ADDIS ABABA UNIVERSITY
DEPARTMENT OF EARTH SCIENCES
SCHOOL OF GRADUATE STUDIES

CONCEPTUALIZATION OF GROUNDWATER FLOW SYSTEM AND AQUIFER CHARACTERIZATION IN AWASSA LAKE CATCHMENT

BY

WONDWOSEN MEKONNEN SEYOUM

JUNE 2005.

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Declaration

This thesis is my original work and has not been presented for a degree in any other university, and that all sources of material used for the thesis have been duly acknowledged.

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ACKNOWLEDGEMENTS

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

All the organizations and individuals, who directly or indirectly involved in this study deserve special appreciations. First Geological Survey of Ethiopia, which allows me to use their data, Water Works Design and Supervision Enterprise, Ministry of Water Resources, National Meteorological Service Agency and Southern Nation and Nationalities People Water Resources Bureau are greatly acknowledged for their data source.

My deepest heart felt thank goes to my family. My father Mekonnen Seyoum, I would like to appreciate him for his endless support up to now. My mother, Shewaye Tilahun, who is my source of strength in every aspects of life, her caring and love, which brought me to this day, I thank you. My brother Gedion Mekonnen, who is my strength and always being at my side, his advise and support is changed my life. I am grateful to thank him for his indispensable helps and advise. I would also like to appreciate the remaining part of my family for their help in every day life. My deepest heart felt gratitude also goes to my girl friend Helen Nigussie, who is my source of inspiration. Her love, encouragement and support played an important role in my academic life.

I would like to express my gratitude to my colleagues and friends in and outside the University, specially Zelalem Shiferaw that we share all the academic and social life together in the two year stay during this study are appreciated. Last but not least I offer my special thanks for those involves directly or indirectly in this study and their names are not listed are greatly acknowledged.

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ABSTRACT

In this work, hydrogeological study has been carried out in order to characterize the aquifers and conceptualize the groundwater flow in Awassa Lake catchment, located 275km south of Addis Ababa in the central sector of the Main Ethiopian Rift. Hydro-meteorological, hydrological, geological, and structural, hydrochemical and isotopic characteristics of the area are assessed through uses of various approaches and methodologies. Fieldwork, observation and measurements of relevant variables along with existing data accompanied by systematic analysis and interpretation helped so as to understand the hydrogeological system.

The Awassa Lake catchment is a closed caldera Lake on its one segment overlaps with the Main Ethiopian Rift. The main geological units in the area are lacustrine sediments characterizing the floor; acidic volcanics covering the caldera rims and escarpment and some basalts, hayaloclastites and scoria cones outcrop on the floor. As it is found on the axial zone of the Ethiopian Rift, it is highly affected by rift structures, recent tectonic features are also observed in the area.

The aquifers in the area generally occur in unconfined condition where their hydraulic characteristics are spatially highly variable, which is the result of the complex nature of the lacustrine sediments and the degree of fracturing of the volcanic rocks. The most permeable unit is the lacustrine sediment with hydraulic conductivity ranges between 5m/day-200m/day, where as the least are those acidic volcanics of the rhyolite, obsidian and lapilli tuff having less than 0.1m/day. The others volcanic rocks lie in between depending on the degree of weathering, fracturing or faulting.

The hydrochemical and isotopic analysis of δ^2H and $\delta^{18}O$ result signifies that groundwater of the floor, caldera rims, and escarpment and highland is found in different flow regime. This is also supported by the large hydraulic gradient between the floor and the highland. Groundwater of the caldera rims, escarpment and highland is characterized by active, shallow flow with low EC less then 300µs/cm and little isotopic fractionation. Intermediate flow characterizes the remaining floor and western caldera rims with relatively higher ionic concentrations (EC ranges between 1000-2400µs/cm) and enriched in isotopic composition. These flows are controlled by the rift faults and structures, which depends on the characteristics of these structures such as depth of penetration. The area gets higher amounts of direct recharge from the eastern and south eastern caldera rims, escarpment and highland where as the other parts are characterized by intermediate and localized recharges. Similar to the groundwater flow, discharge areas are also restricted to rift structures except the swampy areas found on the floor. Not only these structures but also recent tectonics (ground cracks) developed on the area control the groundwater flow. These features facilitate the groundwater flow toward the Lake Awassa by increasing the hydraulic connections of the different rock units, which might be associated with the rise of the Lake level, the main problem of the area.

Key words: ***Aquifer characterization, Awassa Lake catchment,conceptual profile model, ground cracks, hydraulic conductivity.***

CHAPTER ONE

INTRODCTION

1.1 Background

The present day Main Ethiopian Rift is the result of volcano-tectonic processes such as earth movements, volcanism and surface processes which took place in this region. Its central part, which is the so called the Lake District is characterized by a chain of lakes forming an Endoreic basin. The major Lakes are Ziway, Langano, Abiyata, Shalla, Awassa, Abaya, and Chamo that fills the depressions of this segment. Awassa Lake catchment which is the part of the MER is formed by a large volcano-tectonic collapse associated with the Great East African rifting.

The region is rich in its natural resources, where water resource is the significant. Beside their use for water supply and irrigation, the Lakes in this region are habitat for a great variety of fishes, birds, and wild animals, which direct tourist traffic to this area. In addition a geologically confirmed large reserve geothermal resource of the region is vital for electric power generation as well as recreational activities. 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, Pollution and Neo-tectonics 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.

The level rise of Lake Awassa is the main problem showing unusual increasing trend since 1996. In addition the development of recent ground cracks in the area also disrupted the living condition as well as the natural process. Therefore the need for a scientific research is undeniable so as to contribute in tracing the various causes and processes as well as the future condition so as to safeguard the environment and the ecosystem; and for a better use and management of the natural resources.

1.2 Previous works

As far as previous works are concerned, the area has been a major interest for local and foreign researchers in the past. Different issues related to geology, hydrogeology, engineering, environmental, geothermal, paleoclimatological, land degradation, etc are conducted in the area.

The main works related to hydrogeology are: A.T Grove, F. Alaynes Streee and A.S Goudie, 1975, Former Lake Levels and Climatic Change in the Rift Valley of Southern Ethiopia, Geographical Society of Japan. In the nineteenth century, Lake Shallo held a considerable body of water, which Erlanger described in 1901 as united with Awassa Lake in the rains to form a single lake. Nillson (1940) noted that Shalla would rapidly be converted into a papyrus swamp if desiccation continued; aerial photographs taken in the 1950s shows that the lake was occupying about 12 km2 in the north end of the swamp. The diagrammatic section through the southern rift valley lakes for the late quaternary period when Shalla and the other lakes have a very high elevation shows that there was a groundwater flow indication from Awassa Lake to Shalla Lake due to elevation differences.

The hydrogeology of the MER conducted by Geological Survey of Ethiopia(GSE) (Tesfaye Cherent, 1982); The study was conducted to prepare 1:250 000 scale hydrogeological map of the Lake regions. It pointed out that Awassa lake catchment is covered by lacustrine sediments, ignimbrite and tuffs, and acidic volcanics (rhyolites, tuffs, pumice and obsidians). Based on bore holes data and field observations the various rock groups are classified as low, moderate and high permeability. Lacustrine sediments from moderate to high, pumice falls and acidic volcanics from low to high, and Ignimbrites and tuffs from low to high. The study concludes that lake Awassa seems to be sensitive to slight climatic changes. Essentially, lake Awassa is subject to fluctuation in level because of variations in rainfall and evaporation. Another cause could be a decrease in the vegetation cover of the area, which would increase the quick runoff in the streams flowing to the lake and thereby increase the lake level. Thermal springs of Wendo Genet, Wesha and Gara Quhe, which flow to Lake Shallo have high subsurface temperature about 2000oC from SiO2 content and Na/K ratios. These springs have low total dissolved solids and they are considered meteoric water with a short residence time. The meteoric source of the hot water indicates that the current volcanic activity is only in the form of a heat flux which is heating and partially evaporating the circulating groundwater locally and generating gas (UN technical report, 1973). In the Corbetti volcanic center north of Lake Awassa the geothermal manifestations are low geothermal fumaroles and hot grounds. The fumaroles are reported to have temperatures between 67 and 91°C while the hot grounds have temperatures as high as 91oC at 15 cm depth. The hydrogeology of Awassa area (Dessie Nadew, 1997), which outline the hydrogeology of the area surrounding Awassa town; Engineering geology of Awassa (Zemenu Geremew, 2000), this works mostly done on the area of engineering geology and also touches the hydrogeology which related to Lake water balance and water quality assessment; and pollution on Awassa area (Elias Gugsa, 2004) are some of them. These have characteristics of more regional or general and purpose oriented. Recent works are done related with the rise of lake level by Water Works Design and Supervision Enterprise (WWDSE, 1999). This works includes land use/land cover and soils, water balance, analysis of lake level rise and storage Change, as well as gives short and long-term remedial measures and socio-economic and environmental impact assessment of the remedial measures. In addition hydrogeology and engineering geology of Lake Awassa is done by GSE (Zenaw Tessema and Tadesse Dessie, 2003). With the main objective of investigating the problem of lake level rise and forward possible remedial measures through use of hydrochemical and isotopic approach as well as catchment wise water balance, and detail geological mapping also done.

Therefore, the present study comprises the detail works on the hydrogeology of the lake catchment in order to fill the gaps from the previous studies. This includes aquifer characterization, and interaction of the various water bodies as well as the groundwater flow system and assessment of recent tectonics and their role in the general hydrology of the catchment. It contributes a lot to the use and management of the water resource as well as input for further studies using numerical groundwater modeling.

1.3 Research objectives

The main objective of this study is:

- to conceptualize the groundwater flow systems and characterize the aquifers in the catchment.

With specific objectives:

- to identify interactions of groundwater and surface water
- to characterize recharge-discharge conditions
- to study the recent tectonics(ground cracks) and their relation to the hydrogeology
- to conceptualize the groundwater flow regime of the catchment.

1.4 Methodology

Various approaches and methodologies were applied in order to come up with the results. These are:

- Literature reviews of previous works and desk studies using satellite image, topographic maps and existing other maps.

- Data collection and formation of a data base under a GIS (Geographic Information System) environment such as hydro-meteorological, hydrochemical, well data, etc and base map preparation

- Field work accompanied by systematic field methods, measurement of relevant field variables such as EC, pH, Temperature, groundwater level, sampling water points, hydrogeological and structural mapping, georeferencing water points , observations of rock units, and interpretations in terms of previous works and knowledge of the area.

- Data processing, analysis and interpretations of existing and field data, through use of existing maps such as geological, hydrogeological, soil map, satellite images, topographic maps, etc.

- The analysis and interpretation is supported by different Software and methods applicable in hydrogeology such as used for image interpretation, GIS application, hydrochemical analysis, pumping test analysis, etc (envi, Arcview GIS 3.2, Aquachem, Aquitest, 3Dem, Microdem, CorelDraw, Surfer 8) (flow chart for methodologies and approaches is shown in figure 1.1)

1.5 Structure of the Thesis

This thesis contains nine Chapters incorporating graphs, maps and data in the appendices. Chapter one and two gives a clear view of this study and the area. Chapter 3 describes the hydro-metrological variables and surface hydrology where these variables are the major components of the hydrogeological system of the area. Chapters four and five contain the descriptions of the geological units and the hydrogeologic and hydraulic characteristics of these units respectively. Chapter six and seven discuss about the nature, origin and interactions of the water bodies based on hydrochemical and isotopic analysis as well as the recharge-discharge conditions of the area. Chapter eight and nine contains the synthesis results of the work which includes the conceptual model and conclusion derived from the work.

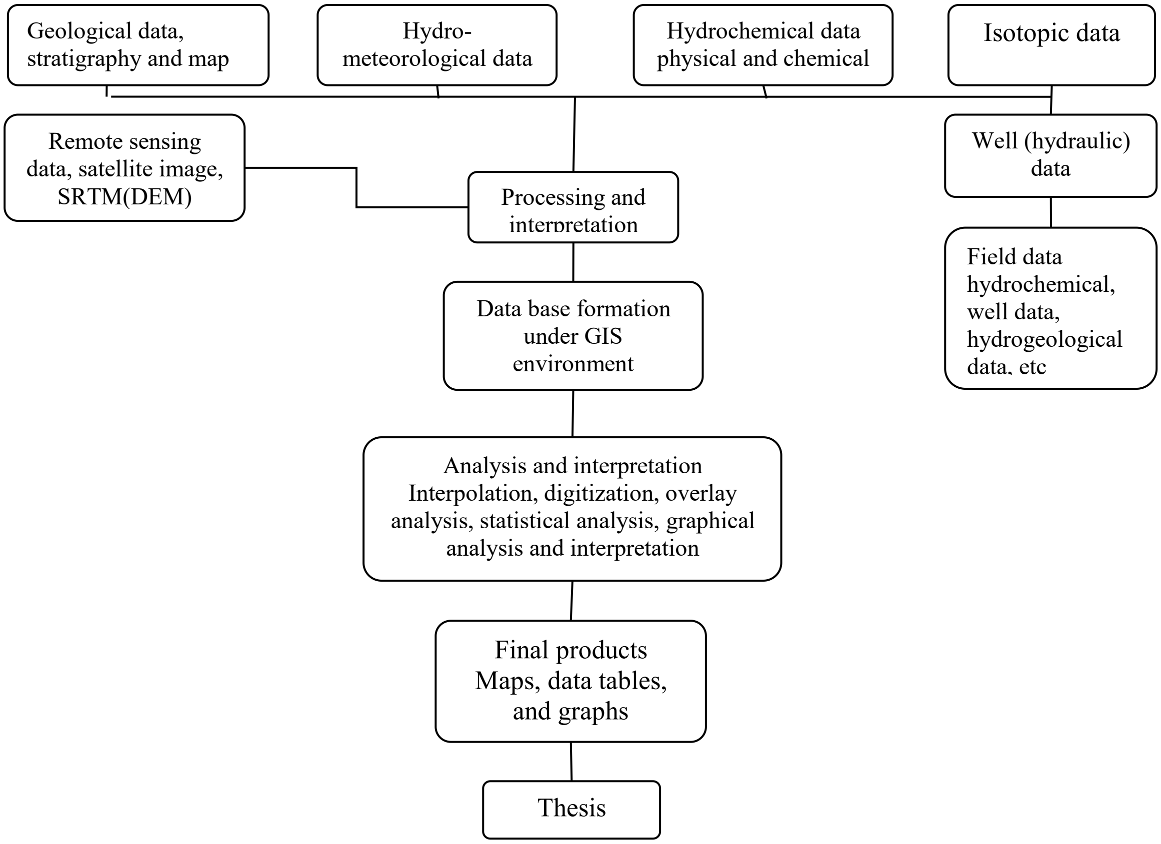


Figure 1.1 Flow chart showing the general methodology of the study

The study area covers an area of 1376km^2, which is the whole lake catchment. The current size of the lake surface area is about 100km^2. Hence the effective catchment area at present is about 1284 km^2.

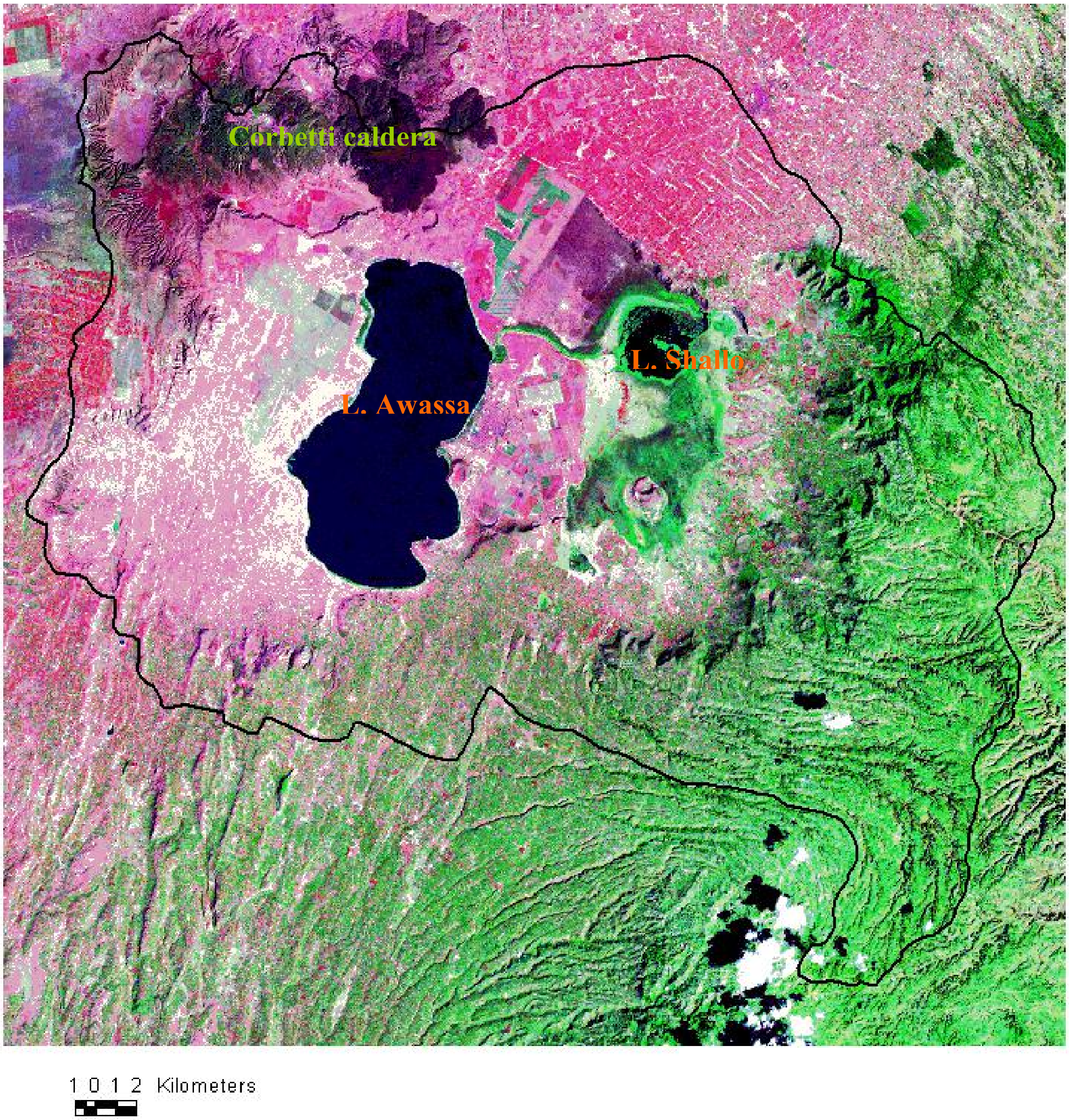


Figure 2.2 False color composite TM image of Band 742 in RGB order respectively (solid line- the boundary of the study area)

2.2 Topography and drainage

The Awassa Lake catchment is found in the lake regions of the central sector of Main Ethiopian rift, which is occupied by a chain of lakes. It is bounded by the north, south, east and west Ziway-Shalla, Abaya-Chamo, Wabi-Shebelle-Genale, and Omo-Gibe Basin respectively. Awassa Lake 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 is coincided with the eastern escarpment of the Main Ethiopian rift whose average throw is about 500m and its maximum elevation reaches 2700m.a.s.l (Fig. 2.3) which is the maximum in the catchment. The catchment area comprises escarpments, ridges, and plateau, undulating to rolling and dissected plains, depressions swamps, and Lake Awassa. The floor of the caldera is characterized by flat land containing Lake Awassa having the lowest elevation in the catchment at 1680m.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. These faults along with the caldera rims form local surface depressions with out surface connection with Lake Awassa such as derba pond. The northern part is bounded by Corbetti caldera, which is a nested caldera within Awassa 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 Awassa, Shallo, and Mt. Tabor.

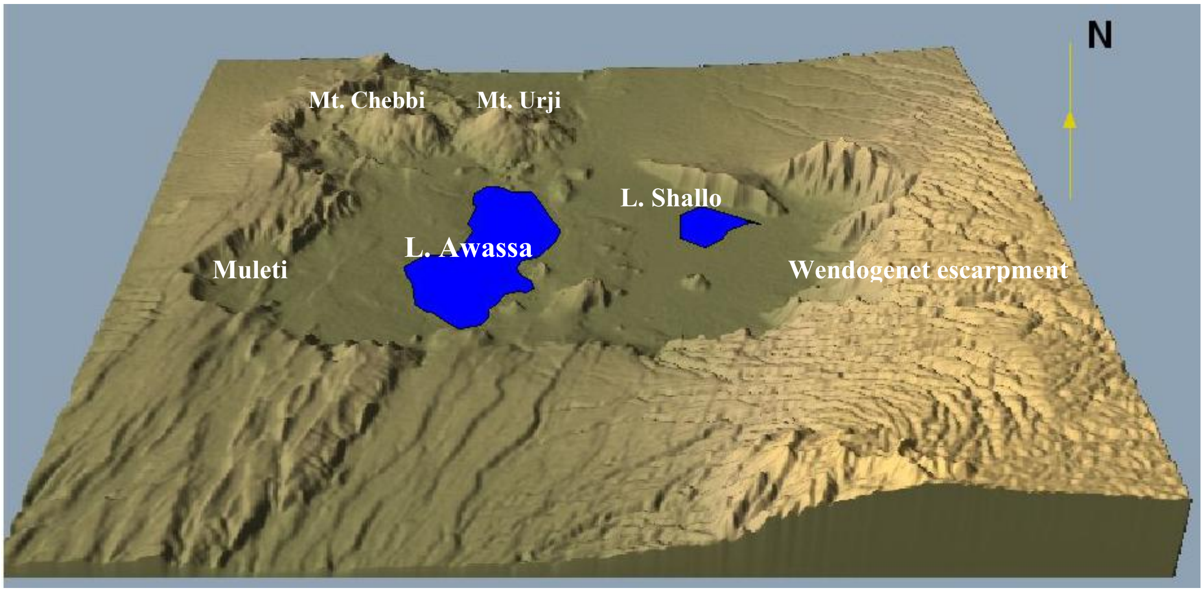


Figure 2.3 Digital Elevation Model showing the topography of the area

As it is a volcano-tectonic depression (caldera), the drainage pattern becomes a radial type (Dessie nadew, 1977). Surfacially the catchment is closed, no surface waters enter or leaves out of the catchment (Fig. 2.4). The only Perennial/significant River that drains the eastern scarp flowing westward, which replenishes Lake Awassa, is Tikur wuha with catchment area of 625km^2, which is 45% of the total catchment area.

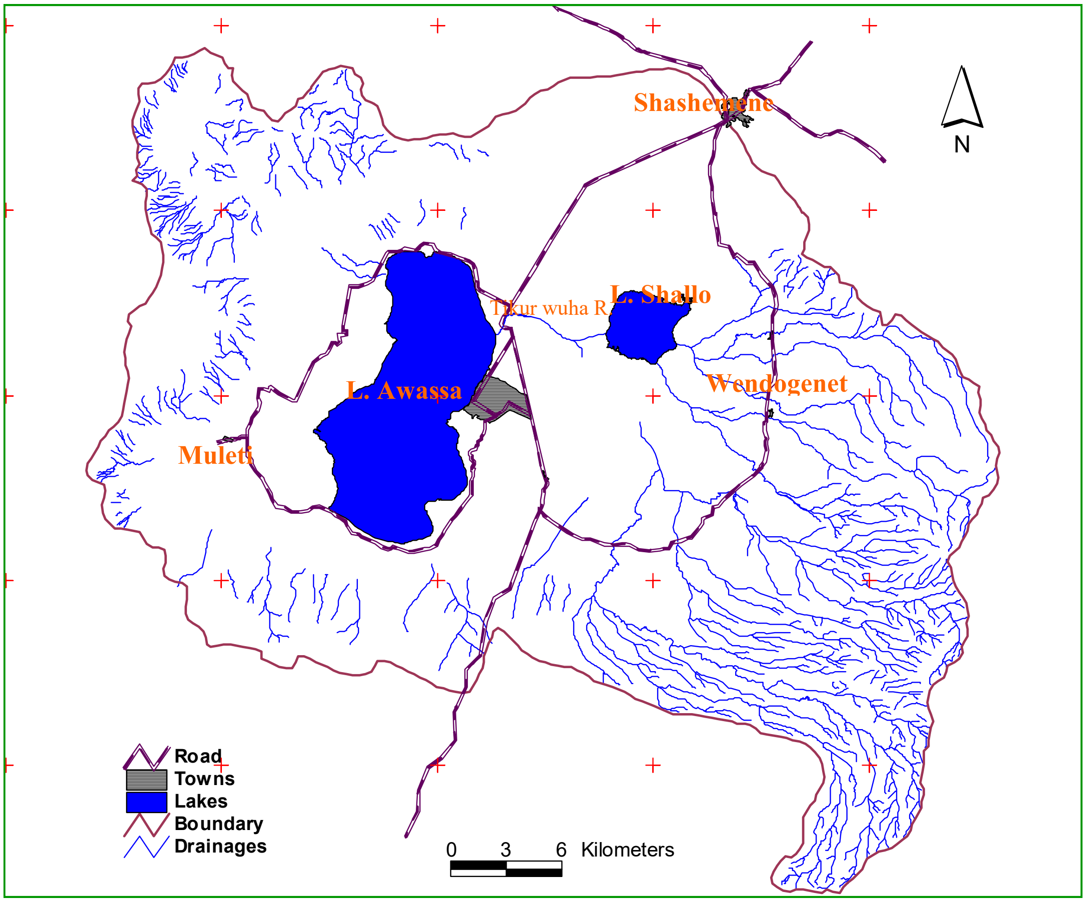


Figure 2.4 Drainage map of the catchment

2.3 Soil and land cover

Soil and land use/land cover map was prepared by Water Works Design and Supervision Enterprise (1999). Figure 2.5 shows a simplified soil map modified from this work. Based on this work the major soil units are cambisols, andosols, alisols and leptosols where they are classified based on the physical and chemical characteristics which include depth, color, structural development, texture and evidence of profile development such as presence of diagnostic horizons, reaction to 10% HCl, pH value and others. These soil units have characteristics of their parent material where they are developed. The soils on the floor are developed in recent alluvial deposits specially the eastern part where as the others are associated with lacustrine sediments and volcanic material. Generally based on their dominant characteristics these soil types are classified in to four groups. These are clay loam, fine sand, fine sandy loam and silty loam.

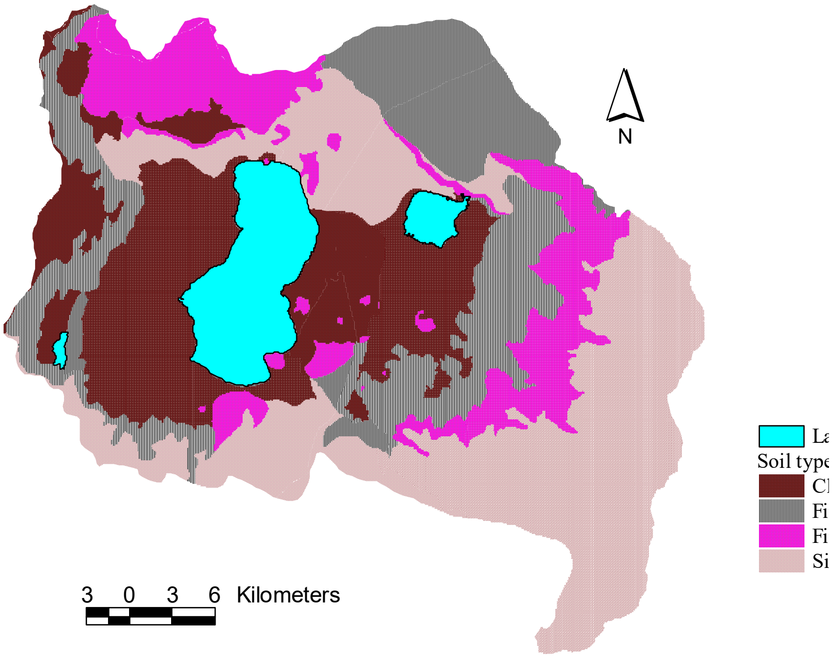


Figure 2.5 Simplified soil map (after WWDSE, 1999)

As far as landuse is concerned, the main land use of the catchment is rain fed agriculture with agro-forestry practices. On the floor of the area mechanized farms such as Shallo basic seed and Awassa state farm exist. Private small holding farms are also occupying a considerable large portion on this area surrounding the lake. Swampy area south of Lake Shallo is found and serves as a very important grazing land. Almost all of the rural populations are farmers and their living standard is based on farming with a considerable income generated from cattle production and cash crops. In addition, other important land uses in the area are fishing and recreation on the Lake and collection of firewood and charcoal production at the northwest hilly areas. The Landuse/land cover condition (as of 1998 surveyed by WWDSE) of the area are open bushy woodland with cultivated land found on the floor and southern part of the area; Cultivated land with exposed bare rock and soil found on southwest corner of the area; Open grassland with bare soil covering the eastern escarpment western caldera rims; Open grassland with open bushy woodland on the volcanic hills.

2.4 Climate

The Awassa area has a sub-humid climate (FAO, 1984) and gets a mean annual rain fall of 1032mm over the entire catchment. The area is characterized by an eight month long rainy season from March to October where the big rain (Kiremet) occurs from July to September with rain fall range from 70-140mm and the dry period is from November to February that gets less than 20mm rain fall. The mean annual temperature at Awassa is 19.5^0C and the mean annual temperature ranges from $12\text{-}26^0$C. Maximum temperature occurs in January, February and March that reaches around 29^0C where as minimum temperature occur during months of November and October which decreases up to 10^0C. Daily sunshine hours range between 4-9 hrs, where the minimum occurs during rainy seasons and the maximum during dry months. The mean monthly relative humidity at Awassa ranges between 54-76% which depends on the variation of dry and wet seasons.

There is an eight month long rainy season from March to October with mean monthly range of 50-150 mm where in the remaining months less than 25 mm and the area gets high amount of rainfall in July, August and September.

As it is seen from the graphs there is no as such high variability spatially in the area where the maximum amount of mean annual rainfall reaches 1150mm on the wall of the caldera at Wendogenet where as the minimum is 918mm at Shashemene. The long-term mean annual rainfall in the area poorly correlated with the variation in altitude (Fig. 3.2).

Stn No.	NAME	Altitude (m)	Mean Annual RF (mm)
1	Awassa	1750	953
2	Wendogenet	1800	1151
3	Aje	1860	1272
4	Shashemene	1950	918
5	Yirba	2000	1120
6	Haisawita	2240	999

Table 3.1 Long-term mean monthly precipitations and altitude in the catchment

From Awassa to the East and southwest, the rainfall variability correlates with the variation in altitude, however to the south (Haisawita station) doesn't correlated with altitude, which might be due to the quality of the data and/or orographic effect but generally on the rift rainfall with altitude is highly correlated (Tenalem Ayenew, 1998). In general there is no correlation between rainfall and altitude.

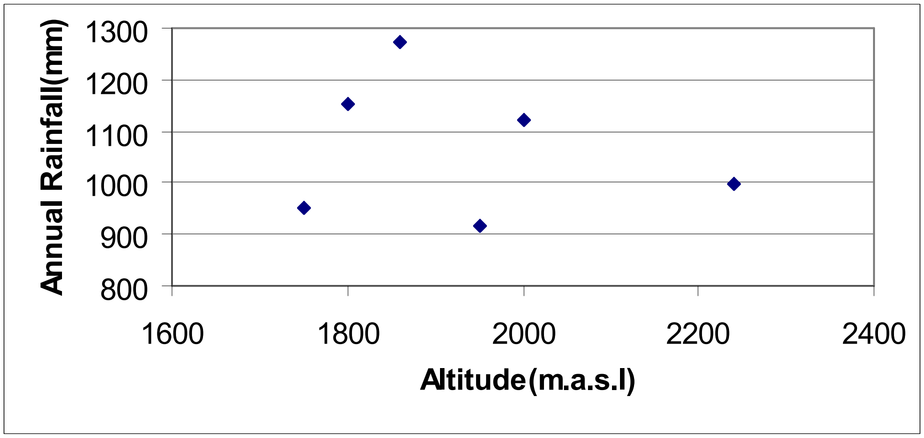


Figure 3.2 Altitude-rainfall relation ship

The aerial depth of precipitation was estimated using three methods, arithmetic mean, isoheytal and theissen polygon methods (table 3.2, fig. 3.3 and fig. 3.4). Based on the arithmetic mean method the catchment precipitation is estimated to be 1028mm.

Stn No.	NAME	Altitude (m)	Mean Annual RF (mm)
1	Awassa	1750	953
2	Wendo genet	1800	1151
4	Shashemene	1950	918
5	Yirba	2000	1120
5	Haisawita	2240	999
Arithmetic mean			1028

Table 3.2 The arithmetic mean annual precipitation

On the basis of the isoheytal map and the data presented in table 3.3 the total catchment mean annual precipitation is estimated to be 1031mm.

Isoheytal range (mm)	Average precipitation (mm)	Area (km^2)	Area (%)	Mean annual precipitation (mm)
<950	940.000	31.5	2.29	21.5
950-1000	975.000	331.6	24.10	235
1000-1050	1025.000	564.2	41.00	420
1050-1100	1075.000	315.3	22.91	246
1100-1150	1125.000	132.2	9.61	108
>1150	1160.000	1.2	0.09	1.01
Total area		1376		1031.51

Table 3.3 Inter-isoheytal areas and average annual precipitation

From the results of the theissen method shown in table 3.4, the total annual precipitation over the catchment is 1038mm.

Stations	Mean annual rainfall (mm)	AREA	Area (%)	Theissen mean
Haisawita	999.00	229.5	16.68	166.6
Wendogenet	1151	282	20.49	235.9
Shashemene	918	147.6	10.73	98.5
Yirba	1120.00	178.5	12.97	145.3
Aje	1272.00	79.4	5.77	73.4
Awassa	953.00	459	33.36	318
	Total area	1376		1037.7

Table 3.4 Theissen polygon areas and average annual precipitation

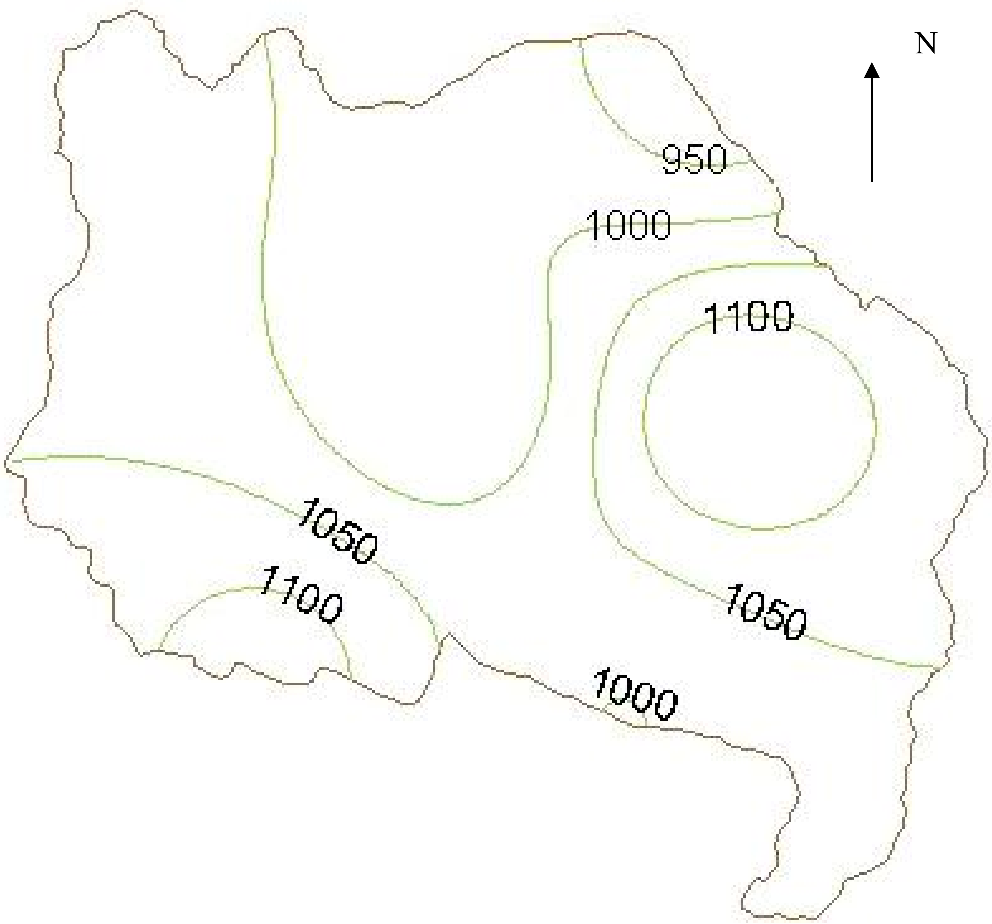


Figure 3.3 Isoheytal map of the Area

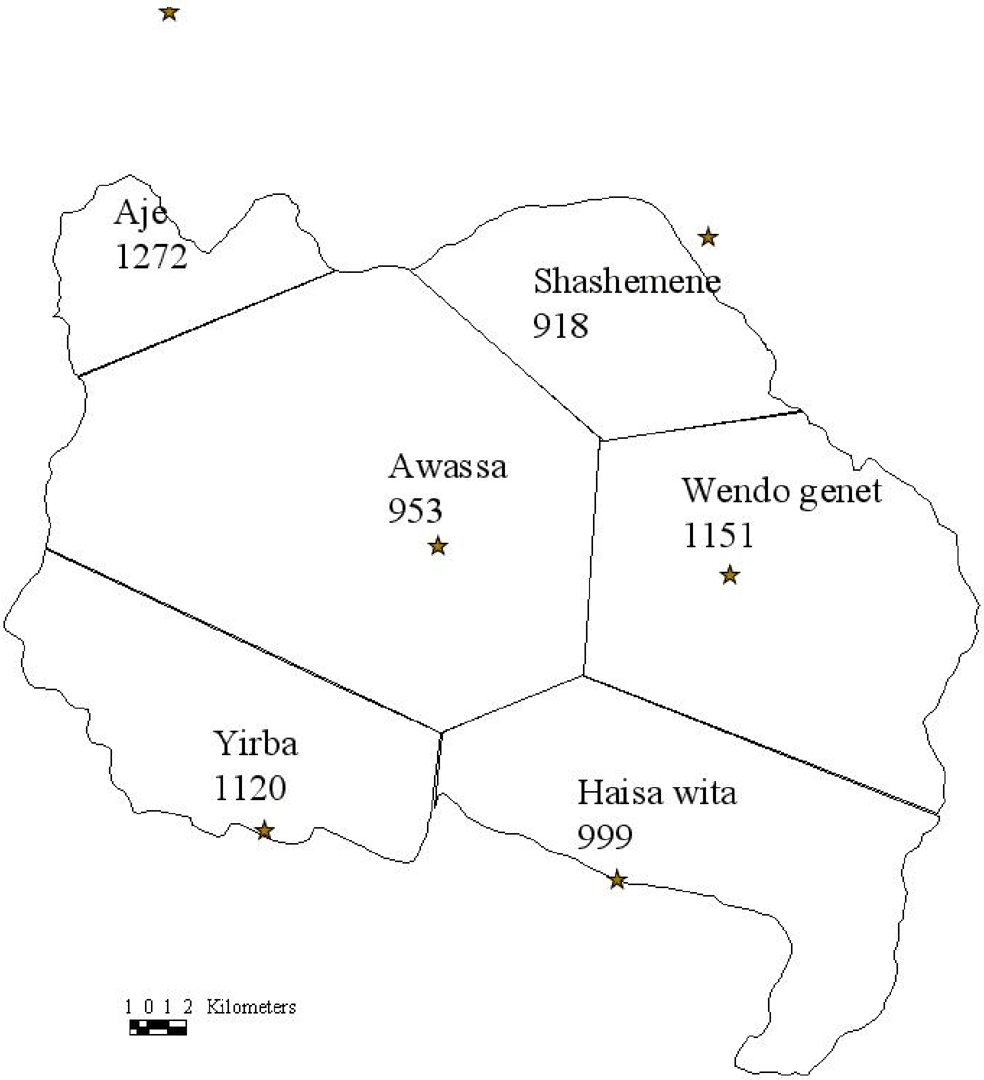


Figure 3.4 Theissen polygons of the catchment

3.1.2 Temperature

Temperature, wind speed, humidity, and sunshine hours affect the evaporation processes whereby it controls the hydrologic cycle of a given catchment. Thus the long-term data of these variables of the Awassa NMSA station was used in order to observe these variables. From the long-term temperature data, the mean annual temperature in the area is 19.5^{0}C. The hottest months are March and April where as the coldest are November and December. Figure 3.5 shows the variability of mean monthly values at Awassa station.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann
Min	10.4	11.7	12.6	13.6	13.8	13.9	14	13.7	13.1	11.7	9.3	9.3	12.26
Max	28.5	29.1	29.2	27.9	26.6	25.1	23.6	24.1	25	26.4	27.5	27.9	26.74
Mean	19.45	20.4	20.9	20.75	20.2	19.5	18.8	18.9	19.05	19.05	18.4	18.6	19.5

Table 3.5 Mean monthly minimum, maximum, and average air temperature at Awassa (1988-2003).

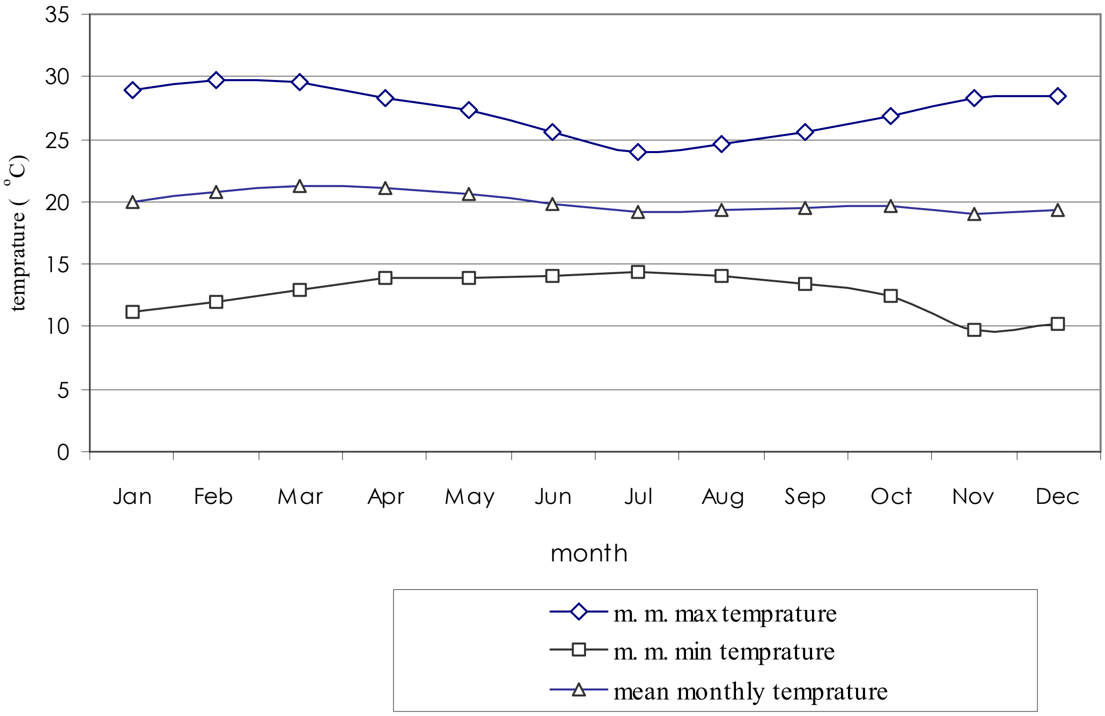


Figure 3.5 Mean monthly minimum, maximum and average temperature at Awassa

3.1.3 Wind speed

Wind speed influences the aerodynamic situation, which a decrease in wind speed results in a decrease in the rate of evaporation because the saturated vapor above the surface could not be removed instantaneously. Wind speed at Awassa station is measured 2m above the ground surface and from 1973 to 2003 mean monthly data was analyzed. The mean monthly wind speed ranges from 0.74-1.26m/s, where as June and July are the windiest while Oct. and Nov. are the least (Fig. 3.6).

	Jan	Feb.	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean	1.10	1.07	1.03	1.08	1.26	1.17	1.06	1.00	0.74	0.88	1.01	1.06
SD	0.31	0.33	0.38	0.35	0.28	0.23	0.23	0.21	0.56	0.22	0.27	0.31

Table 3.6 Mean monthly wind speed (m/s) at Awassa station (1973-2003).

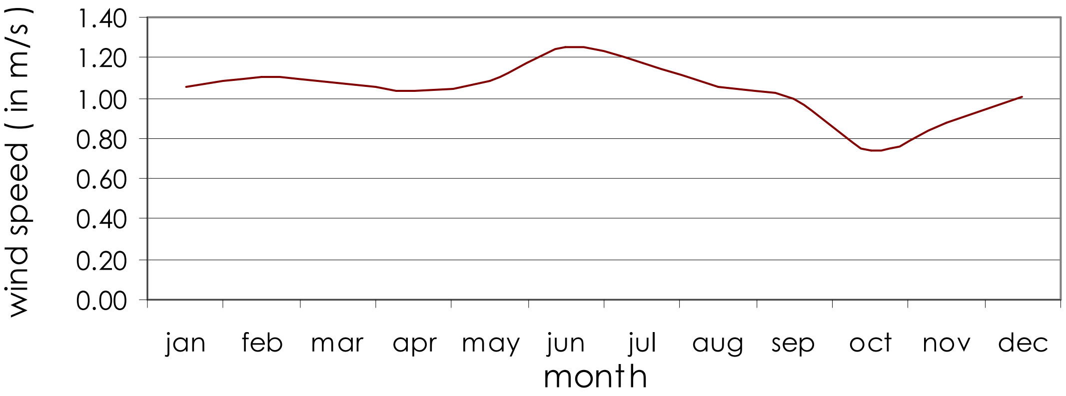


Figure 3.6 Mean monthly wind speed at Awassa (m/s)

3.1.4 Sunshine hours

A daily sunshine hour also affects the total amounts of daily evapotranspiration. From 1975 to 2003 mean monthly sunshine hours of Awassa station was used for the analysis. The mean monthly sunshine hours range from the minimum of 4.81hrs to 9.14hrs. The minimum sunshine hours occur in June, July and August where as in November, December and January reaches the maximum.

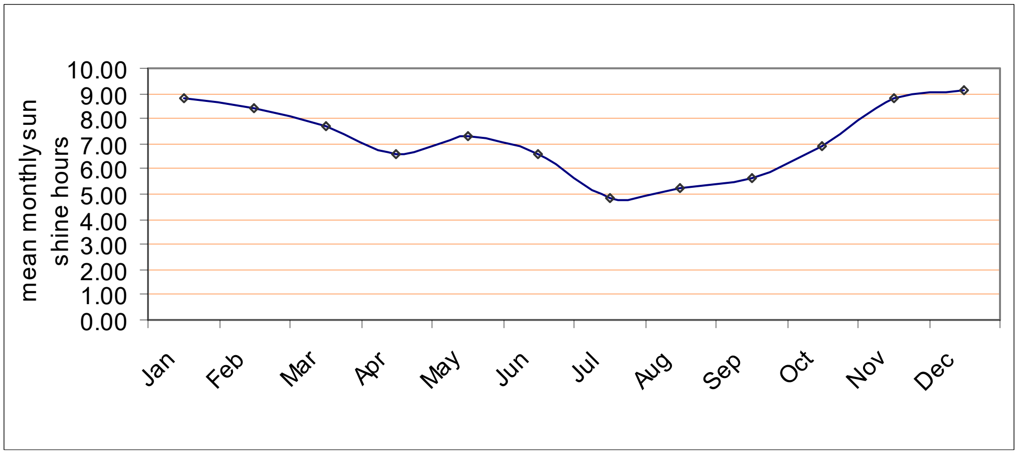


Figure 3.7 Mean monthly sunshine hours at Awassa (hrs)

3.1.5 Relative humidity

At any given temperature, air can hold a maximum amount of moisture: the saturation humidity, the relative humidity for an air mass is the percent ratio of the absolute humidity to the saturation humidity for the temperature of the air mass. As the relative humidity approaches 100%, evaporation ceases. For most practical purposes the relative humidity is used. Relative humidity is measured at three different hours at Awassa station, so that from the analysis of 15 years data of Awassa station the mean monthly relative humidity ranges from 54.4-76.3% (table 3.7) where the minimum in February and the maximum on September.

The variation in mean monthly relative humidity at different hours can be observed from figure 3.8.

Jan	Feb.	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann.
6:00	84.56	81.75	88.19	92.25	93.69	92.14	92.00	92.00	94.93	93.80	88.20	86.50
12:00	44.06	43.63	46.44	52.63	58.94	62.87	67.80	65.29	61.27	53.27	43.20	43.64
18:00	38.75	37.81	51.06	59.81	63.38	60.73	65.33	66.07	72.80	61.93	42.80	39.57
Mean	55.79	54.40	61.90	68.23	72.00	71.91	75.04	74.45	76.33	69.67	58.07	56.57
SD	25.06	23.87	22.89	21.11	18.91	17.55	14.74	15.20	17.11	21.34	26.10	26.00

Table 3.7 Long-term mean monthly relative humidity (%) at different hours (1988-2003)

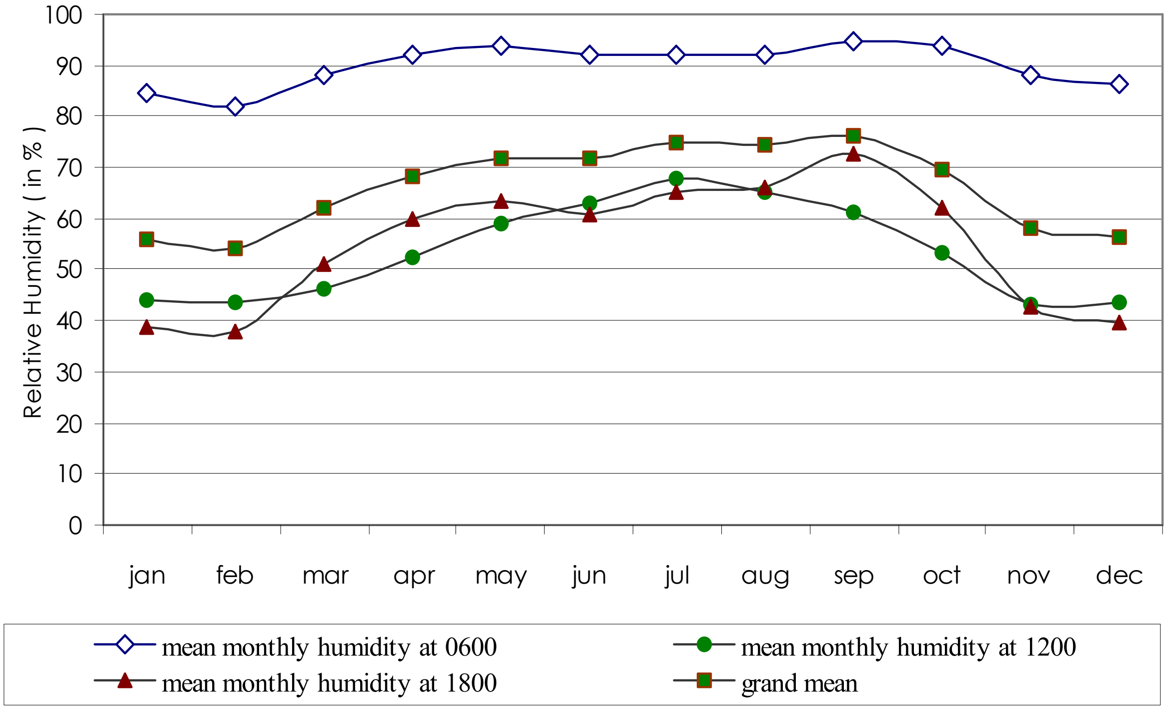


Figure 3.8 Mean monthly relative humidity (%) at different hours in Awassa.

3.1.6 Evaporation

Long-term pan evaporation data from NMSA at Awassa station is used and it was recorded using class A pan. From table 3.8 it shows that high evaporation occurs during dry months while during the summer time decreases due to high rainfall and relatively increased humidity. Since pan evaporation is greater than evaporation from the lake, pan coefficient of 0.8 is used in order to correct the various effects during evaporation from the pan. As a result the mean annual lake evaporation at Awassa is 1581mm.

Months	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Ann.
Mean	195	182	194	163	166	155	131	135	133	153	181	187	1976
SD	36	3	41	26	32	27	23	22	22	32	37	31	
Lake evap.	156	146	156	130	132	124	105	108	107	122	145	149	1581

Table 3.8 Mean monthly pan evaporation and Lake evaporation (mm) (1986-2003)

As it is seen from Figure 3.9 the mean annual pan evaporation trend decreases since 1996, this could be the effect of the increased in rainfall and the slight decrease in wind speed.

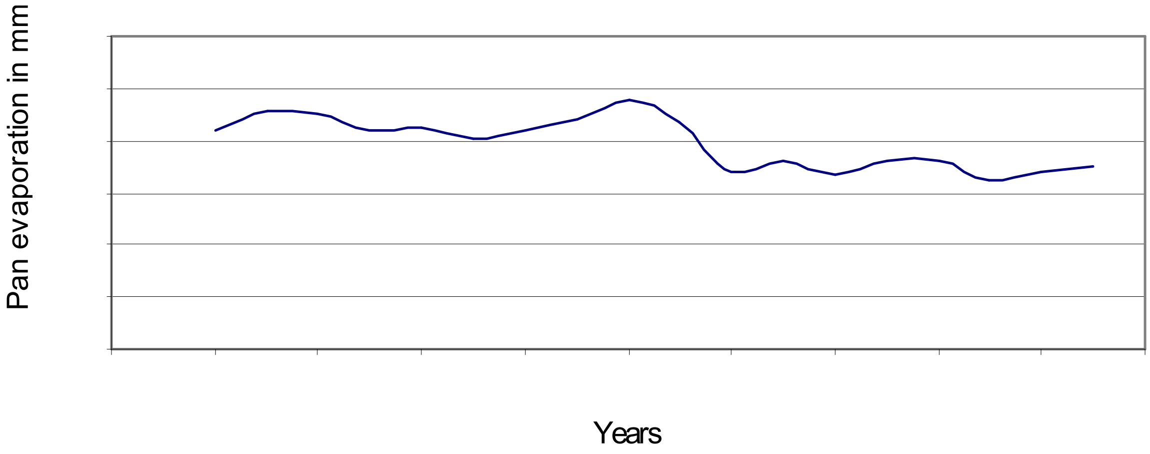


Figure 3.9 Mean annual pan evaporation trend at Awassa.

3.2 Surface hydrology

The studied area is a closed catchment with out surface connection with the surrounding basins. There is no surface water that enters or leave the catchment. The catchment contains lake, swampy areas, perennial rivers, ponds, dry gullies and open channels that drains during rainy season. Lake Awassa is the main water body in the area, following Lake Shallo, which at present becomes a swampy area. Tikur Wuha River is the main perennial river that drains the eastern escarpment and highland toward Lake Awassa. There are also perennial and intermittent streams on the eastern escarpment which later joins Tikur Wuha River or Shallo swamp, such as Wesha, Werka, Gemesha, Kedo, and Bela are some of them. The characteristics of some water bodies are discussed below.

Lake Awassa

Lake Awassa is the main water body situated on the center of the floor of the caldera. The Lake morphology of Lake Awassa as stated by (WWDSE, 1999) is:

- Lake area: 100km^2
- Maximum depth: 23m
- Mean depth 13.5m
- Maximum length: 17km
- Maximum width: 9.5km
- Lake volume: ≈1350mcm
- Catchment area: 1376km^2
- Surface elevation: 1680m.a.s.l

Climate:

- Mean annual precipitation on the Lake: 953mm
- Mean annual evaporation from the Lake: 1581mm

At present Lake Awassa shows an increase in its level, which is the main problem of the area. The rise of the Lake level is evaluated by using a 34 years lake level measurement data from the Ministry of Water Resource (appendix II). As shown in figure 3.10, the lake level fluctuate following the dry and wet seasons previously, however unusual increasing trend is observed from 1996 to 1998. The maximum stage increment is in 1998 which is 3.26m.

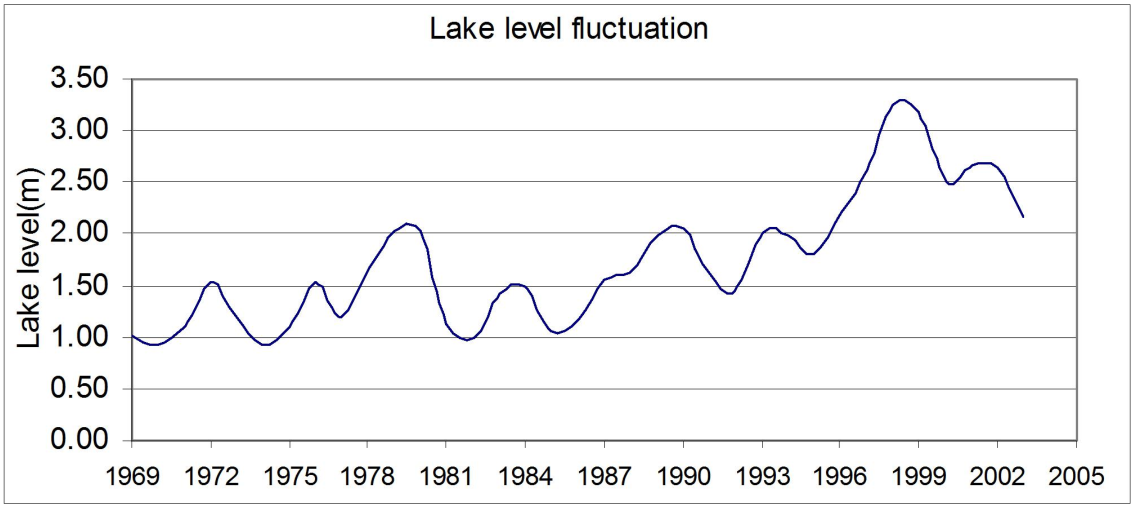


Figure 3.10 a graph showing the stage increment of Awassa Lake level

Lake Shallo

This Lake is found on the floor the caldera east of Lake Awassa where they were united as a single lake before (Mohr, 1970). Now this Lake becomes a swampy area and covered by papyrus like grasses, however it was about 12km^2 covered by water during 1972.

Derba Pond

This is a small pond found on the south western parts of the catchment. It is situated in a depression formed by parallel NNE-SSW/N-S running rift faults. It has no surface connection with Lake Awassa. This pond covers an area of around 5km^2 and with approximate depth of 2m. Now this pond is disappeared as a result of the formation of the cracks in the area (from local residence information, which took place in 2000).

Tikur Wuha River

This river is the only perennial river that enters in to the lake with a drainage catchment of 625km^2. It has been gauged since 1981 at Dato village and from 1981-1998 flow measured data was found from Ministry of Water Resources (MoWR). Flow component separation (Table 3.10) of this river is done by Zenaw Tessema, (2003) as a result the long-term mean annual discharge of this river is 84mcm of which 30mcm was its base flow. This is 36% of the total run off however, this river gets significant amounts of base flow from the groundwater and the base flow might exceed this value.

Table12 Flow components of Tikur Wuha River Discharge in MCM (1981 -1998)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann
Total runoff	3.88	2.65	2.30	2.77	5.10	7.40	7.76	9.64	12.17	14.16	9.50	6.46	83.80
Direct runoff	0	0	0	0.96	3.49	5.97	6.26	7.90	10.36	10.68	5.62	2.17	53.41
Base flow	3.88	2.65	2.30	1.81	1.61	1.43	1.50	1.74	1.81	3.48	3.89	4.29	30.39

Table 3.9 Flow components of Tikur Wuha River in million cubic meter (mcm) after Zenaw Tessema, (2003)

Precambrian. As far as the development is concerned, eruption of huge volumes of vulcanite started in late Eocene-early Oligocene in the MER and adjacent plataeux (Merla et al., 1979; Kazmin et al., 1980; Woldegebreil et al., 1990; Ebinger et al., 1993) in (Benvenuti et al., 2002), preceding the rift formation.

The early rifting phase (Late Oligocene-Early Miocene) was characterized by the formation of alternating half grabens (Woldegebreil et al., 1990), following these event full symmetrical grabens and rift-in-rift structures were developed (Di Paola, 1972; Woldegebreil et al., 1990). The most important volcano-tectonic event in the central sector of the MER occurred in early Pliocene, with the outbreak of voluminous flows of rhyolitic ignimbrites and the collapse of very large calderas (Di Paola, 1972; Woldegebreil et al., 1990). The full symmetrical rift configuration was achieved during this event (Woldegebreil et al., 1990).

The youngest parts of the MER are the axial zone, which presently coincide with the Quaternary Wonji Fault Belt (WFB). The WFB is characterized by NNE-SSW trending active extensional fractures and normal faults (Gibson, 1969; Mohr, 1987) where arranged in a dextral en-echelon configuration (Mohr, 1968; Bocalleti et al., 1998), with vertical displacements in the order of several tens of meters (Gibson, 1969; Acoccella et al., 2002). The axial zone is associated with several types of calderas such as remnants of Quaternary calderas (Tulu), complex calderas with nested systems (O’A, Corbetti and Awassa caldera) and active calderas with sub-vertical rims (Fentale, Garibodli and Gedemsa) are some of them (Mohr, et al., 1980; Tesfaye Korme et al., 1997; Cole, 1969; Le Turdu et al., 1999). From early Pleistocene to the present, tectonic and volcanic activities concentrated along the WFB and SDZFZ (Mohr, 1962; Di Paola, 1972). Since then middle Pleistocene fluvio-lacustrine basins developed along the WFB, under a tectono-volcanic control (Le Turdu et al., 1999) and occupies large area of the MER.

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 Awassa 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 (Gidey Woldegebriel, 1968). The caldera is composite, containing the younger 15km wide nested Corbetti caldera with in it in the northern margin. The main Awassa caldera is asymmetrically overlapped against the eastern rift escarpment causing this rift margin arcuate, while Corbetti is along the rift axis.

This sector of the MER and its shoulders are made up of volcanic and pyroclastic rocks where as large part of the floor is covered by volcano-lacustrine and fluvio-lacustrine deposits (regional Stratigraphy is given in appendix III).

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 range from 40-25Ma and the rhyolites 37-27Ma (Merla et al., 1979; Woldegebriel et al., 1990).

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 (Di Paola, 1972; Merla et al., 1979; Woldegebriel et al., 1990), 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 (Mohr, 1962; Di Paola, 1972; Woldegebreil, et al., 1990). 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), 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.). It is very recent and localized, with a radiometric age of 0.13Ma (Woldegebriel et al., 1990). 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., 1990). 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 (Gianelli, et al., 1993).

The Late Quaternary fluvio-lacustrine sediments cover the large part of the floor of the MER (the Lakes region) where the lakes in this region, they were in a very wide lake in the past occupying most of the rift floor (Merla et al., 1979).

4.2 Stratigraphy

Figures 4.1 & 4.2 indicates the geological map of the studied area modified by the author, (Fig. 4.1) shows the detail rock types with in each geological units and (Fig. 4.2) contains the generalized geological units classified in order to use for interpretation purposes. The description is given starting from the oldest.

4.2.1 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 30-50m 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 Awassa caldera was constructed with age of 9.8Ma (Gidey Woldegebriel, 1987; Woldegebriel et al., 1990).

4.2.2 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 is covered by ignimbrites underlying moderately welded coarse tuff of this unit. The ignimbrite usually forms low relief flat-topped hills, porphyritic with rock fragments of various size and intercalating weak tuff layers. The ignimbrite is also found south of Lake Awassa forming a ridge (Dulecha ridge).

The northeastern part of the area is covered by ignimbrites and tuffs of this unit, with age range of 3.7-1.6Ma (Gidey Woldegebriel, 1987). This unit is also exposed on the southern, southwestern and northwestern parts of the area. Pyroclastic deposits containing silty-gravely sand with angular coarse pumaceous pyroclastics and lava rock fragments characterize the southern & southwestern part. The Pumaceous pyroclastics on the southwestern periphery is composed of pumice fragments with lapilli tuff of fragmental texture. This deposit is affected by the N-S/NNE-SSW trending faults forming elevated blocks and parallel basins. The northwestern part is covered by unwelded coarse tuff with thickness more than 200m (Zemenu Geremew, 2000). The rhyolitic ridges at Wendogenet, with age 2.45Ma (Gidey Woldegebriel, 1987) and the rhyolitic necks on the floor of the caldera south east of lake Awassa are also included in this unit, having vertical sheeting and flow folding structures.

4.2.3 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 Awassa such as Mt. Tumura. Its color range from dark brown to reddish brown where as 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. This unit is found on the west & north east of Lake Awassa such as Werensa ridge.

4.2.4 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 Awassa around Corbetti volcano. The pyroclastic deposits, welded & unwelded tuff deposits of the 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.

4.2.5 Volcano-lacustrine deposits (Pleistocene to recent)

This unit is the only non-volcanic 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. Awassa 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 (Tenalem Ayenew, 1998), i.e. they are either quiescent lake deposits, water deposited volcanic ejecta or coarse sediments intruded into 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.

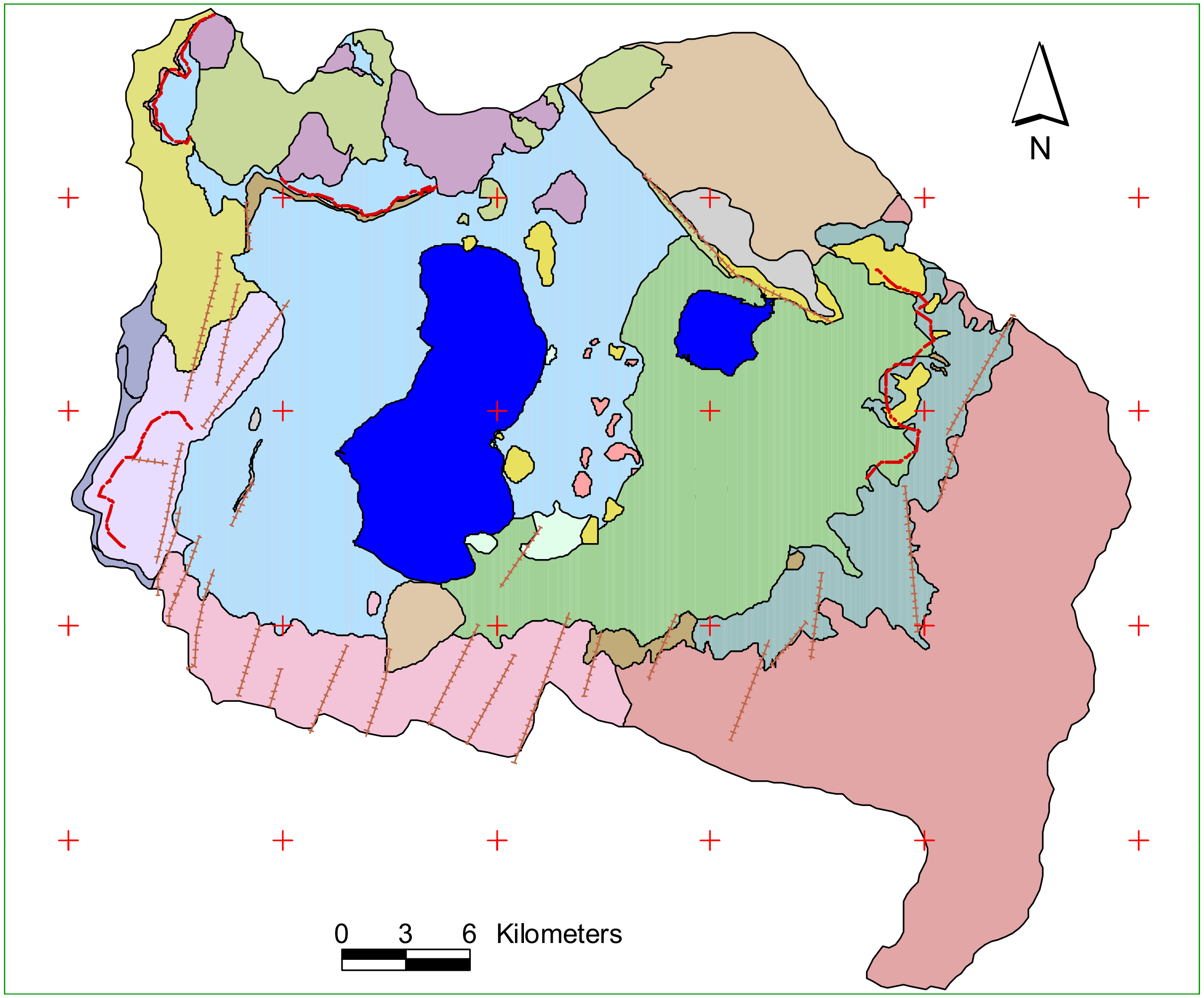


Figure 4.1 Geological map of the studied catchment (modified after Zenaw Tessema, 2003)

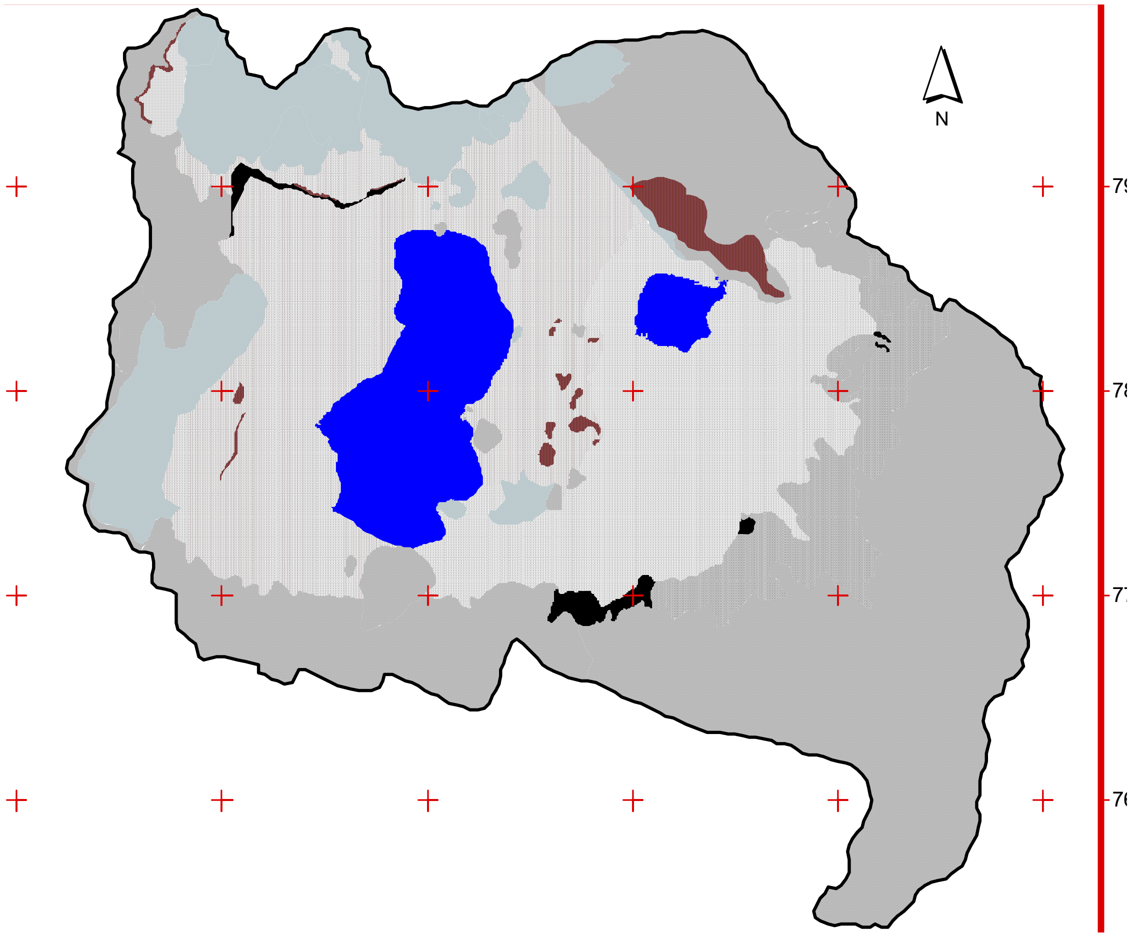


Figure 4.2 Generalized geological units of the area

4.3 Geologic structures

The studied area is found on the axial zone of the MER, where caldera structures and Wonji Fault Belt (WFB) is concentrated. In order to map the geologic structures of the area, Visual interpretation of enhanced Landsat TM colour composite (741) image and Digital Elevation Model (DEM) derived from a 90m-resolution Shuttle Radar Terrain Model (SRTM) image was used. Some field observations also added to define the throw directions of the normal faults and their significance for groundwater circulation.

Therefore, normal faults, fracture zones and faults, volcanic domes and cones, lineaments and collapse structures are mapped. There are at least three types of structures, which are present in the area based on their strike directions, NNE-SSW, N-S running, NW-SE and E-W running faults/fracture zones (lineaments).

The NNE-SSW, N-S running faults are the Rift escarpment faults, dominant in the area where Lake Awassa is also oriented in this direction (Fig. 4.3). These faults are expansion normal faults forming steps and are found mainly on the southern and eastern part of the catchment. These faults made parallel-elevated blocks and depressions such as southwest of the Lake near Muletti, where the depressions have no surface connection with the Awassa Lake. The NW-SE transfer faults are rare in the area but observed on the northwest part of the area around Corbetti, northeast part of the Lake and on the eastern margin of the rift. The E-W running faults are dominantly found on the southern watershed where the rivers/streams in this area are controlled by the direction of these faults/fracture zones. Buried faults of this type are also found on the floor west of the Lake, which are traced by geophysical survey from WWDSE, (1999).

Structurally the area is complex by the presence of Corbetti caldera, which is affected by the NNE-SSW running faults; it is nested in the larger Awassa caldera. The remnants of the larger Awassa caldera preserved on the eastern and western part accompanied by normal faults and fracture zone.

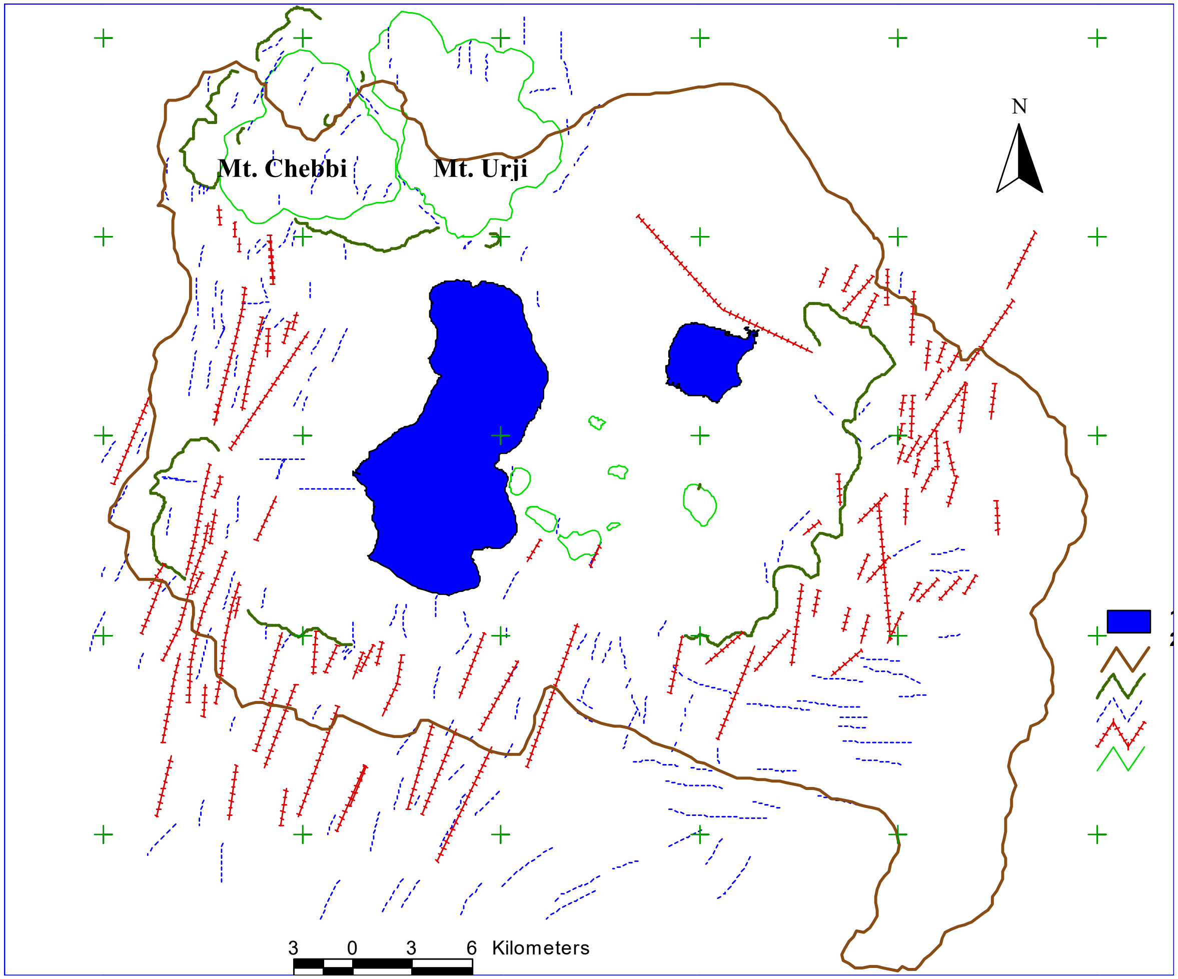


Figure 4.3 Structural map of the area

4.4 Recent Tectonics/Ground Cracks

The Awassa caldera is situated on the axial zone of the MER. The axial zone is a place where younger and active volcanism and recent tectonic activities are took place as evidenced by high seismicity and geothermal activities. This zone is presently coincides with the NNE-SSW trending WFB where active extensional fractures and normal faults are found. Recent ground cracks were developed in the area west of Lake Awassa since 1996. This ground cracking is situated on the axial zone with similar trend of propagation with the adjacent fault scarps and mountain ridges. The ground cracks occurred in two places; west of Lake Awassa around Muleti village and further south of Muleti on Derba area (fig. 4.4). The cracks on Muleti developed in 1996 and have average width of 2.5m, with measurable depth of 8-12m and maximum length of 2.4km (Lulseged, et al., 2004). The cracks on Derba area have a width of 2-8m and observable depth up to 5m with no vertical displacement. The cracks strike approximately N30^{0}E with a characteristic of intersecting oblique extension cracks trending N60^{0}W. The features are observed on the top alluvial deposit (fig. 4.5 shows the photographs of the cracks in Derba and Muleti area).

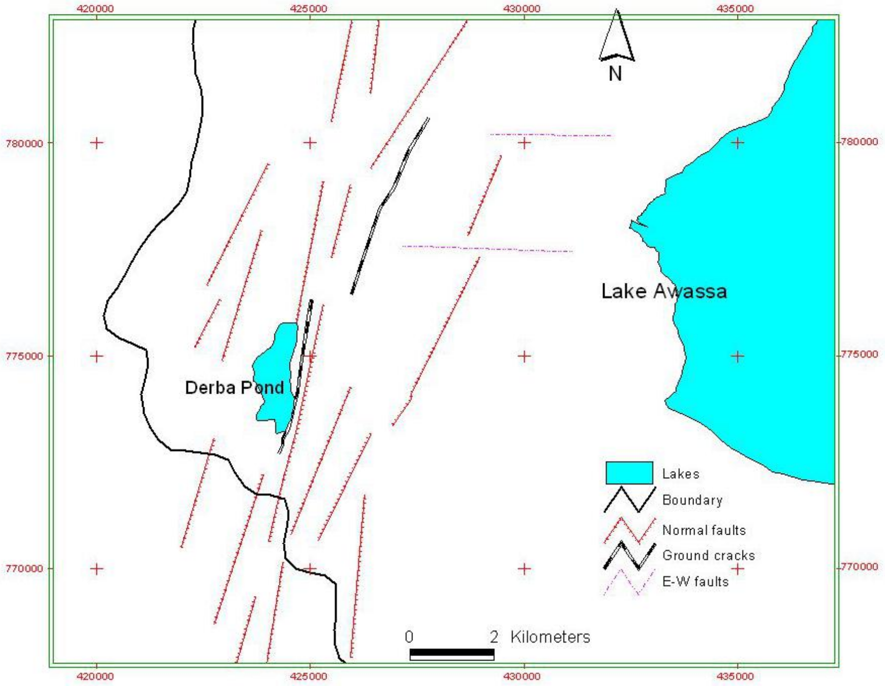


Figure 4.4 A map showing the location of ground cracks and Faults west of Lake Awassa

The Derba area is previously occupied by a pond which is Derba Pond. The water of this pond was disappeared through these cracks three years before (2002) when they were formed (information from the residents). From this it can understood that these cracks are also propagated with depth. Even though, there are no substantial evidences, their process of formation is speculated to be associated with large scale tectonic activity. Similar features are found in the axial zone of the MER around Shalla, Adami Tulu, and Fentale area. Those found on Fentale area, their characteristics of development is modeled by Acoccella, et al., (2002). According to him, time to time development of these features leads to the formation of normal faults and their origin is associated with rifting. They are at different stage of evolution of normal faults. Similarly the features found in the study area are speculated to be a surface response of interior tectonic movements, which affect the surface and groundwater hydrology of the area.

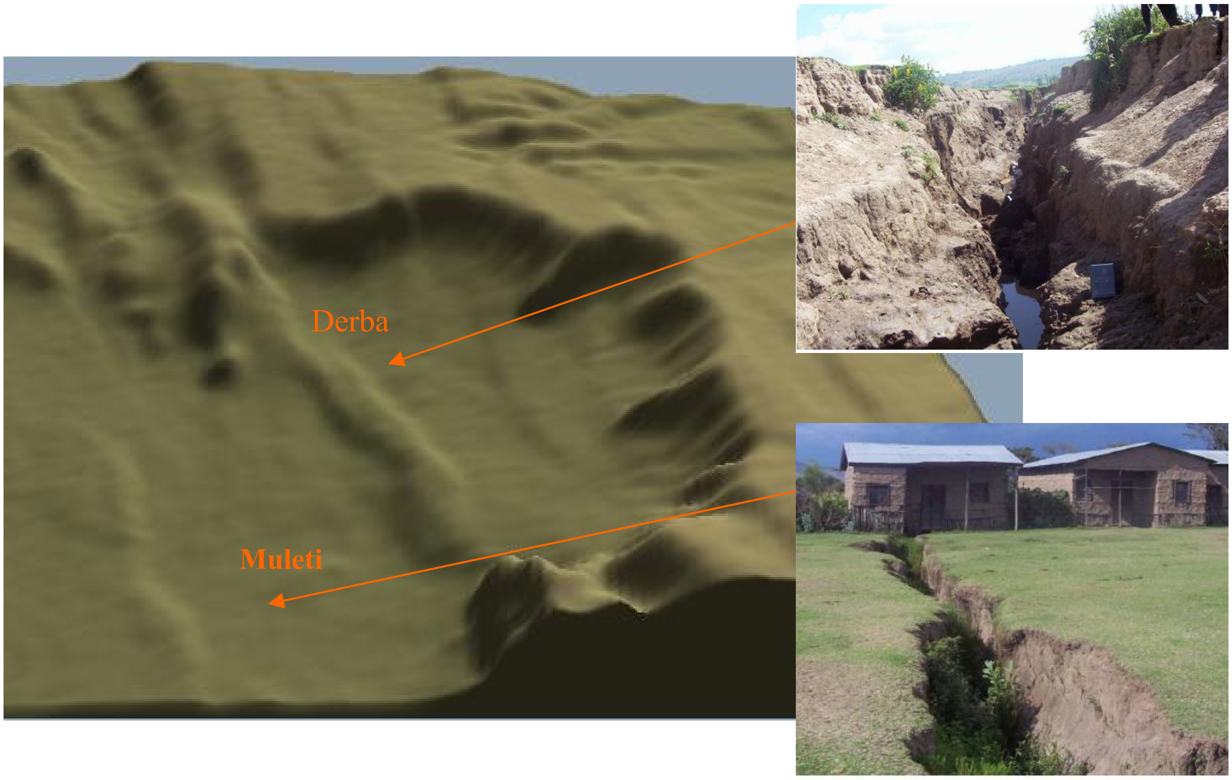


Figure 4.5 A DEM along with a photographs showing the area where the cracks are formed.

Figure 4.6 photographs showing the ground cracks found in Derba area

Besides the quantitative hydraulic nature of the rock units, qualitative properties of the different rock units are used during characterization, for instance in areas where there is the lack of hydraulic data, topography, the presence of surface water features, degree of weathering and fracturing, recharge/discharge conditions, data from similar areas outside the catchment and results of geophysical survey of Water Works Design and Supervision Enterprise (WWDSE, 1999), etc are used.

5.2 Aquifer characteristics

Aquifer characteristics are very essential, when dealing with problems of groundwater flow, resource evaluation and modeling. In order to define these characteristics, such as hydraulic conductivity, transmissivity, porosity, specific storage, and storage coefficient, etc, aquifer tests conducted in open holes and wells, laboratory analysis of rock samples collected from outcrops and drill cores are some of the methods. Here the hydraulic parameters (K, T) are determined from existing data of pumping well aquifer tests that were conducted the past seven years.

In order to derive these parameters, the pumping test analysis was tried by two methods depending on the individual hydraulic conditions at each well. The methods applied are Neumann (1975) and Moench (1993), which is the modification of the Neumann method for partial penetration of wells in unconfined aquifer (Thomas Rhoehrich, AQUITEST). These methods are applied for the interpretation of 8 wells in the area where all of the wells from the lacustrine sediment. The considered assumptions are unconfined aquifers of infinite aerial extent, and saturated thickness is used as aquifer thickness.

The hydraulic characteristics of the area are defined for 19 data points; most of them lie on the lacustrine sediment. From the existing and results of the analysis of pumping test data shows that the hydraulic conductivity in the area is highly variable (Table 5.1), which ranges from 0.24m/day in the ignimbrites and tuffs to 442m/day in the lacustrine sediments and transmissivity ranges from 13m^2/day to 4010 m^2/day, which is the

Borehole Id	Total depth(m)	T(m2/day)	K(m/day)	Drawdown(m)	Q(l/s)	Aquifer type
BH1	40					Lacustrine sediment
BH2						Lacustrine sediment
BH3	145	13	0.24	24	2.17	Ignimbrite
BH4	36					Ignimbrite
BH5	157				2.7	Lacustrine sediment
BH6	120				2.2	Lacustrine sediment
BH9						Lacustrine sediment
BH11		2080	71.72	0.3	2.5	Lacustrine sediment
BH12	46	81.8	3.2		5.25	Lacustrine sediment
BH13	50	52.18	1.5		4.67	
BH14	62	1980	185		5	Volcanic sand
BH15	60	3801.6	442.6		6	Volcanic sand
BH16	83				1.5	Volcanic sand
BH17	119				4.4	
BH18	30	96.8	12.3			Lacustrine sand & tuff
BH19	33	158	20.5			Lacustrine sand
BH20	29					Lacustrine sand
BH21	18					Lacustrine sand
BH22	20	388.8	24.6			Lacustrine sand
BH23	58	1382.4	40			Lacustrine sand
BH24	72					lapilli tuff
BH25	42					lapilli tuff
BH26	54	70	3			lapilli tuff
BH27	65					lapilli tuff
BH28	81					lapilli tuff
BH29	50	4809.6	150.3	0.2	7	pumaceous tuff & scoraceous basalt
BH30	50	453.6	11	3.54		sand & gravel with pumice
BH31	56	41.2	1.2	15	6.5	sand & gravel with pumice & tuff
BH32	62	1540	77	2.01		Sand with some gravel & weathered tuff
BH33	107	528.5	10.5	8.65		Sand & gravel, scoraceous basalt
BH34	50	880	18.7	7.34		sand
BH35	50	501	11.4	8		sand
BH36	100	411.8	4.7	1.2		sand with gravel
BH37	77					scoria
BH38	100					scoria

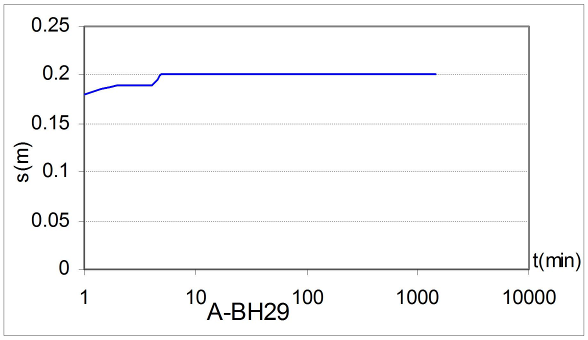
Table 5.1 Hydraulic characteristics of wells in the area

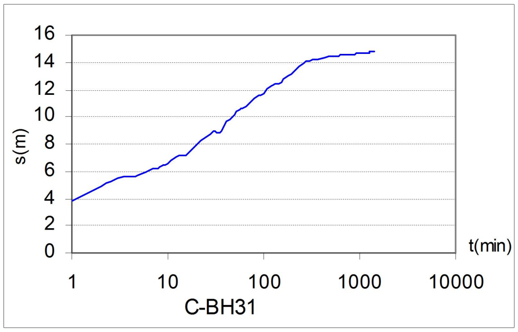
characteristics of the fractured volcanic rocks and the variability in lithology of the lacustrine sediments, more or less similar variations are also found in Ziway-Shalla basin (Tenalem Ayenew, 1998).

The aerial distribution of data values seems random, and has no clear regional trend in hydraulic conductivity, but on some areas zonation is observed even though there are local high values for example a well found east of the Lake (BH-15) shows hydraulic conductivity value of 442m/day, which fracturing and/or weathering of the scoraceous basalt below the sediment may have caused this anomalously large value, generally conductivity values range from 50-200m/day attributed to this area.

Time-draw down plots of existing data is used in order to define the nature of the aquifer. The pumping test data doesn't represent the whole area but the characteristics of some areas with available data of the floor are interpreted. The interpretation is based on theoretical models (semi-log or log-log plots of drawdown versus time), the characteristics of which are assumed to represent the characteristics of the real aquifer system so that it is system identification by comparing the behavior of the drawdown with that of the various theoretical models or standard curves. The theoretical models comprise the type of the aquifer, the initial and boundary conditions, which affects the drawdown behavior of the system during pumping tests. The model that compares best with the real system is then selected; in addition the corresponding well logs support the interpretation. (The various standard curves are found in appendix IV).

Figure 5.1 shows semi-log time-draw down graphs of wells in the area. As a result from the graph of Figure 5.1 A-BH29, a well found east of the Lake, which is a characteristic of unconsolidated unconfined aquifer. At early pumping times, the curve follows similar to the curve of confined aquifer, but at medium pumping time it shows a flat segment. This reflects recharge from the overlying less permeable aquifer, which stabilizes the drawdown, however at later times again the drawdown stabilizes. This might be due to the presence of recharge from the adjacent Lakes or Tikur Wuha River. A similar characteristic of the above is reflected on graphs of wells B-BH30, C-BH31, D-BH32, and E-BH36 where C-BH31 might be affected by a recharge from the near by Shallo swamp that is why it stabilizes at later time . While the remaining F-BH34, G-BH35, and H-BH33 generally taken as unconfined aquifer with multi-layered permeable and less permeable aquifer system.


0.25
0.2
0.15
s(m)
0.1
0.05
0
t(min)
1
10
100
1000
10000
A-BH29


16
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t(min)
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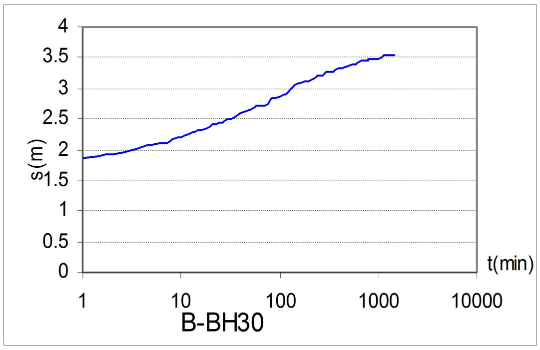
C-BH31


4
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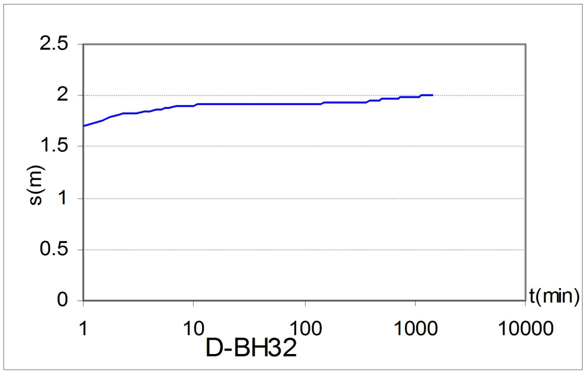
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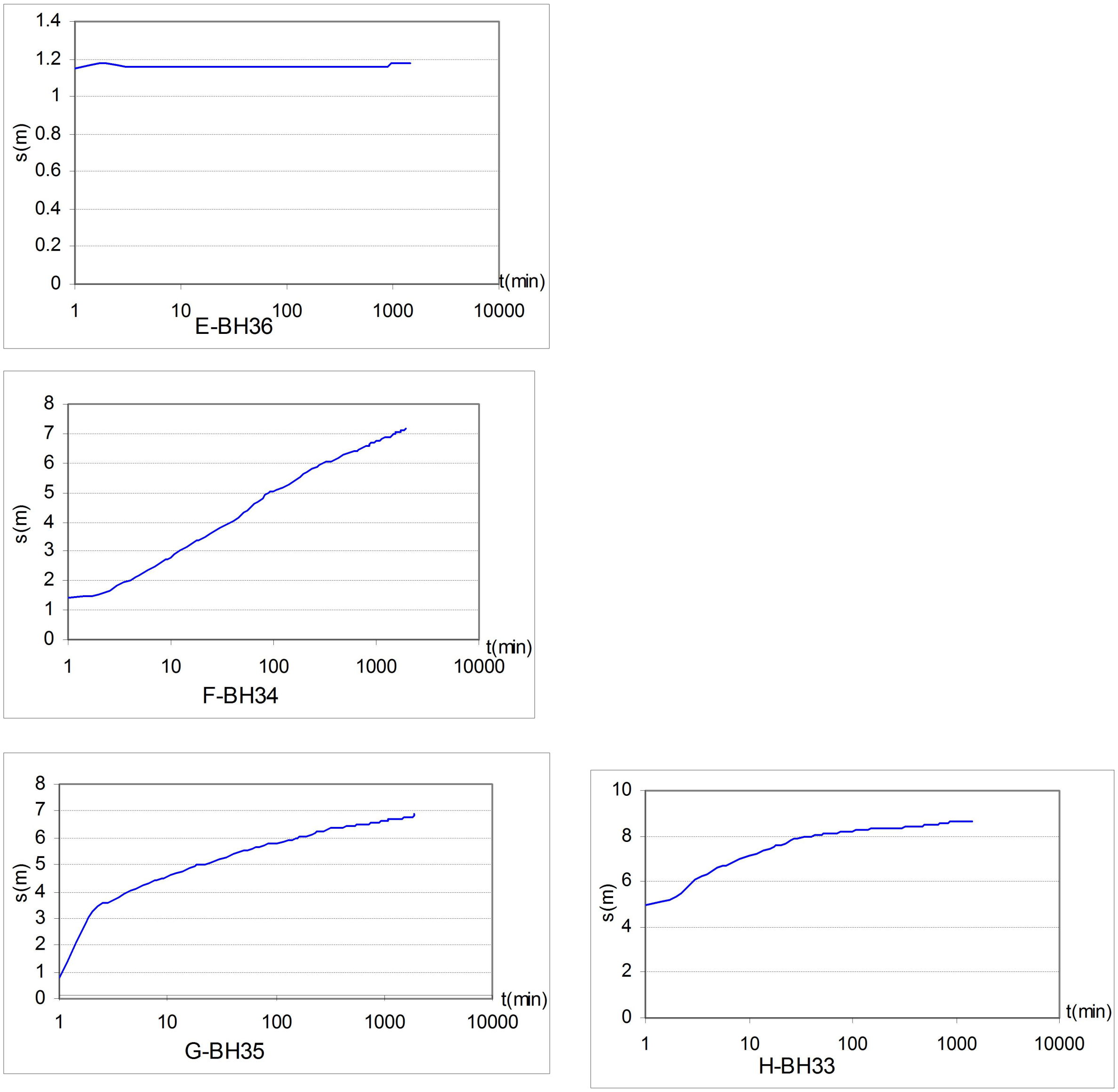


Figure 5.1 Semi-log plots of time Vs drawdown of wells in the area

The characteristics curve are affected by various conditions, for instance F-BH34, the time drawdown relationship first stabilize then at later time becomes linear, this is because of the presence of less conductive fractured ignimbrite aquifer below the sand aquifer. In G-BH35 the curve deviates from theoretical curve at medium pumping period this might be due to the partial penetration of the well where as H-BH33 exists in a three-layered aquifer system where the drawdown stabilizes at earlier and later pumping periods. This is as a result of recharge from the two overlying layers.

Generally, the aquifer system in the studied area is found to be in unconfined condition except aquitard layers of clay and ash deposits exists on some parts of the area. For example free flowing well is found southeast of the lake (Melgae Wendo). The presence of multi-layered aquifer system with variable permeability is also the characteristics of the area. This is the nature of the lacustrine sediment in the area, which composed of clay, sand to gravel, ash, pumice, tuff, and volcanic fragments of rhyolites, ignimbrites and scoraceous basalt (Fig. 5.2 simplified cross-sections from neighboring well logs that shows the vertical distributions of the hydrostratigraphic units of the area). Except local variation, the main aquifer of this unit (lacustrine sediment) is volcanic sand and gravel. Locally aquifers of scoria and basalts are found. Underlying this sediment, aquifers of fractured ignimbrite is found but due to its great depth most of the wells don't penetrate this unit and its characteristic is unknown, however it is the aquifer for Corbetti geothermal wells. Regarding the thickness of the aquifers, it is highly variable as the lithology. It ranges from 20-30m in the lacustrine sediment, even reaches 40m when the well penetrates the underlying ignimbrite, the scoraceous basalt and in areas of thick lacustrine covers.

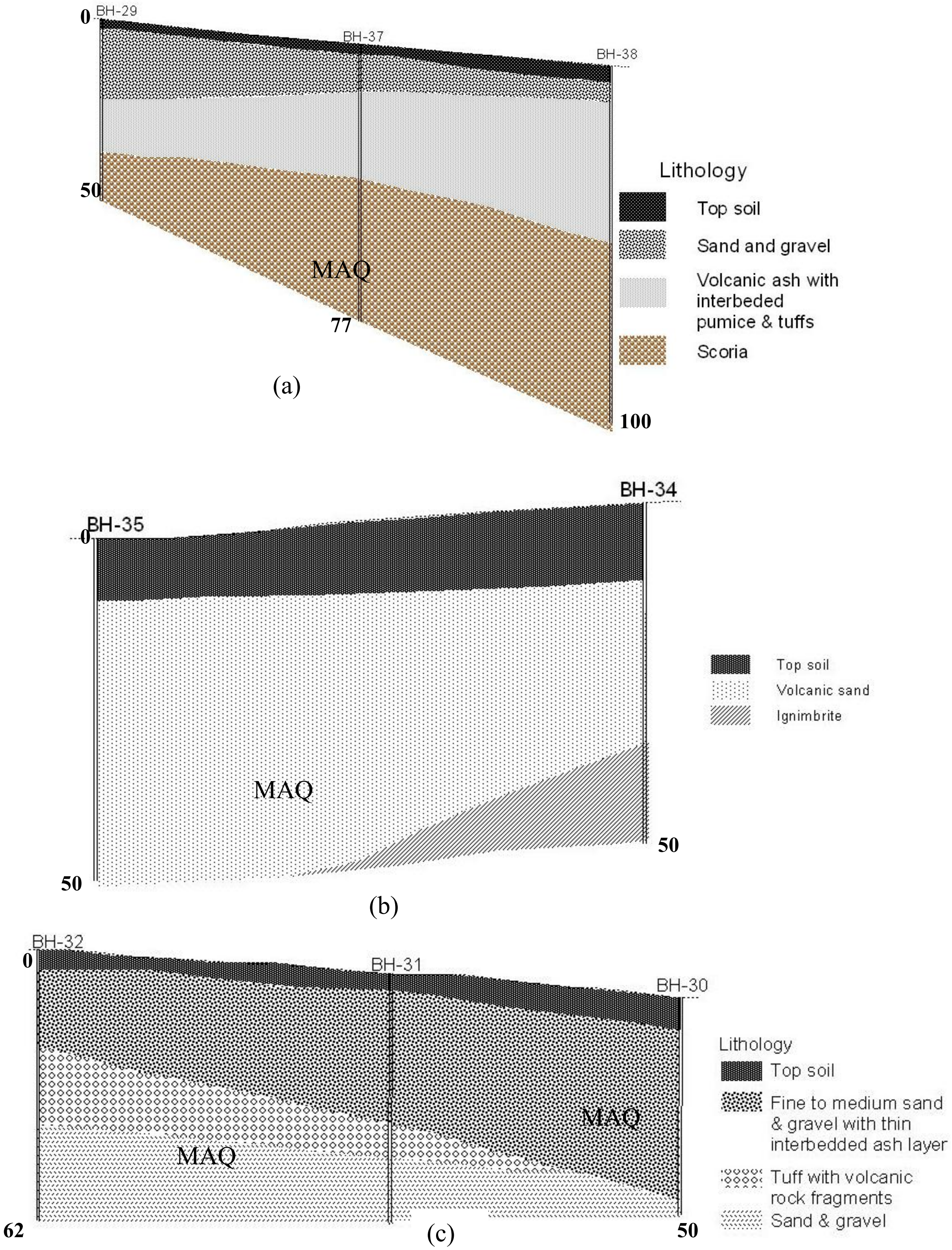


Figure 5.2 Vertical distributions of aquifers correlated by neighboring wells (a, east of the Lake; b, south east of the Lake; c, further south near the caldera wall), MAQ-main aquifer.

5.3 Hydrostratigraphic units

Hydraulic conductivity and transmissivity data derived from pumping test analysis and collected from various organizations show that a high variability spatially in the catchment, this might be as a result of the presence of structures (faults and fractures), the degree of fracturing of the volcanic rocks and/or the complex/reworked nature of the lacustrine sediment.

Figure 5.3 shows hydraulic conductivity map where the studied area is classified into six hydraulic conductivity zones.

Zone 1 (>50 m/day): this includes recent highly fractured scoraceous basalt associated with permeable lacustrine sediments of medium grained sand and volcanic necks of the scoria are also in this group. It is characterized by a high intergranular and fractured permeability of the sediments & scoraceous basalt beneath. The alignment of the volcanic necks of the scoria indicates that, it is a fracture zone; however they have limited lateral extent in the area.

Zone 2 (10-50 m/day): thick lacustrine sediments and recent alluvium deposited on the floor and near the caldera rim with a characteristics of two or more aquifer of sand and volcanoclastic sediments. Fractured ignimbrite of the foot of the caldera south east of the Lake which is affected by NNE-SSW/N-S faults also included in this group. It gets high amount of recharge from the southern part but the presence of clay & ash/aquitard relatively decreases its permeability.

Zone 3 (5-10 m/day): this group includes relatively thin lacustrine sediments in the Northern and Western parts from the Lake with associated acidic volcanics near Corbetti caldera. The presence of unwelded poorly sorted less permeable volcanoclastics, volcanic ashes and lapilli tuffs minimizes the permeability.

Zone 4 (1-5 m/day): these are fractured ignimbrites of the caldera floor and the escarpment with associated ignimbrites and tuffs of this group, less fractured recent basalts, hayaloclastites and pyroclastic deposits of the caldera rims on southwestern parts of the area, which is affected by NNE-SSW/N-S faults. Lacustrine sediments (west of the Lake) at the foot of the caldera are also included in this group.

Zone 5 (0.1-1 m/day): old alkaline & Peralkaline rocks of the escarpment where they are recharge areas rather than aquifers. Unwelded to moderately welded fine to coarse tuff and pumaceous deposits of acidic volcanics with characteristics of very deep water table and massive nature.

Zone 6 (<0.1 m/day): this includes acidic volcanic plugs of the Corbetti caldera with a characteristic of very low permeability such as the rhyolitic lava flows with associated obsidians. Volcanic necks and domes of the old rhyolitic lava flows, lapilli tuffs and lava flows of the floor and caldera rims are also included in this group.

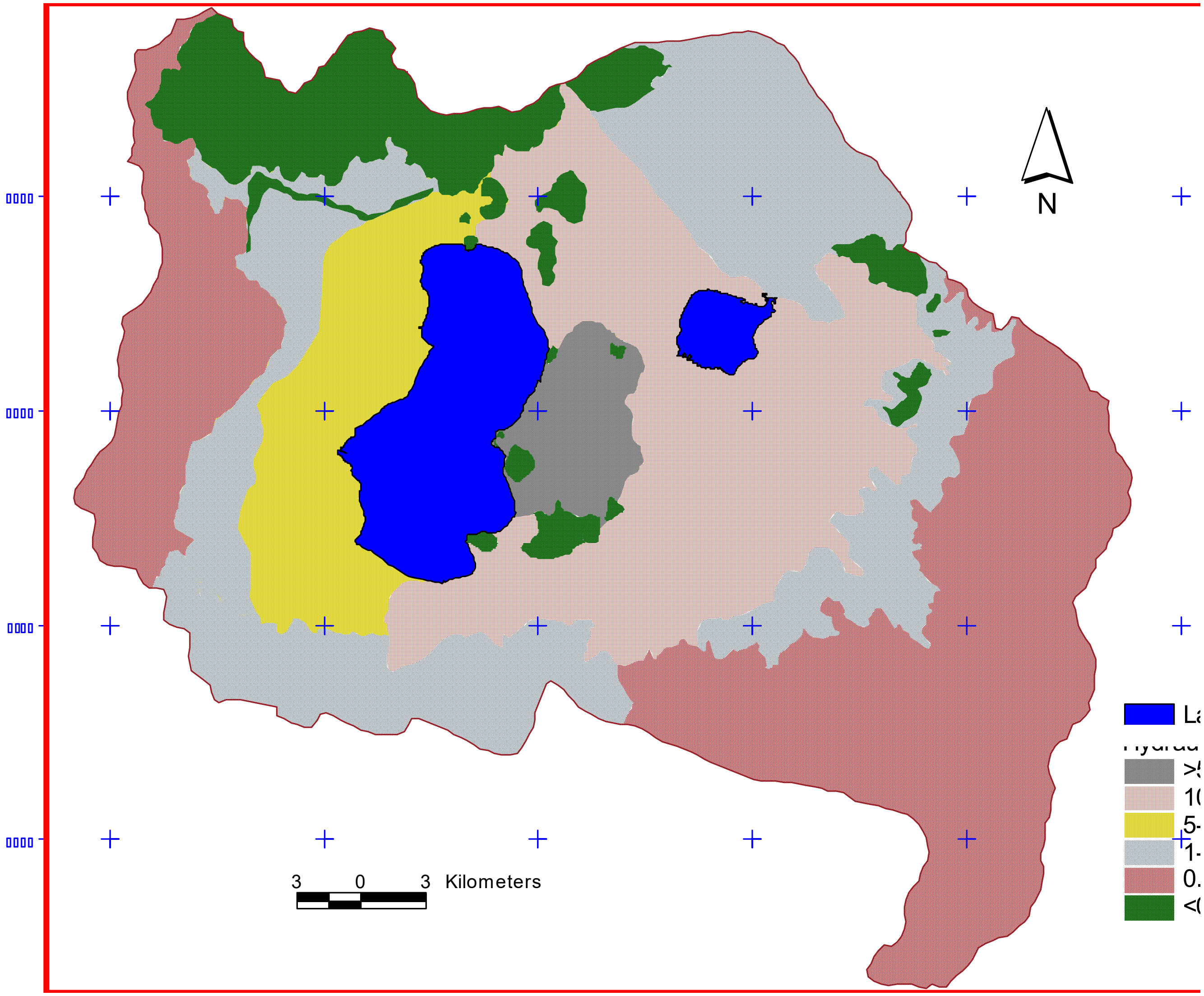


Figure 5.3 Hydraulic conductivity map in m/day

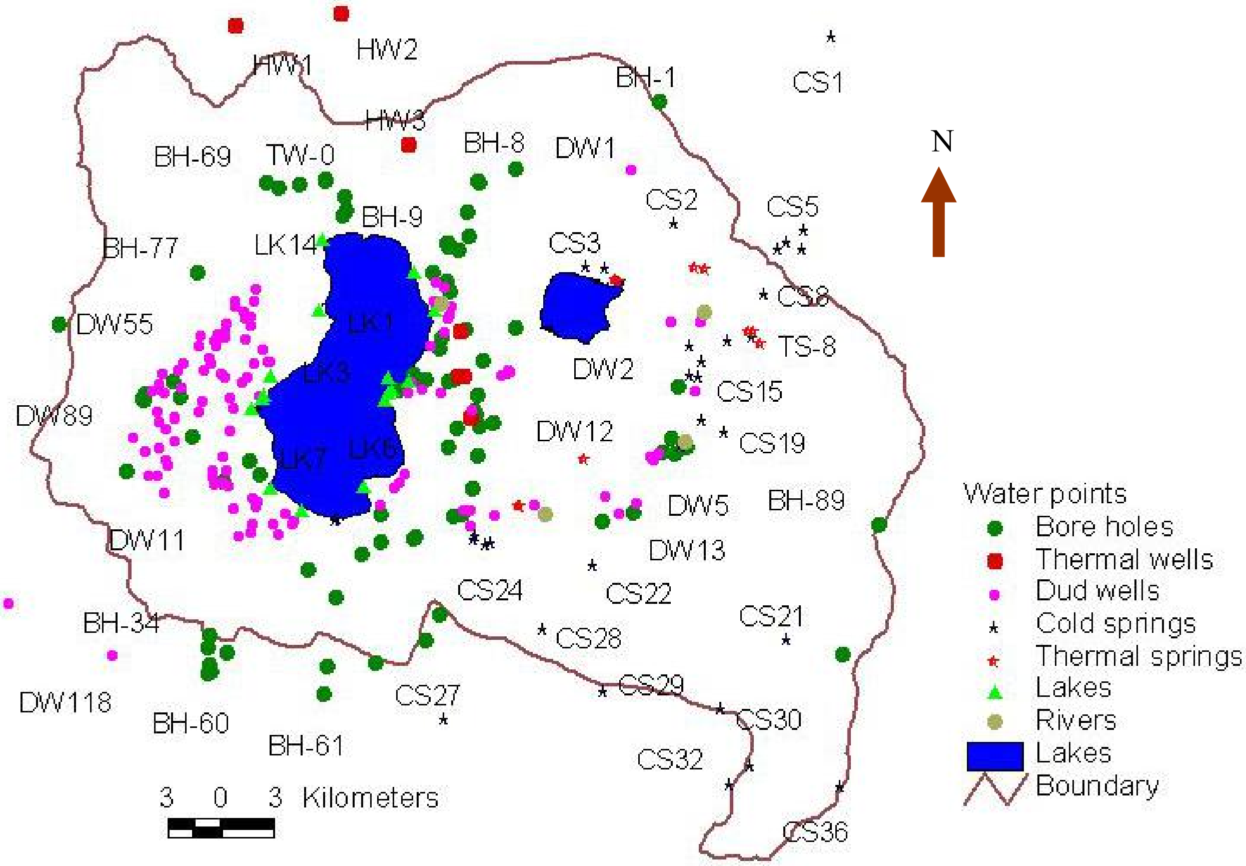


Figure 6.1 Distributions of water sampling points

6.2 Electrical conductivity

Water quality variables measured in the field including, EC, TDS, pH, Temperature and laboratory analyzed hydrochemical and isotopic data are shown in appendix V. From this a map of electrical conductivity surface was prepared that shows the spatial variation of different water bodies (except anomalously large values of thermal waters) in the area (fig. 6.2). From the map, a zonation of electrical conductivity variation is observed. The trend of zonation is from south east of the catchments toward northwest boundary with the characteristics of increasing value. Surface and sub-surface natural waters from the southeastern area, the escarpment and highland are characterized by relatively low EC values, which is less than 300µs/cm. Even the hot springs found on the eastern escarpment are characterized by low EC values relative to waters of the floor.

The floor of the caldera including Lake Awassa shows relatively intermediate value with local exceptions in the presence of hot springs, which shows anomalously large values for example Shallo hot springs north east of Lake Awassa. Further North toward Corbetti caldera, EC values increases considerably up to 3000µs/cm in the thermal wells but generally the cold wells in this area have EC values between 1000-2000µs/cm. The fresh lake awassa is characterized by a value of 810µs/cm. EC values of subsurface waters from lake awassa to the west direction also shows an increasing trend observed from hand dug wells in this area.

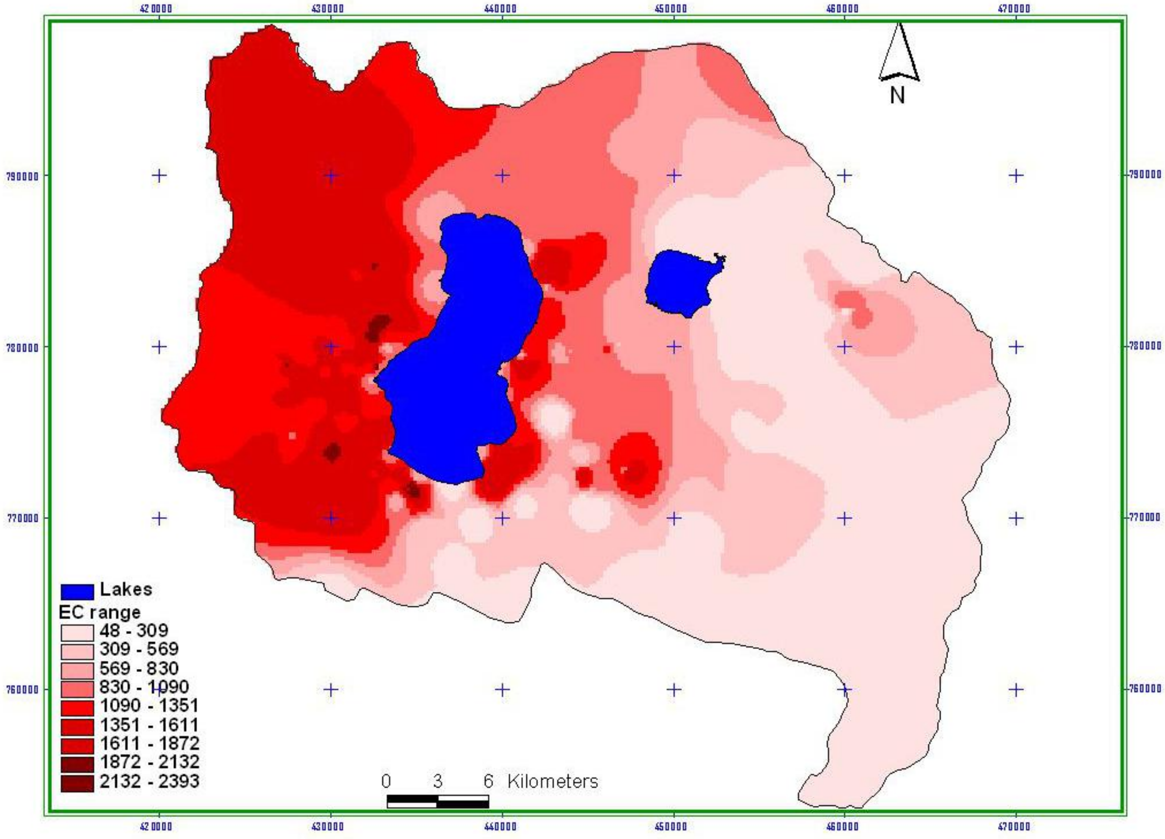


Figure 6.2 A map showing electrical conductivity (µs/cm) variations in the area

6.3 Major Cations and Anions

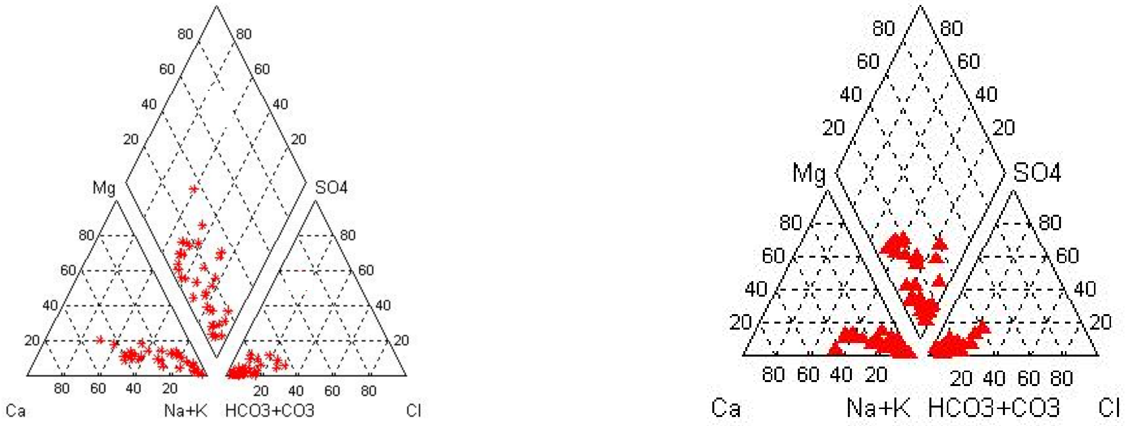
The concentration of major cations and anions of surface and groundwater in the area. There is a relative variation in the concentration of major ions spatially and among water bodies. The dominant cation is sodium followed by calcium; whereas the dominant anion is bicarbonate with minor chloride and sulfate that occur in thermal waters. Figure 6.3 shows 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.

Therefore there are three main water types in the area:

- Na-HCO_3 (Sodium Bicarbonate type)
- Na-Ca-HCO_3 (Sodium-Calcium Bicarbonate type)
- Ca-Na-HCO_3 (Calcium -Sodium Bicarbonate type)

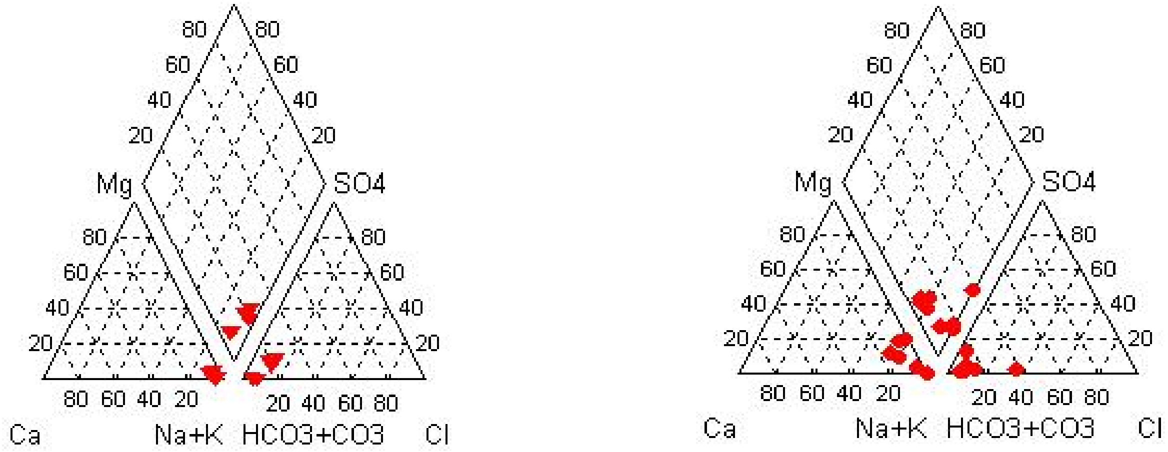
Sodium Bicarbonate type: In this type of water Sodium and Bicarbonate are dominant cations and anions. It is the characteristics of groundwater and surface waters of the floor of the caldera. Lake awassa, Tikur wuha river, cold bore holes and dug wells surrounding lake awassa and around Corbetti, hot springs and geothermal wells contain this type of water. In hot springs and geothermal wells the concentration of chloride and sulfate increases. Dug wells and boreholes of near western caldera wall (Muleti area) also contain this type of water.

Sodium-Calcium Bicarbonate Type: here the dominant cations are Sodium and Calcium, and Bicarbonate is the dominant anion. It is the characteristics of subsurface waters of near the caldera rims and escarpment. Dug wells, cold boreholes and cold springs of the foot of eastern caldera walls and escarpment (Wendogenet area) and, dug wells and cold springs of the south and southwestern hills (beyond the caldera wall) contain this type of water. Rivers that drain the eastern escarpment, which later join Tikur Wuha River and Shallo swamp also characterized by this type of water.



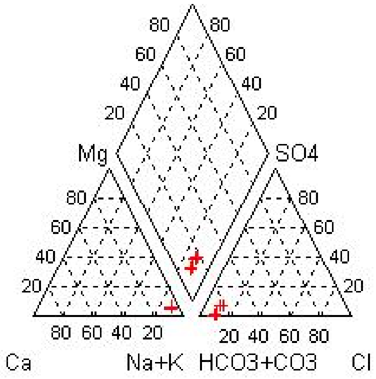
Bore holes

Dug wells



Thermal wells

Cold springs



Lake Awassa

Figure 6.3 Piper diagrams of the different water bodies

Calcium-Sodium Bicarbonate Type: In this type of water the dominant cation is calcium followed by Sodium with Bicarbonate as the dominant anion. However, this type of water is rare in the catchment. It is a characteristic of cold springs of the eastern escarpment and highlands. Calcium bicarbonate type of water is also found only in one sample from cold spring of eastern escarpment.

Generally, Sodium bicarbonate is the dominant water type in the area, which is found from natural waters of the floor of Awassa caldera surrounding the Lake, the western and northern (Corbetti caldera) boundary of the catchment. Lake Awassa, Tikur Wuha River, hot springs of the floor and escarpment and geothermal wells of corbetti are characterized by this type of water. Dug wells cold bore holes, cold springs and rivers of the eastern escarpment, the south and southwestern elevated hills are characterized by Sodium-Calcium bicarbonate type of water. Magnesium ion is less important in the area where as chloride and sulfate ions are largely manifested in hot springs and geothermal wells.

Exceptional water type is found on one water sample (from bore hole) , which is calcium bicarbonate type of water. It is found from cold spring at the foot of the southern caldera rim, which is a fast shallow circulating groundwater emanating from the N-S trending fault and the enclosing rock is the old basalt. The variation in the concentration of the major cations reflects that the interaction of water with the encountering rocks along the flow path. The most dominant cations are sodium and calcium. Calcium ion dominates in waters of the eastern escarpment and highlands where the older basic volcanic rocks (plateau basalts) are found in these parts of the area. Sodium ion is dominant in the remaining parts of the area where it is occupied by acidic and alkaline volcanic products.

6.4 Fluoride

The concentration of fluoride is one of the major problems in waters of the MER. The studied catchment is also affected by fluoride concentration above the permissible limit in drinking water. The concentration of fluoride in cold waters of the area reach 17mg/l. Higher values of fluoride concentration is also found on thermal waters with maximum value of 175mg/l, but most of the cold waters have a value less than 10mg/l. Figure 6.4 shows the range variation of fluoride concentration in the area excluding the thermal waters, the values of thermal waters indicated as a point on the map. As shown on the map the variation has a trend of increasing concentration toward northwest part of the area (Corbetti caldera). Lake Awassa water has relatively higher amount of concentration than the surrounding groundwater.

The possible sources of fluoride in natural waters are chemical weathering, magmatic emissions, atmospheric dust and pollution. The possible sources of the fluoride in the area could be as a result of rock-water interactions and/or from the thermal waters. The source rock might be the acidic volcanics that is why the variation shows an increasing trend toward Corbetti which is constituted by these volcanic rocks such as the pumice, rhyolite and associated obsidian of the Chebbi and Urji volcanoes. The relative increment in Lake Awassa water might be due to the effect of evaporation.

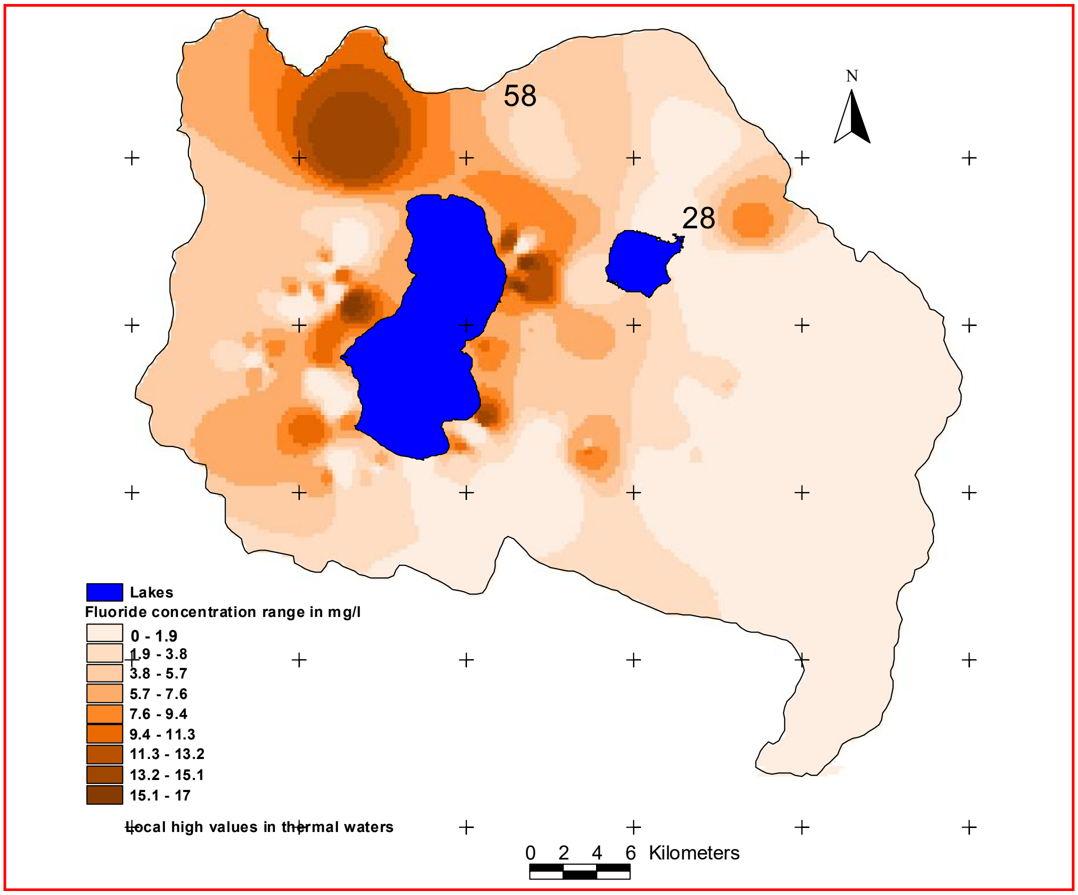


Figure 6.4 A map showing the variation of fluoride concentration in mg/l.

6.5 Isotope Hydrology

Here stable isotopic data of δD & $\delta^{18}O$ collected from GSE, Zenaw Tessema (2003) is used. In order to identify the origin/recharge source of different water bodies, the interaction of surface and ground water and to trace the flow path, which is later used to construct the conceptual model. The basis for interpretation is the variation in the concentration of the two isotopes as a result of evaporation where this variation is governed by time, space and temperature condition. As a result of evaporation, the heaviest isotopes (δD & $\delta^{18}O$) enriched in the water body and depleted in the vapor from this water body. In addition, isotopic fractionation can occur in the subsurface for instance by mixing and rock water interaction.

Measurement of δD & $\delta^{18}O$ are reported in δ units and the data are analyzed by graphical plots of δD versus $\delta^{18}O$. The equation for local meteoric water line (LMWL) of the area that is derived by Zenaw Tessema (2003) is used for interpretation.

It is expressed as:

$$\delta^2H = 7.5\delta^{18}O + 13.3$$

The isotopic data were plotted for different water bodies along with the LMWL, such as rainfall at Awassa, hot springs, cold boreholes, geothermal wells, dug wells, cold springs, lake and rivers (fig. 6.4).

Rainfall

The rain fall samples are from Awassa taken at one station in different months. The samples are plotted not far from the LMWL, but there is a variation between different samples. This comes from the time of sampling, due to seasonal effect. The dates of sampling reported to be from May, 1999 to December 2000.

Lake Awassa

Its isotopic composition is quite different from other water bodies except few boreholes and dug wells around the Lake, which show similar composition as the lake. Lake Awassa is enriched with the two stable isotopes that indicate it is in the state of evaporation relative to the present day precipitation. Slight variation of concentration between lake samples observed (between 1 and 2 on the graph), this might be as a result of incoming less evaporated water from Tikur Wuha River, which decreases the isotopic composition due to mixing.

Rivers

The isotopic composition of rivers doesn't show higher evaporation or fractionation, which is similar to the composition of rainfall in the area. Tikur Wuha River shows a relative shift from the LMWL (indicated as 1 in the graph), which might be affected by isotopic fractionation with rocks of the river bed. Depleted in isotopic composition of this river imply that it is fed by less evaporated base flow up stream where base flow is significant. The other river that drains the eastern escarpment shows similar plotting position as a rainfall.

Cold Springs

Samples from cold springs lie along the LMWL, with similar position as rivers and rainfall plotting position. Since most of the springs are fault controlled and, found on elevated areas. It implies fast, shallow circulating meteoric water, which comes out through them. They are found in areas getting high direct recharge from rainfall with little affected by evaporation.

Hot Springs

The plotting position of hot springs lie on the LMWL, except the one, which is Shallo hot spring (1) below LMWL and relatively enriched with ^{2}H and ^{18}O isotopes. This reflects relatively evaporated water, which is related to mixing of the nearby evaporated Shallo swamp water. The others are hot springs of Wendogenet, with similar plotting position of rainfall and cold springs. They are meteoric in origin and less affected by evaporation.

Cold Bore holes

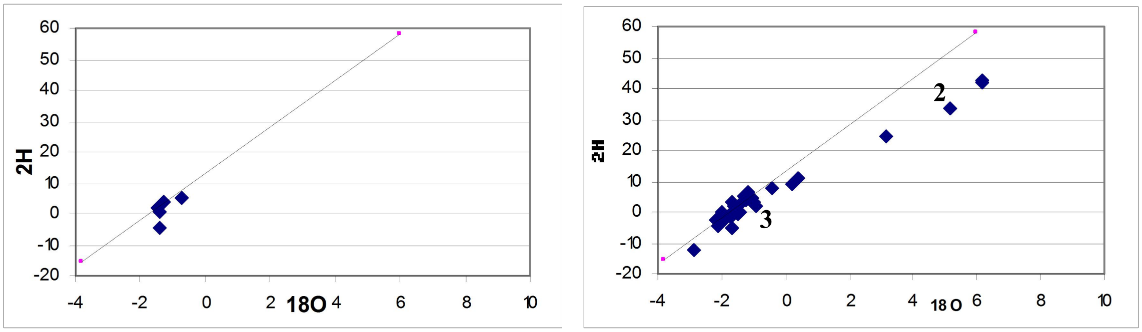
The plotting position of cold bore holes shows large variation. This is as a result of mixing of water from different sources. The majority of the samples from cold bore holes show similar position as rainfall and cold springs (indicated as 3). Where as some of the samples found on plotting position similar to that of Lake Awassa with high enrichment of the heaviest isotopes (indicated as 2). These boreholes are found near Lake Awassa to the west and North West of Lake Awassa toward corbetti caldera. These similar characteristics of the samples support the groundwater outflow from the lake in northwest direction. Sample found in the intermediate plotting position shows relative enrichment with characteristics of mixing with the evaporated lake Awassa water where these bore holes are found east of the Lake shore.

Dug Wells

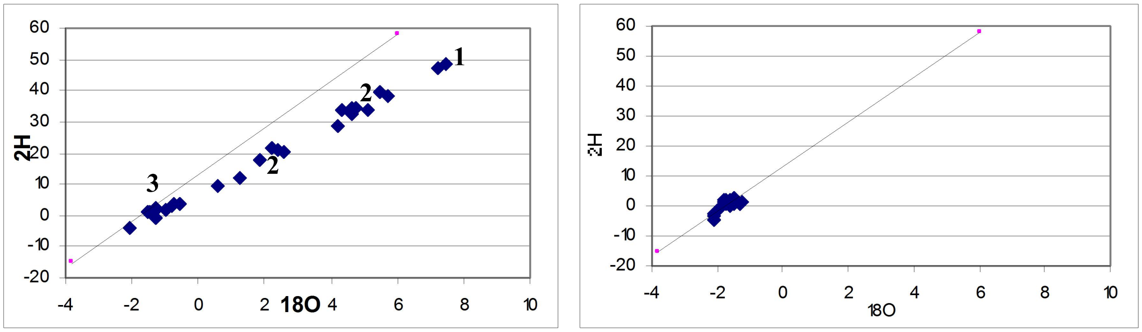
Similar to the cold bore holes, the plotting position of samples from dug wells show high variation in isotopic composition. According to their plotting position they are classified in to three groups. **Group one** (indicated as 1) includes those having similar isotopic concentration as Lake Awassa, enriched with the heaviest isotopes. Dug wells of these groups are found on the west and northwest of Lake Awassa. The relative enrichment of dug wells found west of Lake Awassa might be as a result of recharge from the evaporated Derba pond water, which is found south of this area. Where as those found northwest of the Lake indicates the origin of these waters is from Lake Awassa. **Group two** (2 on the graph) found in the intermediate plotting position, where the wells are found near the eastern shore of the lake awassa. Since dug wells penetrate shallow aquifer and their isotopic concentration shows that mixing of the groundwater with the lake awassa water. The remaining **group three** (3 on the graph) shows similar plotting position as rainfall and cold spring. Dug wells of these groups are found at the foot of eastern caldera wall & escarpment. Their characteristics of isotopic concentration show that they are meteoric in origin with little affected by evaporation.

Geothermal Wells

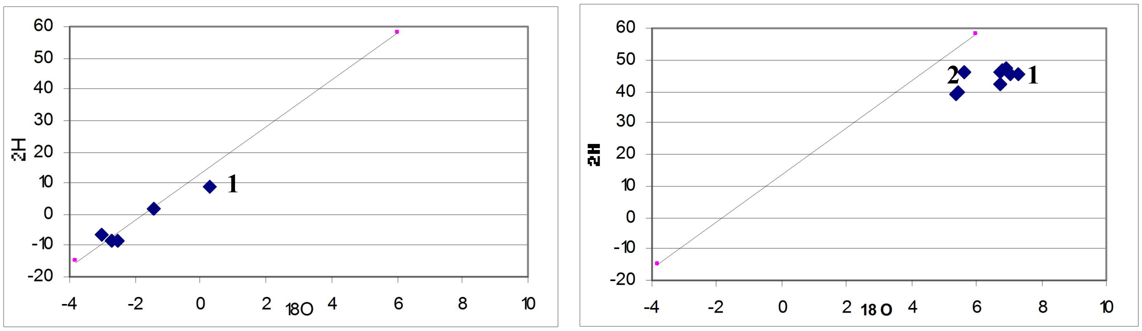
Except the geothermal well of the corbetti, the others are shallow hot wells drilled for water supply. Generally they are depleted in isotopic concentration of the heaviest isotopes. The hot wells with lower temperature lie on the LMWL where as the corbetti geothermal wells, which shows shifting from the LMWL. This is the result of interaction of water with the surrounding rock. Generally the plotting position of thermal wells reveals that their water comes from direct recharge from local precipitation.



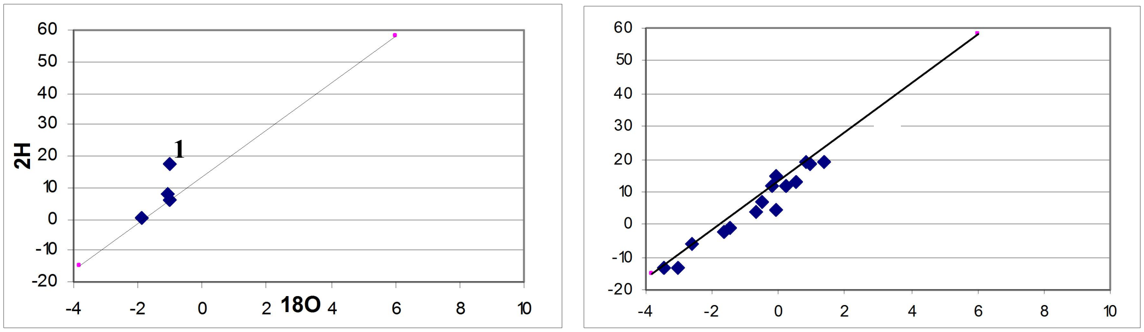
Thermal wells Cold bore holes



Dug wells Cold springs



Hot springs Lake Awassa



Rivers Rain water at Awassa

Figure 6.5 Plots of $\delta^{18}O$ versus $\delta^{2}H$ of water bodies (1, 2 and 3 are identified in the body)

6.6 Concluding Remarks from Hydrochemical and Isotopic Analysis in relation to groundwater-surface water interactions

These remarks are important indicators of the flow system, which is used to conceptualize the flow regime of the area.

- As observed from EC variation map, the ionic concentration of natural waters in the area indicates a clear zonation with an increasing trend from south east of the boundary toward northwest. As groundwater moves from recharge to discharge areas its ionic concentration increases and this variation is attributed to water-rock interaction and residence time, which indicates the flow direction.

- There is an abrupt change in EC value between the surrounding elevated hills (caldera rims and escarpments) and the floor, which indicates different groundwater flow regimes.

- The low EC value of natural water from the eastern and southeastern escarpement and highland indicates that shallow circulating ground water flow, which comes from direct precipitation from this part of the area. This fast shallow circulation is through the highly fractured/faulted zones which is the characteristics of this area.

- In contrast, relatively intermediate and high EC values of the floor, western and northern part of the area imply that it is a different flow regime with respect to the escarpment and highland. There is an intermediate flow with relatively longer residence time and mixing of different water bodies such as Lake Awassa water, cold and thermal ground water, which affects the concentration.

- Similarly the concentration of major cations and anions indicates different ground water flow regimes between the floor, escarpment and highlands. The dominant cation is sodium followed by calcium where bicarbonate is the dominant anion.

- The dominant water types are calcium-sodium bicarbonate, sodium-calcium bicarbonate and sodium bicarbonate, which are found in waters of the highland, escarpment, and the floor respectively.

- Lake Awassa, even though it is a closed lake basin, it shows lower ionic concentration. This supports the groundwater out flow from the catchment, which is concluded by previous researchers.

- From the analysis of δD and δ^{18}O isotopes of surface and sub surface waters show that similar variation in composition as ionic concentration of these waters.

- Most of the natural surface and groundwater bodies lie on near LMWL, which indicates direct recharge from precipitation is significant in the area. Where as Lake Awassa is enriched with these isotopes, that indicates it is in the state of evaporation with respect to modern precipitation.

- Cold springs, cold wells, rivers, and hot springs from eastern and southern part of the area are depleted in the heaviest isotopes. This indicates that their origin is from direct precipitation with little affected by evaporation. The flow regime is fast shallow circulating groundwater. Some cold wells near the eastern shore of Lake Awassa shows intermediate composition of δD & δ^{18}O isotopes. This comes from mixing of the groundwater with water of Lake Awassa and Shallo swamp.

- Cold wells found to the west and north of Lake Awassa, are enriched in the composition of these isotopes as Lake Awassa. It can be concluded that these wells get recharge either from Derba pond or Lake Awassa. This is also supplemented by similarity in their chemical components and an increase in ionic concentration far from the Lake in these directions.

- Dug wells found west of the Lake are enriched with these isotopes. The groundwater in this area was recharged from evaporated Derba pond water.

- There observed mixing of Lake Awassa water and the surrounding wells, which is evidenced by intermediate isotopic composition of these wells. This might be related with the fluctuation of the Lake level, which raises the groundwater table during the rise in the Lake level. As a result the Lake water feds the surrounding wells.

- There is thermal mixing around Lake Shallo. These thermal springs emanate from the foot of NW-SE trending fault (Werensa Ridge). As evidenced by their isotopic composition, these springs show a relatively enrichment in isotopic composition, which is the result of mixing from the near by evaporated Shallo swamp water.

CHAPTER SEVEN

GROUNDWATER RECHARGE AND DISCHARGE

7.1 Groundwater Recharge

Recharge can be broadly defined as water that reaches an aquifer crossing the water table from any direction, which contributes an addition to the ground water reservoir (Lerner, 1997). There are three principal mechanisms of recharge defined by Lerner et al. (1990) as:

- Direct recharge (Diffuse): water added to the ground water reservoir in excess of soil moisture deficits and evaporation by direct vertical percolation from precipitation or irrigation.

- Indirect recharge: recharge to the water table through the beds of surface watercourses, such as beneath rivers and lakes.

- Localized recharge: an intermediate form of ground water recharge resulting from the horizontal, near surface concentration of water in the absence of well defined channels such as small depressions, joints and rivulets.

The above mechanisms usually do not occur individually rather in combination which makes the assessment complex. On the other hand, the recharge and discharge conditions of an area is controlled by several factors such as; climate, topography, drainage, geologic frame work, soil condition, land use/land cover and vegetation etc. For instance in semi-arid areas where potential evapotranspiration exceeds average precipitation, the ground water recharge depends on high rainfall events. Besides, this process is also controlled by soil infiltration capacity, hydraulic nature of sub surface material, the presence of surfacial fractures, joints and depressions so as to escape evapotranspiration, etc. For example poor vegetation cover on a permeable soil cover along with high rainfall can favor the recharge process.

Regarding topography, in areas of steep slopes and rugged terrains, favor run off and evaporation rather than infiltration. Where as in flat land, it creates favorable condition for infiltration. On the contrary, in humid areas recharge is mainly controlled by precipitation surplus (rainfall minus potential evaporation) other factors being present.

Therefore, by considering the various factors controlling the recharge processes, qualitative recharge and discharge characterization is done, which allows a relative zonation of recharge-discharge condition in the area. Later it is the major component for conceptualizing the flow regime.

7.2 Zonation of Recharge

As stated before, geomorphology derived from digital elevation model, soil, geologic and hydrogeologic condition, hydro-metrological variables, hydro chemical and isotopic analysis are involved, in order to see the controlling factors so as to allow the relative zonation. Figure 7.1 shows the relative ground water recharge and discharge area and the characteristics of the area are discussed as follows:

1. *Escarpment and highland volcanic mountains of the eastern margin.*

The studied catchment gets large amount of recharge from this part of the area. It is the most elevated with the characteristics of flat topped hills, which favors infiltration than surface run off. As it is the rift margin, the area is highly affected by rift fault, which produces fracture zone and joints on the volcanic rocks. In addition, the drainage density is high in the area. The fracture and joint along with dense open channels facilitate the recharge processes. The area gets relatively high amount of rainfall. Cold springs emanate from this area have a characteristics of low EC value and similar isotopic composition as the meteoric water. This implies fast infiltration and shallow circulation of groundwater, where the area gets substantial amount of direct recharge.

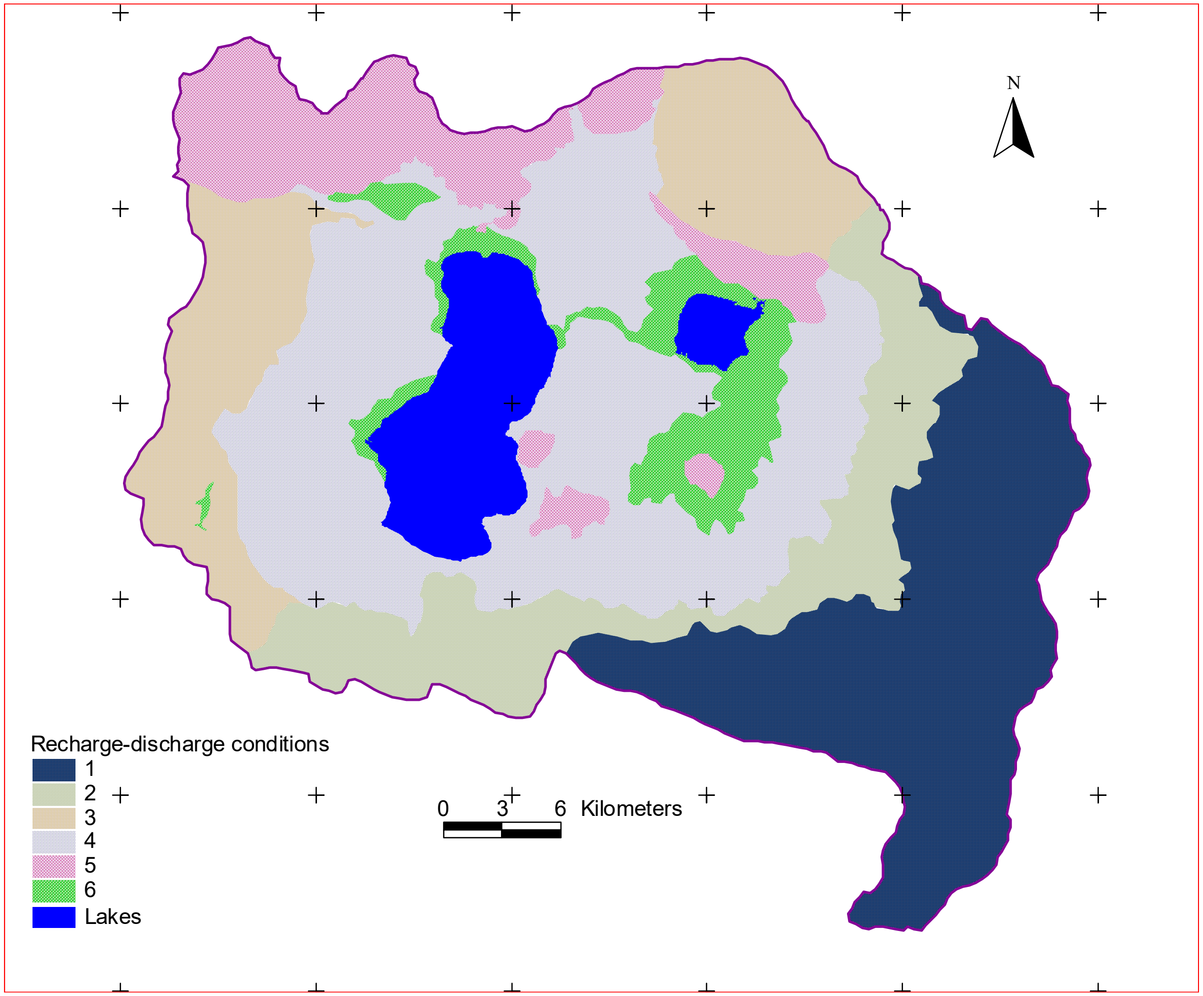


Figure 7.1 A map showing zonation of recharge and discharge areas (1-High direct recharge over the highland & escarpment, 2-moderate recharge with associated local discharge areas over the caldera rims, 3-intermediate recharge zone over caldera walls & volcanic hills, 4-the floor with localized direct recharge during high rainfall, 5-zones of local recharge areas over the volcanic domes & necks, 6-discharge areas)

2. *Caldera walls and the foot of escarpment.*

This area is characterized by steep slope and undulating topography, which minimizes infiltration relative to the highland. The eastern part gets relatively higher amount of rainfall than the western part, which allows direct recharge. The major contribution of recharge is through direct precipitation and indirect infiltration from perennial rivers that drains the eastern escarpment. Similar to the above, this area is affected by faults that permit localized recharge. The hot springs from this area (Wendogenet) shows low EC value relative to waters of the floor, which indicates fast and shallow circulating groundwater, comes from direct recharge of this area and the highland.

The western caldera rims and hills get relatively lower amount of rainfall than the eastern part and there is no perennial rivers. This area is characterized by intermediate direct recharge, which occurs in depression formed by faulted volcanic hill. This part of the area covers relatively shorter distance from the water divide and there are no surface manifestations of ground water.

3. *Volcanic Domes and Volcanic necks of the Floor*

This zone is characterized by little or no soil cover and less permeable volcanic products such as the rhyolitic and obsidian domes of Corbetti and rhyolitic necks of the floor with associated lapilli tuffs. This area gets localized recharge through joints and depressions from precipitation.

4. *The floor of the Caldera*

The floor is characterized by relatively lower amount of rainfall and higher evapotranspiration. Direct recharge in this area depends on high rainfall events and fast infiltration occurs through the permeable lacustrine sediments. It also gets indirect local recharge through the riverbed of Tikur Wuha and associated open channels. The Presence of lake, swamp and shallow ground water table forms discharge area on this part of the floor.

7.3 Groundwater Discharge

Groundwater Discharge can be defined as the release of water from the saturated zone across the water table together with associated flow towards the water table within the saturated zone (Freeze and Cherry, 1979). Groundwater discharge areas can be manifested by surface water features such as springs, swamps and seepages. In addition, in arid and semi-arid regions discharge areas can be identified by topography, vegetation covers, soil and land surface features. Here along with these features it is supplemented by hydrochemical and isotopic results. Therefore, there are discharge areas in the catchment with characteristics of springs (hot and cold), swamps, and depressions (mappable discharge areas are shown in fig. 7.1). All of the cold and hot springs are found on the eastern, south eastern and southern parts of the area, where as swamps occur on low lying depressions when the groundwater table coincides with the surface of the ground.

Most of the cold and hot springs are fault controlled, for instance cold springs of the escarpment and hot springs of Wendogenet where these faults may act as a barrier. Cold springs from the escarpment emanate from NNE-SSW faults of the eastern margin of the rift. Hot springs of the floor are also controlled by faults and fracture zones. Shallo hot springs where emanates from NW-SE trending fault (at the foot of Werensa ridge, northeast of the Lake). Hot springs found south east of the lake comes out from fractures at the foot of scoria cones. This recent volcanic necks of the scoria are aligned in N-S direction where they are on a regional fracture zone. Hot springs from this area are characterized by low temperature and discharge. High discharge cold springs are found near the southern shore of the Lake (Loke palace). It comes out from N-S trending fault with discharge about 72l/s. These fault controlled springs, as supplemented by their hydrochemical and isotopic signature, they are fast, shallow circulating groundwater where the faults may act as a barrier for groundwater flow. Some cold springs with very low discharge less than 1l/s are found on the south eastern highland near the water shed boundary. These springs are formed when the groundwater table coincides with the surface at low depressions and open channels. It occurs when the underlying bed rock unit exposed on the open channels. Swamps and low depressions covered by vegetation are also characteristics of groundwater discharge areas in the catchment. For instance, swamp containing Lake Shallo, depression of Wendokosha area (near Corbetti), and depressions formed by parallel faulted blocks on south west of Lake Awassa (Derba) are some of them.

CHAPTER EIGHT

SYNTHESIS

8.1 Introduction

This study attempts to improve the general information on the hydrogeology of the catchment, which emphasis is given to the characteristics of the aquifer, groundwater-surface water interactions and groundwater flow system. This chapter comprises the results of this work, using evidences from the analysis of each previous chapter. The output maps and descriptive figures prepared in each chapters are used in order to see the spatial distributions and effects of the various hydrological and hydrogeological components. There might be a little uncertainty on the produced maps due to data problems but a lot have been tried to make the best possible results using systematic and indirect approaches. For instance aquifer characterization is done relying on the spatial distributions of pumping test analysis but in areas of limited data it is supported by geology, structures, well logs and hydrological components such as surface water features.

This chapter contains the groundwater flow and conceptual model in relation to groundwater-surface water interactions; the role of recent tectonics on the hydrogeology and the general hydrogeology of the area. In conceptualizing the flow system, all the point and spatial data and their corresponding attributes are put on a three-dimensional topographic view derived from the Digital Elevation Model so as to visualize the interaction of different water bodies. Further more the hydrochemical and isotopic analysis results provide information about the origin of water bodies as well as flow directions. As a result a conceptual model profile and a three dimensional ground water flow views are constructed that illustrate the groundwater-surface water interactions and flow directions.

8.2 Groundwater flow and the conceptual model

Groundwater flow contour map is prepared from existing peizometric data, field well head measurements and head of the point of emergence of perennial springs (fig. 8.1). In most parts of the area the groundwater head distribution is similar to the topography, which follows the elevation variations, with local exceptions that it is believed to be the groundwater outflow direction to the adjacent basin.

As it is seen from the map, there is a large variation in groundwater distribution between the floor, the boundary caldera rims and the escarpment that implies the groundwater flow occurs in a different flow regime. This is also supplemented by the hydrochemical and isotopic signatures of the respective water bodies. On the other hand, the groundwater flow in the area is controlled by geologic structures such as faults and fractures. These structures control the hydraulic connection from recharge areas toward the Lake either by acting as a barrier or a conduit for groundwater flow. For instance the NNE-SSW/N-S trending faults cutting the southern caldera walls act as a conduit, which facilitates direct groundwater inflow toward the Lake. Where as the N-S running faults found south west of the Lake limits direct eastward groundwater flow to the Lake. Figure 8.3 shows a three dimensional groundwater flow distributions in the area.

In addition to buried faults or fracture zones are also involved in controlling the groundwater flow. For instance E-W running buried faults found on the floor west of Lake Awassa favors the flow toward the Lake. These faults are traced by geophysical survey from WWDSE, (1999) are indicated on the structural map in section 4.3. The northward ground water outflow from the catchment is also possible through the NW-SE/N-S running structures.

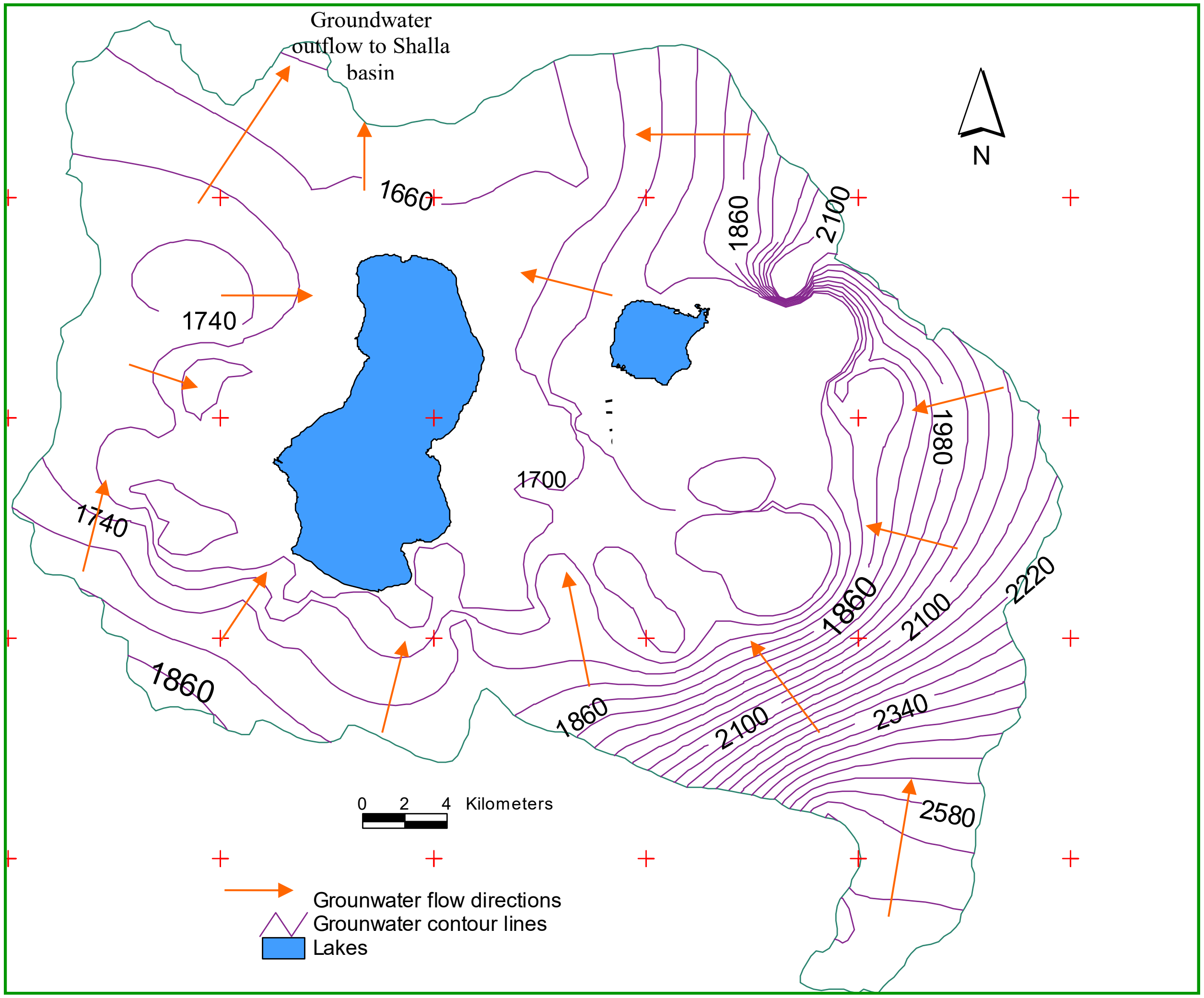


Figure 8.1 A map showing the groundwater head distribution along with the direction of flow

Figure 8.2 shows the conceptual profile model from the western boundary (caldera rims) to the eastern rift margin that illustrates the groundwater-surface water interactions in relation to the flow systems. There are three types of groundwater flows: local flows which are shallow zones of active fast flows; intermediate flows with a characteristics of slow flow that occurs at medium depth and regional flows which are deep groundwater flows with long residence time. Here two types of groundwater flows are identified in the area as evidenced by topography, geology, the presence of springs, seepage zones and the respective hydrochemical and isotopic signatures of the different water bodies.

These are local flows and intermediate flow systems where there is no strong evidence in the presence of regional groundwater flow systems but the groundwater outflow from the catchment toward Lake Shalla may occur at a regional deep flow system. Local flows in the area are restricted to the upper zones of the southern, south eastern and eastern caldera walls, escarpments and highlands. Springs, seepage zones and rivers are only found on these parts of the area where they are fed by these flows. This is also evidenced by their hydrochemical and isotopic signatures (stated earlier) where they have characteristics of fast shallow circulation and their origin is direct recharge from precipitation. The groundwater circulation is facilitated by fractures and faults of the eastern escarpment and caldera walls. These flows are estimated to be found on the top permeable soil cover and fractured volcanic rocks not more than 30m. Rivers and springs of the eastern escarpment get recharge from this type of flow.

Intermediate flows are relatively slow flows and longer residence time that occur at medium depth. These types of flows are found on the floor, caldera walls and escarpment and the groundwater has characteristics of large ionic concentration. These flows fed Lake Awassa through the lacustrine sediments and along the faults and fractures that penetrates greater depths. Hydrochemical signature of a spring found at the foot of eastern caldera wall implies an intermediate flow along the faults. In addition Tikur Wuha River is also fed by this type of flow, which has different hydrochemical characteristics from the escarpment waters.

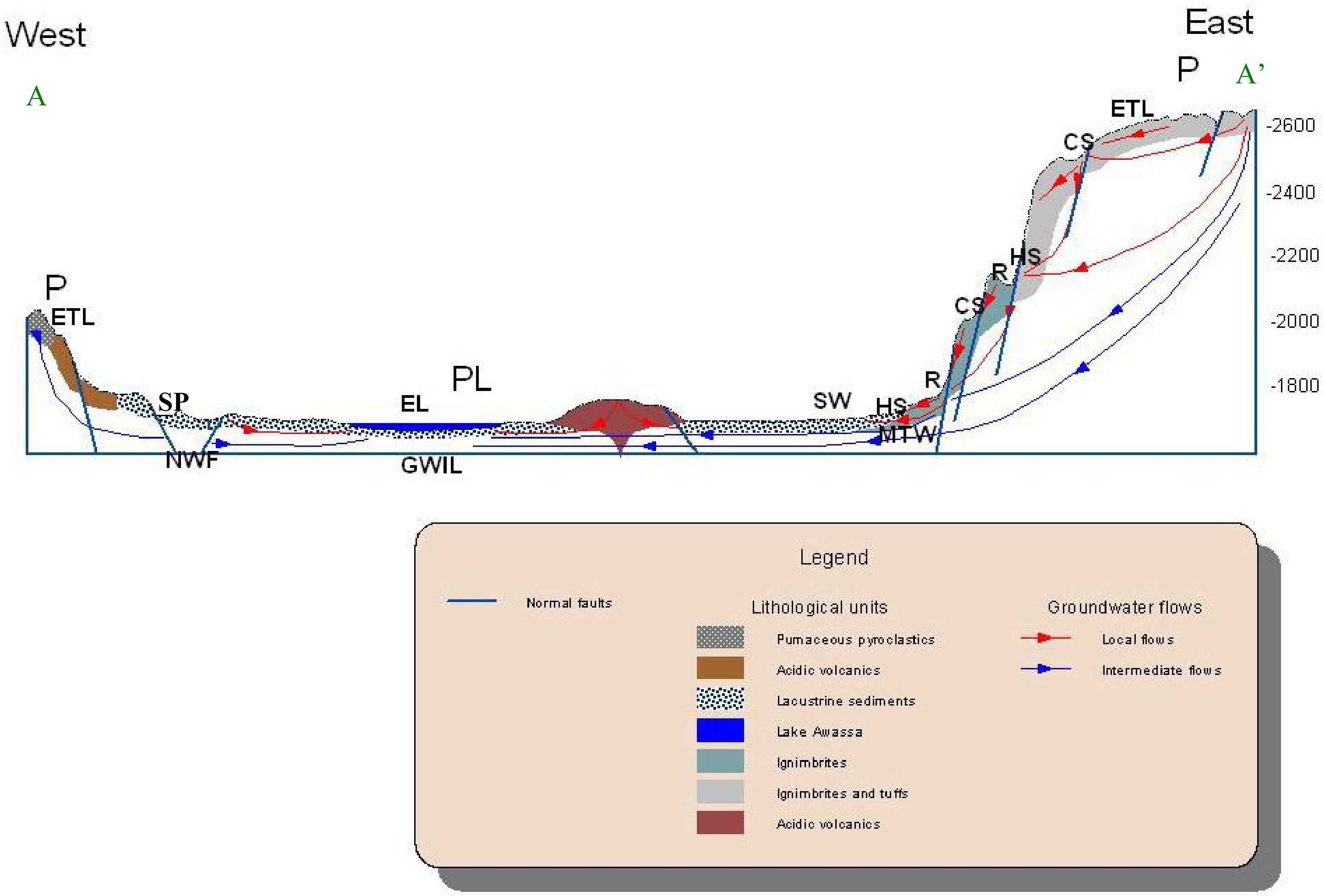
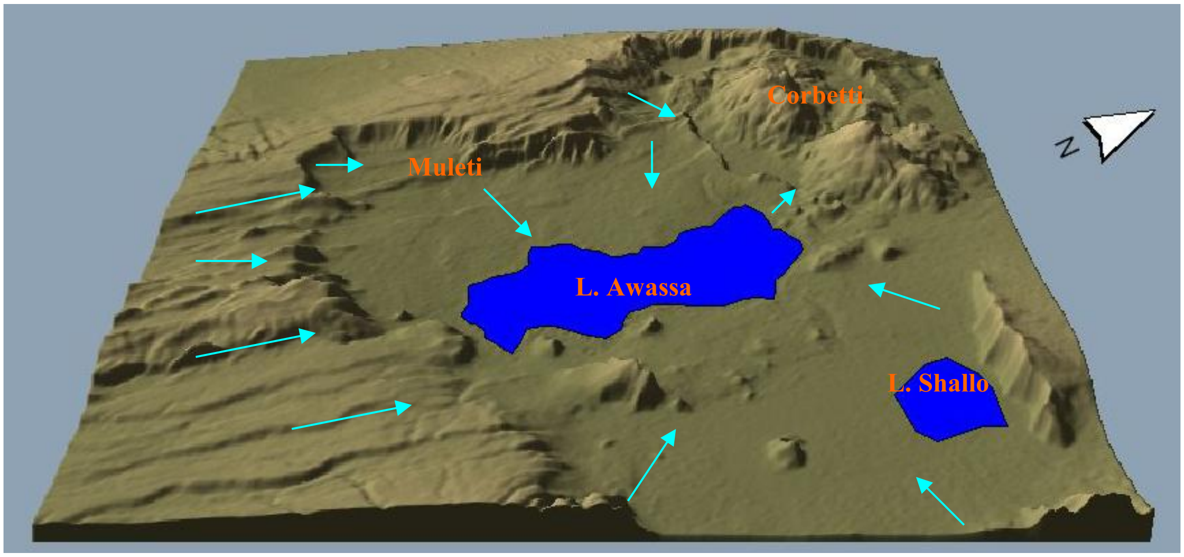


Figure 8.2 The conceptual profile model showing the groundwater-surface water interactions in relation to groundwater flow (P, precipitation on the land; PL, precipitation on Lake surface; EL & ETL are evaporation from the Lake and land respectively; CS, cold springs; HS, hot springs; R, rivers; SW, swampy area (Shallo); MTW, mixing of thermal water; GWIL, groundwater inflows to the Lake; NWF, northward fault controlled flow; SP, seepage). Horizontal scale is approximately 46m. A-A' is shown in Figure 8.5.

The hydrochemical characteristics of the groundwater found on the west and south west of the Lake signifies that the ground water flow is an intermediate that occurs through deep and long N-S running faults of the boundary. These flows are estimated to occur not more than 100m in the lacustrine sediments and fractured volcanic rocks. The sources of thermal waters in the area are restricted to these flows local and intermediate (except Corbetti geothermal), as identified by their hydrochemical and isotopic characteristics. The hot springs of the escarpment have low ionic concentration and similar isotopic composition as the rain fall, which is a characteristics of fast active flushing of groundwater (local flow) that feds them. Where as those found on the floor have characteristics of higher ionic concentration with more or less similar hydrochemical characteristics (except relatively large amounts of chloride and sulfate) with the groundwater in this area. They are fed by groundwater of intermediate flow characteristics. The thermal source of these waters is a heat flow from shallow magma chamber.

Generally, springs and rivers of the eastern escarpment and highland are fed by local flows, as evidenced by their low ionic concentrations, similarity in isotopic composition as rain fall and inconsistency in their discharges. These waters flow toward the floor as surface run off or feed Tikur Wuha River and Lake Shallo. Lake Awassa, Tikur Wuha River, hot springs and cold springs on the floor and at the foot of caldera walls are fed by intermediate flow of groundwater. This is proofed by the ionic concentration, isotopic composition, and high discharge of springs and consistency of the flows. Mixing of different water bodies is observed on some parts of the floor by their isotopic characteristics, for instance mixing of Shallo swamp water with the near by thermal spring and mixing of the Lake Awassa water with the surrounding groundwater, which might be associated with the fluctuation of the lake level.



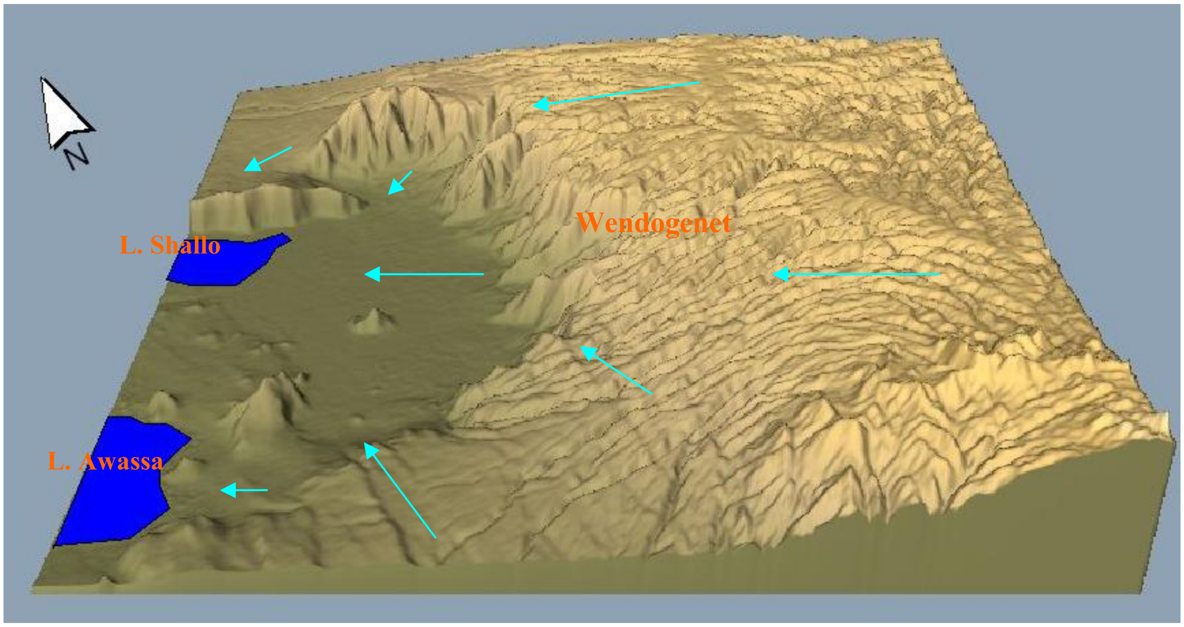


Figure 8.3 shows distributions of groundwater flow direction in the area (above, western part and below eastern part of the area respectively), → Groundwater flow directions.

8.3 The role of recent tectonics (ground cracks) on the hydrology of the area

As stated earlier, the groundwater flow in the catchment is highly controlled by geologic structures where the dominant recharge areas (caldera rims, escarpment and highland) are affected by rift structures. The role of these structures is not only in groundwater flow but also in facilitating the recharge-discharge processes. As described in section 4.4, recent tectonics (ground cracks) are developed on the western part of the study area where this cracks are speculated as they interrupt the hydrology of the area. This is arising from the disappearance of Derba pond; the rise of Awassa Lake level and the geology and geomorphology of the area where these cracks are formed. The area is characterized by elevated parallel blocks (fault scarps) of ridges and depressions where it is dissected by long N-S running faults. The depressions have no surface connections with the Lake Awassa.

As it is seen from the groundwater flow contour map, the groundwater flow is directed toward north, which has a similar trend as the N-S running faults. As a result these faults control the direction of flow by limiting eastward direct hydraulic connection of the groundwater with the Lake and permits flow along their strike direction where later joins Lake Awassa through E-W running buried faults (fig. 4.4).

Similarly the cracks facilitates the northward flow of ground water, however the hydraulic characteristics of these cracks and faults are different. The ground cracks are open and allow fast infiltration where flow is possible through them. These characteristics of the cracks might decrease the groundwater residence time to reach Lake Awassa that was before they were formed. As a result the Lake response to groundwater inflow from this area becomes different what was before and the formation of these cracks might have an impact in relation to the level rise of Awassa Lake other factors being present. This is supported by some evidences.

These are:

- The developments of these cracks are started since 1996 around Muleti. Similarly the Lake Awassa level fluctuation shows unusual increasing trend starting from the same year.

- The isotopic signatures of water from dug wells and bore holes found west of the lake shows that they are enriched with the two stable isotopes. This is a characteristic of evaporated open water body, which might be from the evacuated Derba Pond water by flowing through these cracks. This supports that direct hydraulic connection along these structures with the Lake Awassa. The time of sampling reported for isotopic analysis and the time of evacuation of this pond occurred in similar year.

- As shown in the hydraulic conductivity map (fig. 5.3), the geological units in the area are characterized by low permeability in the range of (0.1-1m/day). From this it can be understood that there might be a limited recharge and groundwater inflow to the Lake before they were formed.

Therefore, from this it can be speculated that the water of Derba Pond joins Lake Awassa which contributes for the Lake level rise. In addition, the formation of these cracks facilitates the rate of groundwater flow that is recharged from this area by permitting direct infiltration and open hydraulic connection to the highly permeable lacustrine sediments found on the western part of the floor. As a result it might increases the response of the Lake level due to recharge and groundwater inflow from these parts of the area.

Figure 8.4 A photograph showing a run off disappears through the ground cracks (Derba) after a rainfall event

8.4 hydrogeology of the area

Figure 8.4 shows a simplified hydrogeological map derived from the contributions of each previous chapters, by considering permeability of the rock units, geologic structures, recharge-discharge conditions, and groundwater flow. The main productive aquifers of the area the lacustrine sediments associated with scoria followed by the ignimbrite unit with characteristics of intergranular and fractured permeability. The lacustrine sediments and ignimbrites found east of the Lake have relatively thicker alluvium and affected by rift faults where these units are found in groundwater discharge areas. The least productive aquifers are those elevated volcanic hills and domes of the rhyolites, obsidian and lapilli tuffs with little permeability. These are recharge areas rather than aquifers. The productivity is highly controlled by faults and fracture zones. The lacustrine sediments associated with scoria that emerged from a fracture zone have relatively higher potential than others. The ignimbrite unit of the escarpment is highly affected by rift faults where high productive springs are emanate from this unit along the faults. The eastern part of the floor gets relatively higher amounts of recharge from the eastern and south eastern escarpment and highland as a result the aquifers of this part gives large amounts of yield than the others. In addition, the thickness and presence of aquitard layers such as clay/ash layers, the degree of sorting of volcanoclastics and the variation in thickness of the permeable sediments vary spatially the productivity and permeability of the lacustrine sediments. Underlying the lacustrine sediments, there is the ignimbrite unit with estimated thickness of 200m (Tesfaye Cherenet, 1982). The hydraulic characteristics of this unit is unknown but it is fractured and the aquifer for geothermal wells of Corbetti. As remarked by different researchers, fractured permeability tends to decreases with depth. This is due to the fact that fracturing is restricted to the top part and tends to terminate with depth, so that the top part of the ignimbrite might be a productive aquifer.

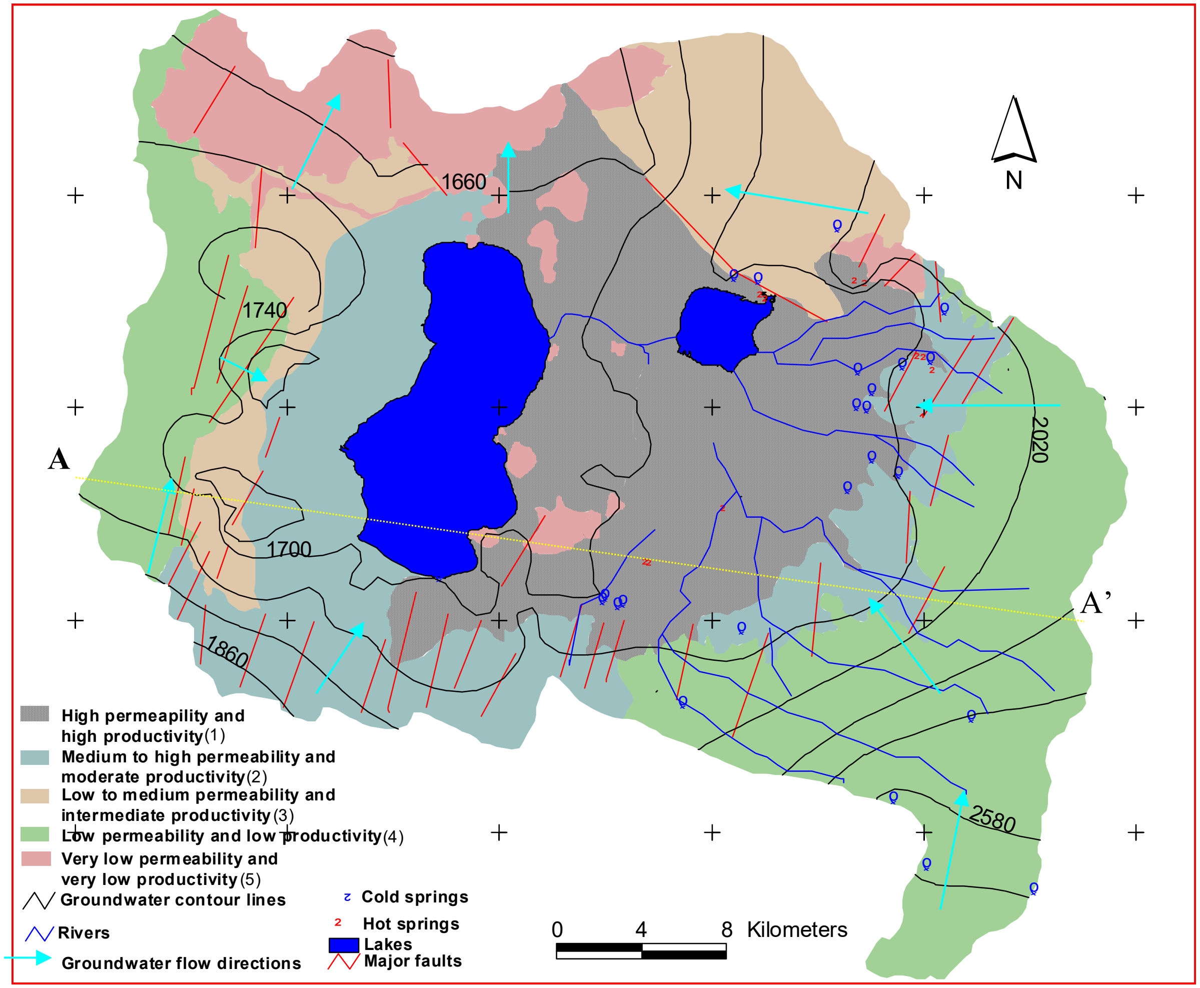


Figure 8.5 Simplified hydrogeological map (1- Lacustrine sediments with alluvium, recent scoraceous basalts, fractured ignimbrite; 2-Ignimdrites of the escarpment, rift pyroclastics, lacustrine sediments and old basalts; 3-Lacustrine sediments at the foot of caldera wall, hayaloclatites, ignimbrite and tuffs; 4-Unwelded to welded tuffs, pumaceous pyroclastics; 5-Recent acidic volcanics of rhyolite, obsidian, lapilli tuffs and old rhyolites of the floor)

CHAPTER NINE

CONCLUSION AND RECOMMENDATION

9.1 Conclusion

This study was intended to improve the knowledge of the hydrology and hydrogeology of the Awassa Lake catchment, which arises form the rise in Awassa Lake level. There are hydrogeological works done previously with a characteristics of regional and rely on issues of water balance in tracing the causes of the lake level rise. This work contains detail aquifer characteristics of the rock units, origins and interactions of groundwater and surface waters, and the effects of neo-tectonism, which rely on geology, hydraulics data of wells, hydrochemical and isotopic dat as well as hydro-meteorological variables. This is achieved by using various approaches and methodologies such as field observations and measurements of relevant variables, georeferencing water points, systematic desk studies, analysis and interpretations of existing and field data through use of various software.

As a result, the hydraulic characteristic (K/T) of the aquifers is highly variable spatially. The hydraulic conductivity is greater than 50m/day in the lacustrine sediments and less than 1m/day in the volcanic rocks. This variability comes from the complex nature of the lacustrine sediments such as pinching out layers, variable grain size distribution, degree of sorting, thickness variability of layers, etc which depends on the origin and mode of deposition of these sediments. In addition, the characteristics of volcanics found in association with the sediments and geologic structures also affect the hydraulic natures of these sediments. The permeability of the highland and escarpment volcanics is restricted to the upper weathered and fractured part of the rocks. Generally the aquifers in the area are found in unconfined condition.

Geologic structure also controls the permeability of the volcanics. For instance the ignimbrite unit of the escarpment where rift faults and fractures are concentrated is characterized by fractured permeability where springs with large discharges are found.

Geologic structures play a major role in the area, not only on permeability but also in recharge-discharge conditions and groundwater flow.
Hydrochemical and isotopic analysis results revealed that there are two types of groundwater flow regimes. The first one is local flow which is the characteristics of the eastern escarpment and highland water with low EC and little or no isotopic fractionation, indicating that fast shallow circulating groundwater with short residence time. The second is intermediate flow with relatively large EC value and isotopically fractionated which is characterized by relatively deeper flow and longer residence time. In addition, mixing of thermal water with Lake Shallo water and Lake Awassa water with the surrounding groundwater is observed from isotopic result.

The area gets large amounts of direct groundwater recharge from the eastern and south eastern escarpment and highland, and from southern and south western hills and caldera rims where as the other parts are largely depends on local and indirect recharges. Groundwater discharges are restricted to the eastern escarpment, southern and south eastern caldera rims and on the floor of the caldera, where they are manifested as springs and swamps. Groundwater discharge is highly controlled by geologic structures, such as NNE-SSW/N-S running rift faults.

From the synthesis results, except the northward flow out of the catchment, groundwater flows toward the center (Lake Awassa) from all direction with two types of flow. The local flow which is restricted to the top weathered and fractured rocks of the eastern and south eastern escarpment and high land confined to not more than the upper 30m. Intermediate flow which is a characteristics of the sediments of the floor, western and eastern caldera rims penetrating not more than 100m. Generally, the groundwater flow is highly controlled by rift structures in the area, such as the NNE-SSW/N-S and E-W running faults.

In addition, the role of recent ground cracks in the hydrology of the area has been tried by assessing their characteristic with some supporting evidences. As a result these structures are speculated as they influence the hydrology by facilitating groundwater flow toward the Lake and might change the hydrological response of the Lake to this in flow.

Finally, geologic structures play a major role in the hydrogeology as well as the hydrology of the area. Even in the lacustrine sediments high productive aquifers are restricted to these structures. They control the recharge-discharge mechanisms as well as groundwater flows.

9.2 Recommendations

In this study, it was also intended to try the numerical groundwater modeling, however due to time constraints it becomes impossible. For the future it is highly recommended to perform the numerical groundwater flow modeling based on the results of this study, which is important to trace the groundwater system in a quantitative sense and helps to understand the degree of various factors that influence the hydrology of the catchment. In addition, it is better to install seepage meter in the western shore of the lake so as to trace the impact of the ground cracks by measuring the inflow toward the lake.

APPENDICES

Appendix I Summary of initial meteorological data

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1972	x	x	x	x	x	x	70.6	143.4	123.7	17.4	8.5	31.1
1973	17.9	7.4	x	65.9	148.2	83.4	116.4	181.5	82	33.9	0.7	6.2
1974	7.7	28.3	97.9	6.8	106.5	118.3	210	159.3	163.9	37.5	0	3.3
1975	10.2	36.5	34.2	103.6	98.4	88.4	175	119.7	107.8	46.7	5.7	0
1976	6.5	33	78	42.1	171	70.4	161.2	134.2	112.6	79.1	47.1	18.2
1977	87.1	53.2	37.9	94.7	113.6	108.1	123.5	120.7	130.4	222.9	122	12.1
1978	3.3	164.9	23.9	96.8	118.9	85.7	74.7	118.2	199.1	58.9	57.1	41.4
1979	65.9	37	53.3	99	121.5	66.6	126.3	136.4	158.8	86.1	0	27.3
1980	13.8	15.5	38.3	110.6	112.5	73.8	88.3	127.7	40.2	139.1	34	x
1981	x	25	198.7	135.9	48.3	127.2	132.9	155.9	157.3	52.4	7	x
1982	49.6	46.6	99.9	92.1	70.8	121.1	166.3	117.1	72.7	95.9	84.4	12.4
1983	60.5	47.9	56.3	186.2	239.4	76.1	102.8	125.9	153.9	90.6	14.2	6.4
1984	x	x	36.5	17.4	170.2	70.7	96.1	92.7	165.7	27.4	34.5	13.3
1985	9.2	x	75.7	201.9	93.3	106.9	146.1	80.7	116.4	50.2	12.8	8.3
1986	x	34.7	69.6	109.8	167.2	193	153.3	194.2	171.8	57.3	22.8	18.4
1987	0.1	11.8	151.4	127.8	230.8	58	97.3	108.1	68.8	100.1	0.4	4.1
1988	25.8	68.5	17.5	80.9	100.1	110.9	117.7	138.8	205	83.9	1.3	6.6
1989	38.8	49.9	62.8	191.8	95.2	123.8	78.1	86.4	166.3	44.7	22.3	50.2
1990	10.5	93.7	121.1	89.9	85.3	44.4	139.5	39.5	94.1	27.3	7.6	3.8
1991	12.3	90.6	87.4	48	129.5	116.7	109.2	90.6	104	21.6	12.2	44.8
1992	23.4	83.2	73	109	60.5	83	92.8	123.6	74.5	142.3	80.1	16.6
1993	101.6	109.1	22.3	104.9	165.3	46.7	54.7	130.8	47.8	130.8	10.5	3.9
1994	x	4.7	56.8	108.7	80.8	146.2	195.7	118.9	68.9	58.8	19.1	2.9
1995	0.8	21.4	61.8	156.1	43.6	118.7	175.7	134.7	166.8	22.3	18.3	84.2
1996	78.4	36.9	89.6	113.8	161.5	243.3	121.2	108.7	145	69.6	19.7	1.4
1997	23.4	1.7	75.1	125	73	111.2	98.6	113.9	118.9	157.1	132.2	24
1998	92	140	90.8	86.4	88.4	56	172.9	108.3	109.6	193.3	10.6	0
1999	19.8	0.4	105.5	27.1	64.7	99.8	135.1	83.8	115.4	120.4	20.1	16.8
2000	1.1	x	11	132	145.1	36.4	80	179.3	87.6	110.7	29	9.3
2001	1.8	39.9	122.7	67	233.7	137.5	93.5	131.7	89.7	80.2	2.6	21.3
2002	52.5	2.4	127.7	119.6	85.2	118.4	76.6	190.4	82.2	37.2	x	51.5
2003	30.4	2	78.2	179.1	40.4	110.5	74.5	76.1	85.7	56.4	6.2	51.8

Monthly rain fall data at Awassa station(mm)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1975	9.4	9	8.2	6.2	7.2	6.5	3.8	3.4	4.9	7	9.3	9.8
1976	9.6	8.9	7.9	7.2	6.8	7.3	4.7	5.1	5.8	7.3	8.3	9.5
1977	7.4	8.4	7.8	6.4	6.9	5.9	4	5	5.3	5	8.5	9.6
1978	9.6	6.6	7	7.7	7.5	6.8	4	5.4	5.1	6.2	8.8	8.6
1979	6.5	8.1	7.4	7.5	6.9	7.4	5	6.1	5.6	7.2	9.7	9.1
1980	8.9	9.3	7.8	6.7	7.2	6.1	5.1	6.3	4.9	7.5	8.7	10
1981	9.6	8.9	5.8	5.6	7.6	7.9	4.6	5.5	4.6	7.8	9.6	9.5
1982	8.5	7.1	8.5	6.5	6.6	7	5	5	5.9	7.3	7.3	8.6
1983	9.2	8.2	8.1	6.3	6.6	7.2	5	3.7	5.3	8	8.7	8.6
1984	9.4	9.6	8.2	7.5	6.4	6.2	6	6.3	5.5	8.9	8.9	9.2
1985	9.3	8.6	8.2	5.7	6.9	7.7	4.8	5.3	5.7	7.1	8.6	9.5
1986	9.5	7.6	7.8	5.5	7.5	5.3	5.4	7	6.6	7.8	9.1	9.3
1987	x	8	x	7.3	6.3	7.2	7.1	6.6	6.2	x	9.7	10
1988	8.8	7.6	8.3	5.8	8.2	6.5	2.9	4.6	5.2	7.1	9.9	8
1989	8.5	8.4	7	5.9	7.9	7.1	3.8	5.9	5.2	x	8.5	7.6
1990	8.8	6	7.3	6.5	6.5	7.3	5.1	4.5	5.5	8	8.1	9.4
1991	8.4	7.3	7.1	7.5	7.4	6.5	3.7	4.1	5.8	7.6	8.2	8.2
1992	7.8	7.5	8.5	8.2	8.1	7.2	5.5	4.5	5.4	6.8	8.7	8.7
1993	7.7	7.2	9.2	6.4	6.8	6	4.3	5.4	x	x	x	x
1994	9.6	8.9	7.4	6.3	6.6	5.7	4	5.1	5.2	8.5	8.4	9.4

1995	9.7	7.6	7.3	5.9	7.9	7.7	4.1	4.8	6.4	2.9	9.5	8.5
1996	8.3	8.9	7.1	2.7	7.1	4.8	1.6	4.3	5.4	8	9.3	10.1
1997	X	10.4	8.3	6.4	6	6.8	5.5	6.6	7.1	7.1	6.8	8.6
1998	7.2	7.9	7.8	7.8	6.8	6.3	4.4	4.4	5.3	3.8	9.4	10
1999	9.4	9.7	6.7	6.9	7.5	7.1	4.6	5.9	6	5.1	8.6	9.9
2000	9.8	9.8	8.9	7	11.3	6.6	5.6	X	5.4	6.2	9.1	9.4
2001	8.8	9.1	6.5	6.9	7.5	5.8	5.5	5.2	5.8	6.8	9.1	9.7
2002	9	9.6	X	7.6	7.1	6.4	7.1	6.3	7.1	6.9	9.7	8.1
2003	9	9.5	8.3	6.8	7.8	4.5	7.3	5.3	x	x	x	x

Monthly sun shine hours data at Awassa station

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1973	x	1.5	1.7	1.6	1.5	1.6	1.5	1.4	1.1	1.1	1.3	1.5
1974	1.7	1.7	1.6	1.5	1.5	1.5	1.3	1.4	1.1	0.9	1.3	1.5
1975	1.4	1.6	1.5	1.4	1.4	1.6	1.3	1.4	1.1	1	1.2	1.5
1976	1.5	1.4	1.5	1.5	1.4	1.5	1.4	1.1	0.9	0.9	1	1.3
1977	1.4	1.4	1.5	1.4	1.4	1.3	x	x	1	0.9	1	x
1978	1.2	1.1	1.2	1.3	1.1	1.4	1.5	1.1	1	0.9	1	1.1
1979	1.2	1.1	1.2	1.2	1.2	1.4	1.1	1.1	1.4	0.9	1	1.1
1983	x	x	x	x	x	1.2	1.3	1.1	1	0.9	0.9	1.2
1984	1.4	1.5	1.5	1.4	1.4	1.6	1.6	1.1	1	1.1	1.1	1.4
1985	x	x	x	x	x	x	x	x	x	x	x	x
1990	1	1.1	0.9	0.9	1.1	1.4	1.3	1.1	0.9	0.8	x	0.9
1991	x	x	x	x	x	x	x	x	x	x	x	x
1992	x	x	x	x	x	x	x	x	x	x	x	x
1993	x	x	x	x	x	x	x	1.1	0.8	0.5	0.7	0.9
1994	1	1.1	1	0.8	0.8	1.1	0.8	1.4	0.7	0.5	1.2	0.9
1995	0.9	0.9	1	0.8	1.1	1.2	0.9	0.9	0.7	0.6	0.7	0.7
1996	0.8	0.8	0.8	0.8	0.7	1	1	0.7	0.7	0.5	0.6	0.7
1997	0.8	1	0.9	0.7	0.9	0.9	1.1	0.9	0.7	0.5	0.5	0.6
1998	0.6	0.6	0.6	0.7	0.8	1.1	1	1	0.7	0.5	0.5	0.8
1999	0.9	0.7	0.6	0.8	1	1.1	1	0.9	3.2	0.5	0.7	0.8
2000	0.9	1.1	0.8	0.8	0.7	1.2	1.2	0.9	0.7	0.6	0.6	0.7
2001	0.8	0.7	0.7	0.7	0.8	0.9	0.9	0.8	0.6	0.6	0.6	0.7
2002	0.7	0.8	0.6	0.7	1	1.1	1.1	0.8	0.7	0.6	0.8	0.8
2003	0.8	0.8	0.8	0.6	0.8	1	0.9	0.9	x	x	x	x

Monthly wind speed data at Awassa station(m/s) at 2m above the ground

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1986	230.5	211.7	240.9	176.6	113.2	140.2	124.4	146.9	162.6	172.4	192.5	188.1
1987	239.8	200.1	179.9	179.9	190.7	173.8	173.5	172.2	154.5	175.1	208.0	230.5
1988	212.9	203.3	243.2	192.1	206.3	171.4	110.2	146.6	140.2	164.5	273.5	193.0
1989	196.4	126.3	227.6	155.4	219.6	183.5	129.4	153.7	166.6	179.7	189.1	158.6
1990	180.5	143.6	167.2	173.9	187.0	187.7	149.7	143.2	158.4	198.6	198.5	224.2
1991	222.3	191.0	178.1	154.6	153.0	159.1	120.6	142.1	149.4	183.6	178.5	188.1
1992	152.5	120.9	254.4	216.2	182.0	185.6	178.4	160.7	135.3	155.5	177.6	184.4
1993	182.7	163.6	237.1	170.0	200.1	161.5	153.2	161.7	148.2	169.7	212.3	234.8
1994	250.1	242.9	235.3	195.1	179.7	179.7	121.6	141.5	162.4	206.1	231.3	248.9
1995	267.2	242.5	240.0	182.0	202.9	198.8	122.6	107.5	118.5	139.2	158.5	202.6
1996	148.1	183.0	159.1	140.3	129.4	109.4	108.3	118.0	103.2	149.9	164.8	176.5
1997	169.6	211.9	203.1	126.6	169.0	143.9	146.3	153.9	114.3	128.1	110.2	139.9
1998	207.6	129.8	149.3	152.5	143.5	141.2	113.8	103.8	110.7	93.4	144.9	170.3
1999	177.8	196.8	150.3	162.0	160.1	152.4	128.9	133.5	109.8	103.3	153.8	171.8
2000	201.5	201.8	205.2	158.2	131.2	142.4	127.6	117.1	113.0	113.9	139.0	158.8
2001	156.4	172.7	137.9	144.2	130.3	105.3	104.7	114.1	109.5	120.9	154.5	170.3
2002	153.8	164.2	149.6	144.7	136.5	131.5	147.3	103.8	111.5	136.4	183.6	138.5
2003	160.3	174.0	149.3	109.9	145.4	130.2	96.8	117.5	129.5	156.6	190.4	183.0

Monthly pan evaporation data at Awassa station(mm)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1988	93	87	88	92	77	90	97	97	96	96	91	85
1989	84	82	86	97	95	99	93	93	97	95	84	96
1990	89	92	96	94	98	92	90	92	94	92	86	78
1991	81	90	92	94	95	x	94	94	97	94	84	86
1992	88	94	89	90	96	92	93	x	95	96	92	93
1993	93	94	89	94	95	93	91	89	95	96	90	82
1994	73	73	88	91	95	92	94	93	94	93	93	86
1995	76	82	92	95	96	93	93	93	97	93	92	91
1996	92	84	96	96	97	94	92	94	96	96	92	83
1997	87	70	82	95	97	93	91	88	92	92	91	87
1998	92	89	90	88	91	89	87	88	92	90	88	79
1999	81	70	91	91	94	90	91	92	95	94	87	85
2000	72	64	68	86	95	90	92	91	95	94	91	91
2001	78	81	88	92	93	92	92	93	95	93	83	x
2002	88	74	93	91	92	91	90	91	94	93	79	89
2003	86	82	83	90	93	x	x	x	x	x	x	x

Monthly relative humidity(%) at 06:00 at Awassa

1988	44	46	37	51	60	63	73	67	63	57	38	39
1989	44	46	37	59	55	66	68	63	65	49	42	58
1990	43	56	58	56	58	56	65	66	57	46	42	36
1991	40	51	55	49	59	65	71	64	61	44	38	41
1992	37	54	44	49	57	60	66	x	62	59	49	51
1993	55	59	37	55	62	67	65	63	61	56	41	39
1994	35	34	43	52	58	65	73	68	61	46	46	41
1995	36	49	50	60	56	60	68	68	64	51	43	47
1996	54	40	52	59	63	71	71	70	66	52	44	40
1997	47	33	43	60	57	65	67	60	57	55	56	49
1998	57	55	51	43	60	59	68	69	62	62	42	34
1999	39	30	53	45	56	60	71	62	59	64	42	40
2000	35	31	33	48	63	60	66	64	62	59	50	45
2001	46	44	56	53	62	64	68	67	61	54	40	x
2002	46	34	50	47	61	62	57	63	58	45	35	51
2003	47	36	44	56	56	x	x	x	x	x	x	x

Monthly relative humidity(%) at 12:00 at Awassa

1988	39	45	54	57	65	61	70	72	79	73	37	36
1989	34	40	51	66	55	63	67	65	79	61	47	52
1990	55	66	65	58	63	55	74	64	68	49	40	31
1991	32	44	57	59	63	61	69	67	75	49	34	39
1992	42	51	45	53	65	58	63	x	78	68	53	44
1993	50	54	37	66	66	63	63	64	71	71	42	33
1994	28	28	50	53	68	58	69	72	73	52	42	34
1995	28	36	51	66	64	60	66	65	72	56	40	47
1996	51	35	62	69	75	69	68	70	73	57	43	36
1997	41	22	39	68	63	66	65	66	70	68	62	47
1998	52	51	60	54	61	57	64	64	69	68	42	30
1999	32	22	54	54	60	59	64	65	71	66	42	36
2000	27	23	28	59	65	57	62	61	75	71	54	40
2001	35	35	62	64	64	65	64	66	73	67	35	x
2002	36	22	52	51	61	59	52	64	66	53	29	49
2003	38	31	50	60	56	x	x	x	x	x	x	x

Monthly relative humidity(%) at 18:00 at Awassa

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1988	29.2	29.6	31	28.4	27.5	24.9	22.8	23.8	24.8	25.9	27.9	27.8

1989	27.7	28	28.7	26.2	27.1	23.9	23.3	24.3	24.4		27.3	27.1
1990	28.6	27.7	27.5	27.8	27.2	26.1	24.4	24.4	25.8	28	29.5	29.2
1991	30.4	29	27.7	29.3	28	26.1	23.3	25.1	26	27.8	29.2	28.1
1992	29.4	28.5	30.5	29.8	27.5	26.3	24.3	23.8	24.9	25.8	27.1	28.5
1993	27.6	26.9	30.8	27	26.9	25.2	24.4	24.8	25.7	26.9	30.1	29.7
1994	30.5	32	30.9	29	26.7	24.7	23.5	25	26.2	28.3	28.3	29.3
1995	30.4	30.7	30	27.3	27.9	27	24.3	24.7	25.9	27.5	29.3	29.3
1996	28.3	30.8	29.4	27.7	26.8	23.8	23.8	24.3	25.2	27	28.1	28.6
1997	28.9	30.3	30.8	26.9	27.5	25.7	23.9	25.5	26.7	26.5	26.4	27.3
1998	27.7	28.7	29	29.7	27.3	26.3	24.3	23.6	25.4	25.3	27.5	28.1
1999	29.1	31.4	28.1	29.1	27.2	26.1	23.6	25	25.6	25	27.2	28
2000	29.5	30.7	31.8	28.8	26.1	25.7	24.7	24.8	25.1	25.6	27.2	28.3
2001	28.7	29.1	28.4	28.4	26.9	24.8	24.4	24.5	25.9	26.7	28.2	28.6
2002	28.2	30.9	28.8	28.6	27.1	25.7	25.6	25.4	26.1	28.3	29.8	28.9
2003	28.4	31.3	30.6	28.1	28.3	25.6	24.2	24.8	25.9	28.2	29.3	27.2

Monthly miximum temperature data at Awassa station(^{0}C)

1988	11.3	13.6	12.2	14.6	13.9	13.9	14.7	14.1	13.9	12.8	6.5	7.9
1989	9.5	10.7	12.7	13.5	12.4	13.1	14.1	13.4	12.9	x	9.7	13
1990	9	14.1	12.6	13.7	13.3	12.8	14.2	10.7	12.9	10.5	10.4	9
1991	11.9	12.5	13.4	12.8	14	15.3	14.3	13.7	12.9	9.5	9.4	9.6
1992	12.4	13.6	12.8	14.3	13.5	14	13.9	14.5	12.7	13.1	10.5	11
1993	12.1	12.3	9.7	14.1	14	14.2	13.9	13.7	12.9	13.2	9.3	9.2
1994	9.7	12	13	13.8	14.3	14.5	14.3	14.7	14	10.1	10	8.9
1995	9.8	12.7	13.6	14.9	13.1	13.6	14.2	14.5	13	12.3	8.4	10.6
1996	12.1	10.5	13	14	14.1	14.3	14.5	14.4	13.7	10.9	8.8	9.6
1997	12.4	10	13.3	13.9	13.2	13.6	14.2	14.2	13.2	13.6	13.8	14.4
1998	13.3	14.3	13.9	14.8	15.7	14.7	15.7	15.9	14.5	14.4	8.9	7.8
1999	10.2	9.9	13.8	12.5	13.6	14	14.2	13.7	13.8	14	9.3	9.3
2000	9.6	10.6	11.1	14.1	14	13.7	14.3	14	13.4	14	10.5	9.7
2001	11.5	11.1	13.7	14.4	14.1	15	14.7	15	13.1	13.8	10.3	10.9
2002	12.4	11.8	14	13.5	14.8	14.5	14.4	14.2	13.4	12.8	9.8	13.2
2003	11.8	11.6	13.2	14.3	14.2	14.3	14.5	14.5	14	11.9	11.2	10.4

Monthly minimum temperature data at Awassa station(^{0}C)

Appendix II Summary of initial hydrological data

year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1969	x	x	x	x	x	x	x	x	x	1.11	1.04	0.89
1970	0.78	0.69	0.70	0.73	0.74	0.73	0.72	0.81	1.08	1.37	1.41	1.26
1971	1.10	0.97	0.81	0.77	0.79	0.89	1.07	1.19	1.30	1.45	1.55	1.48
1972	1.38	1.32	1.26	1.25	1.36	1.43	1.48	1.62	1.83	1.95	1.86	1.71
1973	1.58	1.40	1.23	1.06	1.02	1.01	1.00	1.17	1.28	1.34	1.25	1.07
1974	0.78	0.69	0.70	0.73	0.74	0.73	0.72	0.81	1.08	1.37	1.41	1.26
1975	1.10	0.97	0.81	0.77	0.79	0.89	1.07	1.19	1.30	1.45	1.55	1.48
1976	1.38	1.32	1.26	1.25	1.36	1.43	1.48	1.62	1.83	1.95	1.86	1.71
1977	1.58	1.40	1.23	1.06	1.02	1.01	1.00	1.17	1.28	1.34	1.25	1.07
1978	1.59	1.47	1.45	1.37	1.38	1.42	1.45	1.62	1.88	2.17	2.22	2.14
1979	2.04	2.01	1.93	1.90	1.86	1.87	1.89	1.99	2.12	2.26	2.26	2.14
1980	2.04	2.01	1.93	1.90	1.86	1.87	1.89	1.99	2.12	2.26	2.26	2.14
1981	1.18	1.02	0.95	1.03	1.02	0.97	0.95	1.07	1.26	1.47	1.43	1.28
1982	1.15	1.04	0.96	0.89	0.85	0.81	0.87	0.94	0.99	1.09	1.19	1.18
1983	1.08	1.01	0.90	0.83	0.97	1.29	1.39	1.51	1.81	2.10	2.17	2.14
1984	1.98	1.78	1.61	1.47	1.39	1.41	1.39	1.40	1.45	1.48	1.39	1.23
1985	1.06	0.89	0.72	0.72	0.88	0.93	0.97	1.10	1.19	1.30	1.45	1.39
1986	1.10	0.92	0.83	0.78	0.76	0.90	1.09	1.28	1.46	1.70	1.74	1.61
1987	1.40	1.23	1.19	1.17	1.25	1.62	1.72	1.75	1.81	1.89	1.88	1.73
1988	1.57	x	1.32	1.20	1.19	1.17	1.22	1.48	1.86	2.24	2.36	2.20

1989	2.06	1.96	1.85	1.83	1.82	1.93	1.96	1.96	2.02	2.17	2.17	2.11
1990	2.02	1.96	1.98	2.07	2.13	2.10	2.08	2.11	2.11	2.18	2.10	1.92
1991	1.77	1.65	1.60	1.56	1.57	1.57	1.59	1.62	1.67	1.71	1.60	1.47
1992	1.32	1.27	1.18	1.10	x	x	1.14	1.25	1.48	1.80	2.01	2.00
1993	1.92	1.93	1.83	1.74	1.82	1.93	1.97	2.03	2.09	2.22	2.34	2.23
1994	2.06	1.89	1.76	1.67	1.70	1.69	1.78	2.08	2.30	2.37	2.30	2.14
1995	1.95	1.81	1.72	1.71	1.73	1.67	1.68	1.73	1.94	2.02	1.94	1.81
1996	1.72	1.58	1.49	1.49	1.60	1.91	2.27	2.54	2.82	3.06	3.05	2.90
1997	2.74	2.58	2.41	2.38	2.37	2.36	2.46	2.57	2.62	2.75	3.02	3.13
1998	3.10	3.08	3.12	3.05	3.06	3.07	3.09	3.21	3.31	3.58	3.80	3.70
1999	3.53	3.36	3.27	3.17	3.08	3.01	2.99	3.05	3.05	3.22	3.29	3.17
2000	x	x	x	x	2.58	2.47	2.40	2.38	2.44	2.62	2.71	x
2001	x	x	x	2.22	2.26	2.40	2.52	2.65	2.85	3.02	3.09	3.01
2002	2.88	2.71	2.64	2.63	2.60	2.59	2.55	2.63	2.74	2.73	2.61	2.46
2003	2.35	2.21	2.09	2.04	2.12	x	x	x	x	x	x	x

Mean monthly water level of Awassa Lake(m)

year		**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
1985	I	0.217	0.140	0.078	0.016	1.432	1.857	1.130	1.725	4.730	4.420	1.087	0.331
	II	0.280	0.154	0.126	0.027	2.860	3.300	2.060	2.170	7.560	7.240	1.430	0.461
	III	0.154	0.126	0.029	0.005	0.004	0.413	0.200	1.280	1.900	1.600	0.743	0.200
1986	I	x	0.160	0.199	0.319	0.995	5.400	4.850	5.200	4.000	5.050	x	x
	II	x	0.186	0.271	0.512	2.200	7.800	5.270	5.860	6.060	6.940	x	x
	III	x	0.142	0.160	0.214	0.526	2.460	4.430	3.300	2.740	2.780	x	x
1987	I	0.381	0.207	0.340	1.095	3.483	4.300	1.973	1.399	2.742	2.556	1.504	0.788
	II	0.499	0.238	0.643	1.660	6.370	6.560	2.310	2.030	3.440	3.030	2.000	1.030
	III	0.246	0.193	0.207	0.643	1.720	2.000	1.540	1.050	2.030	2.030	1.050	0.597
1988	I	0.513	0.397	0.424	0.435	0.594	1.141	2.682	5.347	6.423	5.613	3.603	1.817
	II	0.582	0.436	0.499	0.540	0.674	1.570	4.660	5.790	7.010	7.010	4.900	2.390
	III	0.448	0.358	0.358	0.347	0.473	0.401	1.570	4.900	5.790	4.900	2.500	1.600
1989	I	1.374	1.107	0.971	1.050	1.395	2.853	2.239	2.358	3.660	4.477	2.592	1.663
	II	1.570	1.230	1.010	1.280	1.960	3.890	2.620	2.950	4.660	4.960	3.790	1.840
	III	1.260	1.010	0.945	0.674	0.707	2.030	1.930	1.900	2.240	3.890	1.870	1.570
1990	I	1.457	1.356	2.902	5.300	3.507	1.917	1.852	2.632	2.869	5.915	4.339	1.133
	II	1.570	1.540	4.430	5.930	4.660	2.500	2.950	2.780	4.380	7.170	7.170	1.300
	III	1.280	1.230	1.600	4.490	2.540	1.090	0.905	2.580	2.500	4.540	1.350	0.965
1991	I	0.847	0.607	0.452	1.225	3.521	1.334	2.503	3.700	4.527	5.182	3.438	1.971
	II	0.965	0.707	0.526	3.080	4.660	2.130	3.400	4.100	4.100	5.520	5.020	2.310
	III	0.707	0.526	0.337	0.246	2.310	0.945	0.867	3.400	4.840	4.900	2.310	1.430
1992	I	0.778	0.305	0.233	0.319	1.140	1.645	2.165	2.969	6.501	8.050	5.610	1.864
	II	1.430	0.358	0.254	0.401	2.280	2.170	2.620	4.660	7.240	8.660	8.740	2.820
	III	0.358	0.254	0.207	0.262	0.242	1.260	1.600	2.170	4.660	7.320	2.860	1.280
1993	I	1.090	0.766	0.504	0.420	1.420	3.630	4.450	4.300	5.020	5.900	4.540	3.840
	II	1.260	0.925	0.612	0.582	2.350	4.320	5.080	4.900	5.590	6.200	5.590	4.780
	III	0.925	0.627	0.424	0.358	0.582	2.390	3.790	3.940	4.260	5.590	3.740	2.860
1994	I	2.180	x	0.336	0.625	1.000	1.680	2.820	5.530	6.110	4.040	2.830	2.210
	II	2.860	x	0.448	0.829	1.330	2.170	3.790	6.420	6.780	4.660	3.490	2.420
	III	1.380	x	0.271	0.473	0.643	1.330	2.200	3.890	4.720	3.490	2.420	1.960
1995	I	1.740	1.440	0.411	0.959	x	2.460	2.830	3.630	4.440	4.780	6.020	6.860
	II	1.930	1.540	0.965	1.720	x	3.490	3.490	4.160	4.660	5.400	6.710	7.320
	III	1.540	1.030	0.238	0.317	x	1.680	2.500	2.780	4.210	4.210	5.580	5.930
1996	I	x	x	x	1.710	x	6.870	5.900	5.870	6.210	7.670	6.290	4.800
	II	x	x	x	1.930	x	8.480	8.220	6.780	6.780	8.740	7.480	5.660
	III	x	x	x	1.410	x	5.270	4.050	4.320	5.520	6.420	5.720	3.890
1997	I	3.290	2.580	2.150	1.719	2.200	2.359	2.030	2.306	2.546	3.948	5.028	6.032
	II	3.840	2.660	2.500	2.200	2.460	2.600	2.540	2.660	2.820	4.720	5.790	6.200
	III	2.660	2.500	1.720	1.540	2.100	2.130	1.780	1.870	2.310	2.620	4.260	5.790

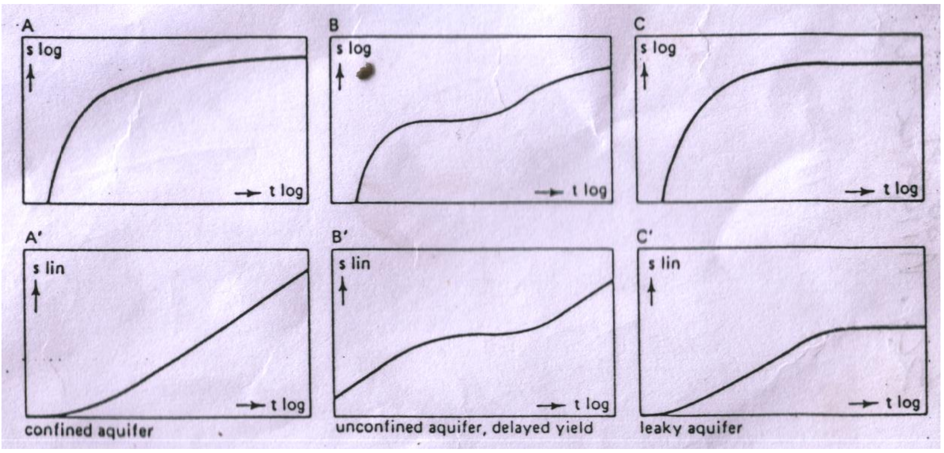
1998	I	6.876	6.629	3.979	1.738	3.490	7.113	7.222	5.700	5.980	8.009	x	x
	II	7.480	7.560	5.520	2.460	5.660	7.970	8.050	5.990	6.860	8.220	x	x
	III	6.270	5.660	1.840	1.380	2.540	5.720	6.060	5.270	5.270	6.710	x	x

Monthly Tikur wuha discharge at Dato village, I-mean(mcm), II-maximum(m^3/s), III-minmum(m^3/s)

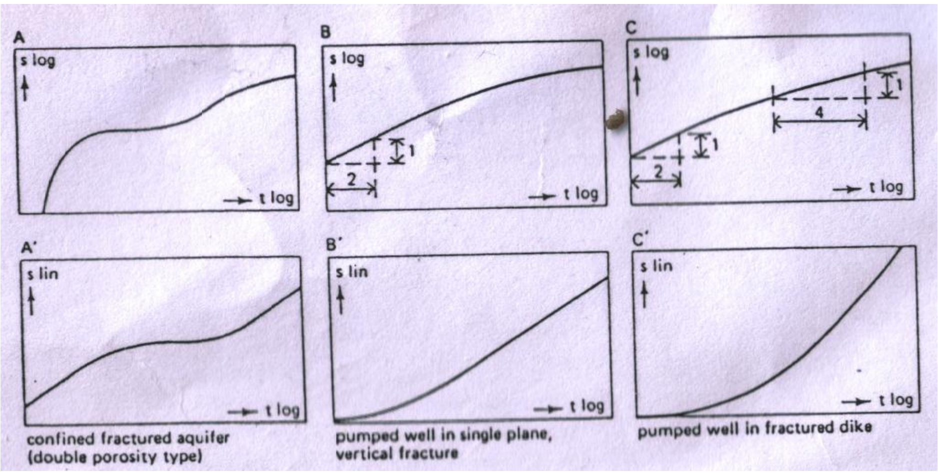
Appendix III Stratigraphy of the Central sector of the MER (after Gidey Woldegebriel et al., 1992)

Ethiopian Rift Valley 7^0-$8^040'$ Lat. North and adjacent plateau (Di Paola, 1972)	**Central sector of MER (Gidey Woldegebriel et al., 1990)**	**Awassa caldera: Eastern wall (Gidey Woldegebriel et al., 1990)**	**Aluto area (Rift floor) Geothermal well LA-3 (EIGS,1985) (Gidey Woldegebriel et al., 1990)**
Alluvium and lacustrine sediments (Recent)	Silicic and mafic rocks of the Wonji group (≤1.6Ma.)	Silicic and mafic rocks of the Wonji group (≤1.6Ma.)	Silicic, trachytic and basaltic units of the Wonji group (≤1.6Ma.)
Alkaline and peralkaline silicic flows (Holocene)			
Trachyte flows and basaltic tuff (Recent Pleistocene)			
Alkaline and peralkaline silicic rocks (Early Pleistocene-Late Pliocene	Chilalo trachytes and silici rocks (Late Pliocene, 3-1.6Ma)	Chilalo trachytes/Trachytic tuff (1.85Ma)	Chilalo trachytes (Late Pliocene)
Alkaline and peralkaline silicic rocks (Pliocene)	Butajira ignimbrites (Pliocene, 4.2-3Ma)	Butajira ignimbrites (3.55-3.69Ma)	Butajira ignimbrites (Early to Mid-Pliocene)
Basalts and ignimbrites of plateau trap series (Pliocene-Early Eocene)	Guraghe basalt splus silicics (Miocene, 11-5Ma)	Guraghe basalt splus silicic flows (8.7-8.8Ma, Late Miocene)	
	Shebele trachytes (Mid-Miocene, 17-12Ma)		
	Kella basalts (Oligocene, 31-29Ma)		
	Pre-Tertiary units (Mesozoic & Precambrian)		

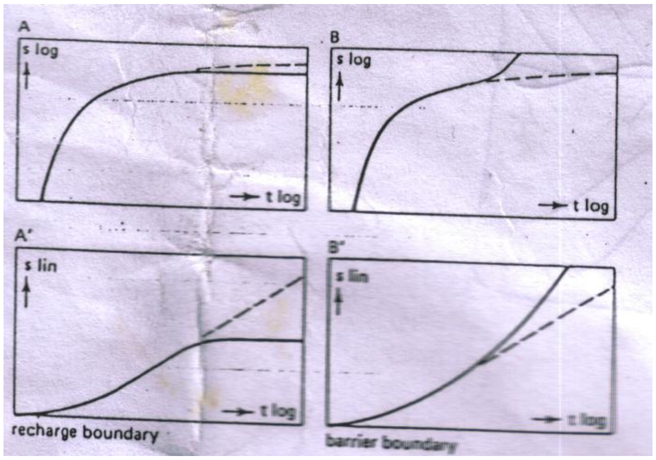
Appendix IV Standard curves



Log-log (uppers) and semi-log (lowers) plots of standard curves for unconsolidated confined, unconfined and leaky aquifers from left to right respectively.



Log-log and semi-log plots of standard curves for consolidated confined, unconfined and leaky aquifers from right to left



The effect of recharge boundary(A, A') and barrier boundary(B, B') in a consolidated confined aquifer.

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