	775368	-	GSE, 2003	7.7	-0.41
BH07	444574	773563	-	GSE, 2003	5.9	-1.15
BH08	444086	772115	-	GSE, 2003	5.3	-1.31
BH09	439500	772100	-	GSE, 2003	9	0.21
BH10	441362	770748	-	GSE, 2003	-2.85	-2.17
BH11	438521	769883	-	GSE, 2003	-4.35	-2.12
BH12	439293	763859	-	GSE, 2003	-12.53	-2.84
BH13	436541	763710	-	GSE, 2003	0.2	-1.57
BH14	429989	763353	-	GSE, 2003	-1.28	-1.73
BH15	434404	759498	-	GSE, 2003	0.05	-1.44
BH16	438015	759244	-	GSE, 2003	-0.98	-1.65
BH17	433187	790548	-	GSE, 2003	24.3	3.13
BH18	426416	778488	-	GSE, 2003	-4.93	-1.68
BH19	447033	791288	-	GSE, 2003	-0.4	-1.48
BH20	430824	773951	-	GSE, 2003	33.7	5.15
BH21	455627	776365	-	GSE, 2003	0.88	-1.59
BH22	456448	775840	-	GSE, 2003	3.4	-1.36
BH23	453503	772256	-	GSE, 2003	0	-1.96
BH24	467137	771511	-	GSE, 2003	3.28	-1.35
BH25	465072	764373	-	GSE, 2003	2.95	-1.66
BH35	440128	779062	-	GSE, 2003	10.9	0.38
BH36	437015	767515	-	GSE, 2003	-2.5	-1.93
BH37	437181	756601	-	GSE, 2003	4.8	-1.12
BH38	430804	755288	-	GSE, 2003	6.5	-1.16
BH39	435598	752687	-	GSE, 2003	4.1	-1.23

Id	X	Y	Date	Data Source	δD(‰)	$\delta^{18}O$(‰)
BH40	431250	752170	-	GSE, 2003	4.45	-1.05
BH41	431299	747854	-	GSE, 2003	3.85	-1.06
BH42	432260	775132	-	GSE, 2003	42.9	6.14
BH43	451782	771715	-	GSE, 2003	2	-1.59
CS01	456672	781620	-	GSE, 2003	0.3	-1.63
CS02	458776	781867	-	GSE, 2003	-3	-2.08
CS03	460084	782090	-	GSE, 2003	-1.2	-1.98
CS04	457343	777517	-	GSE, 2003	2.15	-1.82
CS05	458592	776758	-	GSE, 2003	1.25	-1.76
CS06	462037	765283	-	GSE, 2003	1.25	-1.79
CS07	451238	769452	-	GSE, 2003	0.35	-1.8
CS08	445646	770671	-	GSE, 2003	1	-1.71
CS09	445381	770562	-	GSE, 2003	1.5	-1.61
CS10	444676	770823	-	GSE, 2003	1.5	-1.38
CS11	436985	771887	-	GSE, 2003	-4.5	-2.13
CS12	443002	760888	-	GSE, 2003	1	-1.33
CS13	448464	765928	-	GSE, 2003	0.85	-1.49
CS14	451888	762462	-	GSE, 2003	3	-1.47
CS15	458388	761450	-	GSE, 2003	2.2	-1.74
CS16	459946	758292	-	GSE, 2003	2.3	-1.64
CS17	464996	757168	-	GSE, 2003	2.3	-1.62
CS18	451992	785880	-	GSE, 2003	-2.53	-2.1
CS27	430472	758306	-	GSE, 2003	1.25	-1.22
DW01	453439	791221	-	GSE, 2003	1.3	-1.36
DW02	430456	773897	-	GSE, 2003	20.3	2.59
DW03	433918	771026	-	GSE, 2003	-0.95	-1.28
DW04	434741	771816	-	GSE, 2003	17.6	1.85
DW05	424724	764354	-	GSE, 2003	12	1.28

Id	X	Y	Date	Data Source	δD(‰)	$\delta^{18}O$(‰)
DW06	441086	778907	-	GSE, 2003	3.9	-0.54
DW07	441823	779103	-	GSE, 2003	1.9	-0.97
DW08	443037	782227	-	GSE, 2003	2.75	-0.8
DW09	443282	783063	-	GSE, 2003	3.95	-0.74
DW10	443429	783712	-	GSE, 2003	20.95	2.42
DW11	442636	785021	-	GSE, 2003	28.35	4.2
DW12	457004	779044	-	GSE, 2003	1.3	-1.47
DW13	431531	783983	-	GSE, 2003	33.9	4.32
DW14	432378	783143	-	GSE, 2003	33.5	5.12
DW15	454686	775165	-	GSE, 2003	1.15	-1.53
DW16	431880	779484	-	GSE, 2003	47.4	7.22
DW17	452000	773211	-	GSE, 2003	2.1	-1.28
DW18	429445	777840	-	GSE, 2003	34	4.62
DW19	431402	778053	-	GSE, 2003	38.35	5.69
DW20	428165	777563	-	GSE, 2003	32.77	4.62
DW36	418913	767227	-	GSE, 2003	-4.3	-2.08
DW37	440309	773630	-	GSE, 2003	9.3	0.57
DW38	443109	784770	-	GSE, 2003	21.7	2.24
DW39	431993	783459	-	GSE, 2003	34.2	4.6
DW40	433423	780608	-	GSE, 2003	48.5	7.48
DW41	427183	779130	-	GSE, 2003	34.1	4.77
DW42	430913	773875	-	GSE, 2003	39.6	5.5
HW01	443985	782246	-	GSE, 2003	5.4	-0.75
HW02	444116	779738	-	GSE, 2003	3.65	-1.31
HW03	444066	779743	-	GSE, 2003	0.45	-1.38
HW04	444530	777465	-	GSE, 2003	2.1	-1.46
HW06	437301	799860	-	GSE, 2003	-4.2	-1.41
LK01	439731	778581	-	GSE, 2003	42.5	6.74

Id	X	Y	Date	Data Source	δD(‰)	$\delta^{18}O$(‰)
LK07	432362	778049	-	GSE, 2003	45.5	7.01
LK08	433263	777260	-	GSE, 2003	45.9	6.74
LK09	439136	772380	-	GSE, 2003	46.1	5.65
LK10	440154	779082	-	GSE, 2003	46.5	6.77
LK11	442878	783718	-	GSE, 2003	39.3	5.36
LK12	442552	783488	-	GSE, 2003	47	6.92
LK13	439922	778929	-	GSE, 2003	45.6	7.31
LK14	435118	772381	-	GSE, 2003	39.5	5.46
TS01	452526	785341	-	GSE, 2003	9	0.28
TS02	456965	786018	-	GSE, 2003	-8.5	-2.54
TS03	459944	782463	-	GSE, 2003	-6.85	-3.01
TS04	460642	781786	-	GSE, 2003	-8.2	-2.72
TS05	447156	772809	-	GSE, 2003	1.8	-1.42
Gemeto R	456391	775144	-	GSE, 2003	6.3	-1.03
Kerama R	448661	772091	-	GSE, 2003	8.1	-1.08
TW. R	443820	784270	-	GSE, 2003	17.75	-1.03
Wesha R	460223	782440	-	GSE, 2003	0.45	-1.88

Annex VI: Environmental Isotope Data (^{3}H)

ID	Data Source	x	y	U. T.	Date
BH 01	Primary data	444521	785432	0,0 ± 0,3	08/03/2014
BH 11b	Primary data	446796	785559	0,0 ± 0,3	8/3/2014
BH 03b	Primary data	444859	775359	1,0 ± 0,3	15/03/2014
BH0 4	Primary data	437318	767643	0,4 ± 0,3	11/03/2014
BH 07	Primary data	443250	787150	0,1 ± 0,3	08/03/2014
BH 11	Primary data	446796	785559	0,3 ± 0,3	13/03/2014
HS 12	Primary data	460028	782322	0,2 ± 0,3	12/03/2014
BH 13	Primary data	444763	776932	0,9 ± 0,2	14/03/2014
BH 16	Primary data	443450	782566	0,8 ± 0,3	13/03/2014
CS 18	Primary data	456837	783125	1,7 ± 0,2	12/3/2014
CS 19	Primary data	453032	785244	1,1 ± 0,3	12/03/2014
LK 20	Primary data	442347	783187	1,0 ± 0,2	16/03/2014
BH 21	Primary data	444521	785432	0,6 ± 0,2	13/03/2014
HS 23	Primary data	447095	772805	0,3 ± 0,2	14/03/2014
HS 27	Primary data	452926	785196	0,6 ± 0,2	12/03/2014

DECLARATION

I the undersigned declare that this thesis is my original work and has not been presented for a degree in any other university. All sources of material used for the thesis have been duly acknowledged.

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Date of Submission: February, 2015