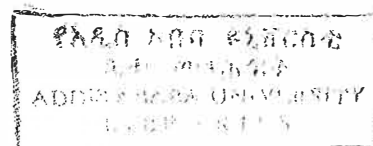


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HYDROLOGY, HYDROGEOLOGY, AND HYDROCHEMISTRY OF THE
LAKES SYSTEM HAIQ-ARDIBO, NORTHERN ETHIOPIA.

A THESIS
SUBMITTED TO THE SCHOOL OF GRADUATE STUDIES
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THE REQUIREMENT FOR THE DEGREE OF
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CONTENTS

ACKNOWLEDGMENTS	I
ABSTRACT	VIII
1. Introduction	1
1.1 Back ground	1
1.2 Previous works	2
1.3 Objectives and scope of the present work	4
1.4 Materials and methods	5
2. General overview of the study area	7
2.1 Location and accessibility	7
2.2 Phsiography, drainage and slopes	9
2.3 Land use / land cover and soils	12
2.4 Climate	18
3. Geology	21
3.1 Regional geologic setting	21
3.2 Geology of the studied area	26
3.2.1 General	26
3.2.2 Rhyolites and ignimbrites	28
3.2.3 Unwelded acidic materials	29
3.2.4 Weatherd basaltic units	29
3.2.5 Upper basaltic unit	30
3.2.6 Quaternary sediments	30
3.3 Geologic structures	35

4. Hydrology	36
4.1 Hydrometeorological data	37
4.2 Rainfall analysis	39
4.3 Evapotranspiration	45
4.3.1 Open water evaporation	45
4.3.2 Potential evapotranspiration (PET)	53
4.3.3 Actual evapotranspiration (AET)	55
4.4 Runoff characteristics of the catchment	58
5. Hydrogeology	63
5.1 General	63
5.2 Fractured volcanic rocks	63
5.3 Quaternary sediments	65
5.4 Recharge and discharge zones	66
5.5 Springs	69
5.6 Groundwater flow and surface water-groundwater interactions	71
6. Water balance	75
6.1 General	75
6.2 Ardibo subcatchment	76
6.2.1 Lake Ardibo	78
6.3 Haiq subcatchment	80
6.3.1 Lake Haiq	81
6.4 Water balance for the entire study area	82
7. Bathymetry of the lakes	85

7.1 Lake Haiq	85
7.2 Lake Ardibo	86
7.3 Lake level fluctuations	87
8. Hydrochemistry	91
8.1 Introduction	91
8.2 Water sampling and analysis	91
8.3 Water type classification	92
8.4 Chemical composition of different water samples	95
8.5 Temporal variation of the chemistry of the lakes	97
8.6 Oxygen and temperature profiles of the lakes	100
8.7 Water quality	100
8.7.1 Water quality criteria	100
8.8 Water pollution	104
9. Conclusion and recommendation	105
References	109
Annexes	114

I LIST OF FIGURES		PAGE
Fig. 2.1	Location map of the study area	8
Fig. 2.2	Drainage map of the catchment	11
Fig. 2.3	Landuse-land cover map of the area	14
Fig. 2.4	Soil map of the catchment	16
Fig. 2.5	Slope map of the catchment	17
Fig. 2.6	Histogram of long term mean annual rainfall and temperature of the study area	20
Fig. 3.1	Regional geologic map of the study area	26
Fig. 3.2	Sketch of the volcanic successions of selected traverse	31
Fig. 3.3	Geologic map of the Haiq-Ardibo catchment	32
Fig. 3.4	Geological cross sections across the lakes	33
Fig. 3.5	Structural map of the Haiq-Ardibo catchment	34
Fig. 4.1	Temporal variability of rainfall	44
Fig. 5.1	Hydrogeological map of the Haiq-Ardibo catchment	74
Fig. 7.1a	Bathymetric map of lake Haiq	86
Fig. 7.1	Old bathymetric map of lake Haiq	89
Fig. 7.2	Bathymetric map of lake Ardibo	90
Fig. 8.1	Piper trilinear plot of the chemistry of waters	94

II LIST OF TABLES	PAGE
Table 2.1 Areal proportion of different land use/land cover units	12
Table 2.2 Slope classes of the studied area	15
Table 3.1 Regional lithostratigraphy and chronostratigraphy of the eastern central plateau	24
Table 4.1 Mean monthly air temperature of the study area	37
Table 4.2 Mean monthly surface temperature of the lakes	38
Table 4.3 Relevant meteorological stations considered in the study	39
Table 4.4 Isohyetal range and mean precipitation of the area	41
Table 4.5 Mean monthly areal rainfall	42
Table 4.6 Summary of the results of open water evaporation for lake Haiq and Ardibo	52
Table 4.7 Summary of soil type, vegetation, AET, and moisture surplus in the studied catchment	57
Table 4.8 Relation between land use/land cover, slope and soil type	59
Table 5.1 Discharge and EC measurement of the Ankerka river along the flow path	73
Table 6.1 Mean annual water balance for Ardibo sub catchment	77
Table 6.2 Mean annual water balance of lake Ardibo	79
Table 6.3 Mean annual water balance of Haiq sub catchment	80
Table 6.4 Mean annual water balance of lake Haiq	81
Table 6.5 mean annual water balance of the Haiq-Ardibo catchment	83
Table 7.1 Present day depth-area relation of lake Haiq and Ardibo	88
Table 8.1 Chemical composition of lake Haiq and the Ankerka	99

	river at two different times	
Table 8.2	Oxygen and temperature profiles of lake Haiq	100
Table 8.3	Water quality of samples in the Haiq- Ardibo catchment	102
Table 8.4	Water quality for irrigation of representative water samples in the area	102
table 8.5	Wilcox water quality classification for irrigation	103

III. LIST OF ANNEXES

Annex. 1	Pan evaporation data	114
Annex. 2	Long term mean monthly precipitation data	114
Annex. 3	Evaporation computation summary	115
Annex. 4	Values of runoff coefficient for different land uses/land cover unit	118
Annex. 5	Computation of AET using Thornthwait and Mather method for different vegetation soil types	119
Annex. 6	Spring inventory	123
Annex. 7	Hydrochemical data	126
Annex. 8	Bathymetric data of lake Haiq and Ardibo	127

ABSTRACT

The geology, hydrology, and hydrogeology of Haiq-Ardibo catchment was studied. The main objectives is to understand and map the different lithologic units and characterize them in to hydrostratigraphic units, to analyze the water balance of the catchment including lakes Haiq and Ardibo. Hydrochemical and bathymetric studies were also conducted.

The geology of the area was mapped at the scale of 1:50,000 and this was used as a basis to establish the hydrogeological map by taking into account the permeability, geomorphic setting and recharge conditions.

Two major hydrostratigraphic units are mapped. These are the Quaternary unconsolidated sediments and the fractured volcanic rocks, both having a good permeability. Due to morphologic setting, the fractured volcanics are referred to as poor aquifers, but good recharge zones, recharging the Quaternary unconsolidated sediments that occupy low lying flat areas in the studied catchment.

Land use/land cover, soil, and slope maps of the area were prepared so that the rate of evapotranspiration for a vegetation-soil complex is computed, and the runoff into lake Haiq and Ardibo estimated.

Areal mean annual rainfall was analyzed using arithmetic mean of the long term mean annual rainfall of four stations, Thiessen weighted averages of these stations and Isohyetal methods; a value of 1158.5 mm depth was obtained by taking the average of the first two methods.

Open water evaporation on the lakes surface was estimated using Pan evaporation data, radiation, Penman , and mass transfer approaches. The first three methods gave reasonable values and the average was taken and is 146.5 mm depth over the surface of the lakes. Potential evapotranspiration (PET) computed using modified Penman gave 1200 mm depth over the area of the studied catchment.. Using the computed PET and effective rainfall, actual evapotranspiration and groundwater recharge over the catchment using Thornthwaite and Mather (1957) soil-water balance method obtained is 805 and 43.2 mm respectively.

Runoff into the lakes was also calculated using a weighted average runoff coefficient of the Haiq and Ardibo subcatchments taking in account soil, slope, and vegetation cover. An annual runoff into lake Haiq and Ardibo is 18.82 and 12.68 million cubic meter (mcm) respectively.

Taking into consideration all the inflows and outflows into the catchment and lakes, the water balance of the studied area was analyzed. The annual inflow into lake Ardibo is estimated to be 30.98 mcm and outflow is 26.3 mcm. The residual found is 4.68 mcm. Representing the groundwater net flux. Using a Darcy, the groundwater outflow from lake Ardibo is estimated to be 3.2 mcm. The groundwater inflow into this lake therefore is 1.48 mcm. In the same way the annual input into lake Haiq is 46.83 mcm. and the outflow is 33.4 mcm, the residual remaining in the balance is 13.43 representing the net groundwater flux.

The water balance computed for the entire study area is estimated to be 162.3 mcm. inflow and 138.434 mcm out flow. The residual found is therefore 23.87 mcm, assuming that the groundwater divide coincides with the surface water divide, the residual term is the annual groundwater outflow from the studied catchment.

The current bathymetric survey indicates that both lakes have experienced significant lake level reduction. This lake level change is attributed to land use changes, neotectonics and general decrease in the rainfall of the area.

Hydrochemical study of the surface and groundwater indicated two major water types. The surface water being magnesium bicarbonate type, while the groundwater is calcium bicarbonate type . Further observation of the chemistry of the ground and surface water bodies indicated that the waters are suitable for irrigation. Except for the trace non metals, the chemical analysis of the inorganic constituents show that the water is potable provided , bacteriological analysis should be done.

Chapter 1

INTRODUCTION

1.1 Background

Among the many lakes of Ethiopia, which covers more than 7000 km², Lake Haiq and Ardibo are situated at the Northwestern Ethiopian plateau margin within the escarpment zone of the Afar Rift and are probably the least studied of the Ethiopian lakes. Unlike other lakes in the country, such as the system of lakes in the main Ethiopian and Afar Rift, the hydrologic and hydrogeologic characteristics of these lakes is poorly known and scientific data on these closed basin lakes system is scanty.

The studied area, the closed catchment of Haiq–Ardibo, consists of two lakes of intermediate size. Lake Haiq is a terminal lake with in this drainage system and has a surface area of 22.8 km², and lake Ardibo has 15.8 km² surface area. The low salinity (freshness of the lakes), the beautiful scenery that the lakes are endowed, and the good productivity of fish and their protein content (Zenebe Tadesse, 1998) are some of the typical features that make these lakes suitable for development. Despite the freshness of these lakes, their beautiful disposition in an area attacked by recurrent drought, their suitability for fish production (farming) and other related activities, attempts were not done so far in studying systematically the hydrology and the hydrogeology of these lakes and the catchment they are draining.

Due to the aesthetic value that many lakes provide, the gradients of land prices generally decreases from the lake shores land ward (Lerman, 1978). But, this is not the case for the

studied lakes Haiq and Ardibo. There is hardly any recreational development works made regardless of the beautiful disposition of these lakes. If one sees for instance the expansion of Haiq town, which is found near the south western shore of lake Haiq, one will ask the question, why it is away from the lake. This clearly shows the infancy of tourism development in the country, particularly in the Haiq-Ardibo area. In fact, this by its own has a positive aspect when looked from the perspective of pollution.

In addition to the above mentioned, there is an interesting irrigation development scheme using these lakes, but these development works were not backed by scientific studies and as a result, some are subject to serious problems to the extent that they were abandoned for some time. A case in point is a pump irrigation scheme (Kekewa pump irrigation project) constructed at the western shore of lake Haiq.

Initiated with the scientific interest these lakes have, with the role which these lakes might play in the economy of the country, and with the personal knowledge that we have on the study area, the research was initiated on the catchment of the lakes system Haiq-Ardibo.

1.2 Previous Works

Relevant research work in the study area dates back to the Italian occupation during the 1930s where a number of limnologists have visited lake Haiq (Baxter & Golobistch, 1970), some to mention: Vatova (1940); Zanon (1941); Cannicce & Almagia (1947). Later Baxter & Golobistch (1970) have described the limnology of Haiq based on their visit in 1969. Recently, Elizabeth et al., (1992) and Kebede Alemu (1995) reported on some aspects of the hydrobiology of lake Haiq.

A chemical data on lake Haiq based on the works of Baxter & Golobistch (1970) is reported by Wood & Talling (1988). Isotopic composition of the same lake is also published by Schoell & Faber (1976).

The regional geology of the area and the geology of neighboring catchments were described by many authors: Gass (1975) outlined the magmatic and tectonic activities in the development of the Afro-Arabian Dome; Kronberg et al., (1975) have reported, using Earth Resources Technology Satellite 1 (ERTS 1) data, on the geology and tectonics of the Afar and adjacent regions; Zanettin et al.,(1978) have presented the volcanic successions, tectonics and magmatology of central Ethiopia and suggested the trend and age of the Western Afar Escarpment and correlated the volcanic and tectonic events of the East African Rift System; Zanettin et al.,(1974) reported the migration of the Oligo-Miocene ignimbritic volcanism in the central Ethiopian plateau from north to south and southwest following the rift escarpment; Justin Visentin & Zanettin, (1974) distinguished and reported the stratigraphy of the Kombolcha – Eloa area and suggested the volcanotectonic phenomena; Gregnanin et al., (1973) have studied the volcanites of the Dessie – Kombolcha area and suggested a modified stratigraphy of the volcanics presented by Abbate et al., (1968); Zanettin & Justin Visentin (1975) have identified three volcanic cycles in the Afar margin and surrounding areas, i.e., pre-Oligocene, Oligocene, and plio-pleistocene in age; each being characterized by definite volcanic formation. More recently, Chorowicz et al., (1999) reported about the marginal basins of Western Afar and attributed their formation to be initiated by north-trending left lateral motion. Ketema Tadesse (1978) has investigated groundwater for the town of Dessie. The same author, has studied in 1980 the hydrogeology of the Borkena river basin which is situated immediately southwest of the study area.

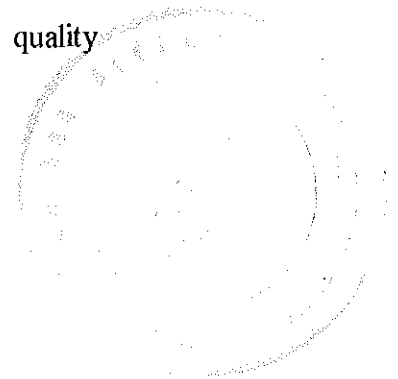
Apart from the aforementioned few limnologic and hydrobiologic studies on lake Haiq, no study was made so far on the limnology, hydrobiology, and bathymetry of lake Ardibo which is found a few kilometers away from lake Haiq. Moreover, specific publication and/or studies on the geology, hydrology, and hydrogeology of the research area is lacking.

1.3 Objectives and scope of the present work

The present work covers the area bounded within the drainage of lake Haiq and Ardibo having a total area of about 140 km², out of which the lakes cover some 38.6 km² area.

The main objectives of the research work is:

1. To assess the water balance of the two lakes (Haiq and Ardibo) and their catchments using conventional hydrologic balance technique.
2. Preparation of the hydrogeologic map of the area at the scale of 1: 50,000.
3. Analyzing the chemistry of the different water bodies and compare them with previous records and suggest possible reasons of temporal variation (if there is any).
4. Establish the bathymetry of the two lakes, and compare the bathymetry of Haiq with that made in the 1949's.
5. Analyzing the quality of different water bodies for domestic, and agricultural purposes, and compare with national and international water quality standards.



1.4 Materials and methods

Different materials and equipment were used to accomplish the objectives mentioned in section 1.3.

1. Black and white air photos of two strips, ten in number, produced by the Ethiopian Mapping Agency in 1986 at the scale of 1: 50,000.
2. Topographic maps (Dessie, Haiq, Bistima, and Degan Sheets), published in 1991.
3. Geological and Hydrogeological map of Ethiopia at the scale of 1: 200,000.
4. Garmin model GPS is used for positioning during the bathymetric survey.
5. Water quality kits (EC, DO, pH meters).
6. Current meter.

Preliminary interpretation of air photos and preparation of base maps were done in the office. The fieldwork was conducted in two phases: The first phase was from Jan. 25 to Feb. 15, 2000. The main purpose was sampling surface and ground waters, measurement of river and spring discharges, in situ measurement of electrical conductivity (EC), pH, Dissolved Oxygen (DO), temperature, depth and preliminary geological and hydrogeological mapping. The second phase lasts from March 15 to April 3, 2000. This time detailed geological, land use, land cover, slope and soil mapping, and detailed bathymetric survey was conducted.

Nineteen water samples were collected from rainfall, surface and groundwater bodies; these samples were kept in a refrigerator till analyzed in the Ethiopia Geological Survey's Laboratory. The methods employed in the lab for the analysis of the water samples were:

Atomic Absorption Spectrophotometry was used for the major cations (Na^+ , K^+ , Ca^{2+} , Mg^{2+}). For Na^+ , a wave-length of 589.6 nm and slit of 0.5 nm; for K^+ , a wave-length of 766.5 nm and slit of 1.0 nm; for Ca^{2+} , a wave-length of 422.7 nm and slit 0.5 nm; and for Mg^{2+} , a wave-length of 285.2 nm and slit 0.5 nm using a flame of Air-Acetylene for all.

Titrimetric method for CO_3^{2-} , HCO_3^- , and pH.

Ion-selective electrode method for F^- .

UV-visible Spectrophotometric method for NO_3^- , SiO_2 , HBO_2 and SO_4^{2-} .

Titrimetric (Mohr Method) for Cl^- .

Hydrometeorological data of five stations (Haiq, Dessie, Kombolcha, Wuchale and Bati) collected from the Ethiopian Meteorological Service Agency was used for the computation of the water balance of the study Area. Lake level measurement collected from the Ministry of Water Resources was also used to study the pattern of lake level fluctuations and to compare with other meteorological variables.

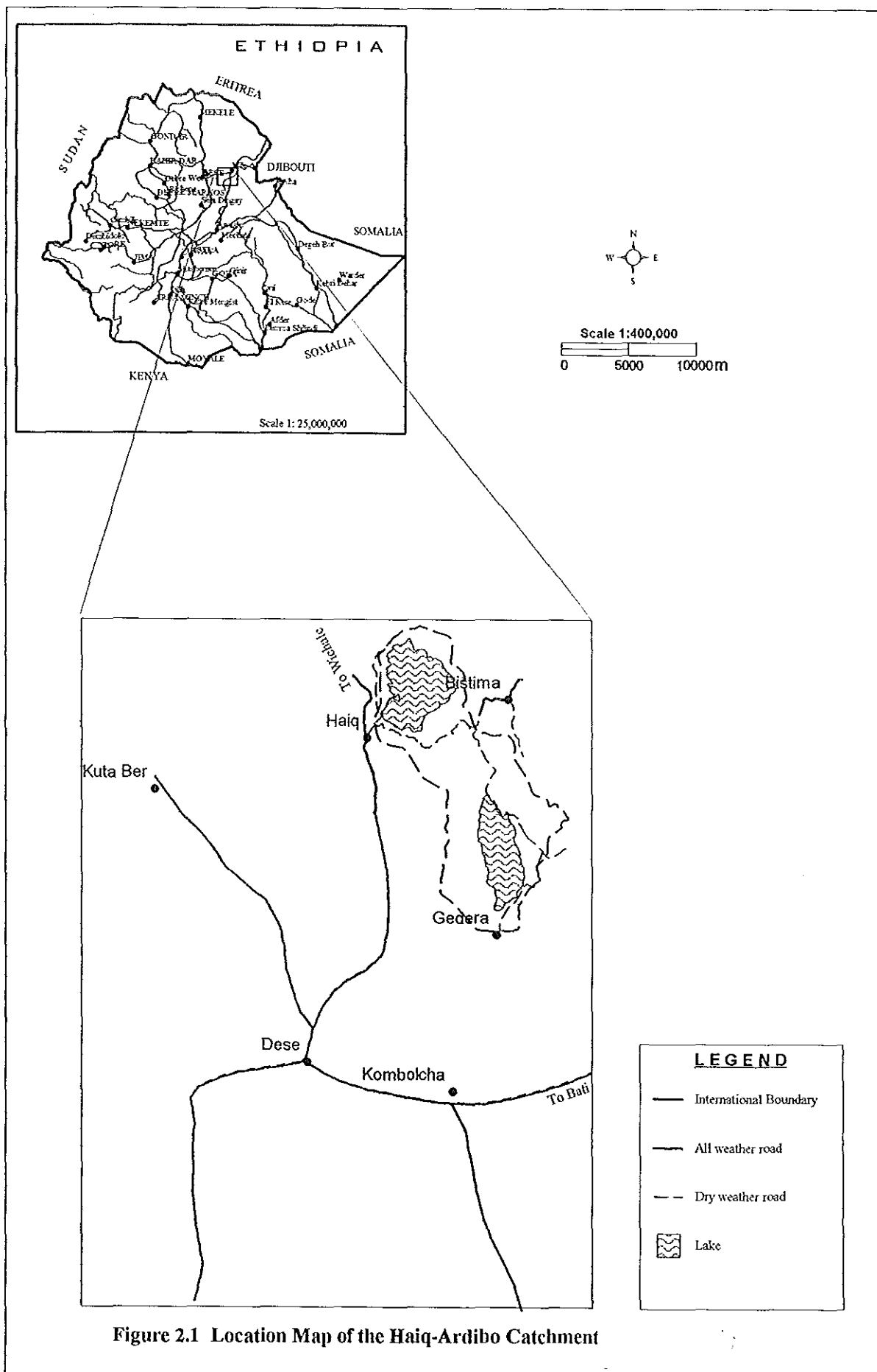
Chapter 2

GENERAL OVERVIEW OF THE STUDY AREA

2.1 Location and Accessibility

The studied area is located in the western margin of the Afar rift on the escarpment zone of the northwestern Ethiopian plateau. The study catchment is found within the northwestern watershed of the Awash river basin, near the head waters area of the Mille river (a tributary of the Awash). It is a closed drainage system within a 110,000 km² area of the Awash river basin. The area is situated some 435 km, northeast of Addis Ababa, 35 km northeast of Dessie town bounded between 11°11' – 11°23' N latitude, and 39°45' – 39°49' E longitude (Fig.2.1); and at an average altitude of 2100 m. above mean sea level (a.m.s.l.)

The accessibility of the area is very poor. The access to lake Haiq is good since there is a gravel road that leads to the Monastery of Haiq Istifanos and since the lake is not far from the town of Haiq and the main road that leads to Woldia. On the other hand, lake Ardibo is accessible to motor vehicles with difficulty since the dry weather road that leads to the lake is almost out of use.



2.2 Physiography and Drainage

The physiography of the study area is a result of both volcano-tectonic and erosional processes. The morphology of the catchment is such that steep fault escarps have an elevation of more than 2800 m. a.m.s.l. and the fault bounded subsided grabens make up relatively flat low lying areas which comprise lakes, surrounding swamps and agricultural lands. Within these lie volcanic hills which rise above the local flat lands. There is a large elevation difference, that is, a minimum elevation of about 1900m at lake Haiq and a maximum of about 2800 m at the northeastern water divide of lake Ardibo catchment that drain into lake Haiq.

From geomorphologic point of view, lake Haiq looks like a subsided caldera bounded in the west, north and east by very steep crater walls; while in the southeast, south and southwest, the topography gets gentler and the rim becomes flatter. On the other hand, lake Ardibo which is aligned in the NW – SE direction following the general trend of the major structures in the area, looks like a fault bounded graben. It looks like and follows the trend of the major grabens of Borkena in the south and Corbetta in the north.

Main drainage pattern is radial, i.e., streams drain towards the nearby lakes locally (Fig.2.2). The only river that flows with a well defined channel in the catchment is Ankerka, which is a perennial stream that drains starting from northeast of lake Ardibo and then enters lake Haiq at the southeastern shore. From the present morphology of the area between lake Haiq and Ardibo, it can be inferred that in the near past the two lakes were connected via the Ankerka river, lake Ardibo flowing into lake Haiq. This is also confirmed by the elder people of the area. It is worth noting that there is a 250m drop in elevation from lake Ardibo (at 2150 m

.a.m.s.l.) to lake Haiq (at 1900m. a.m.s.l.). There are also morphologic evidences for the presence of an ancient paleo surface channel at the eastern shore of lake Haiq, where during the pluvial times, lake Haiq was overflowing through this channel into the Wazi stream (a tributary of Mille river) and then to the Mille river far to the east in the rift.

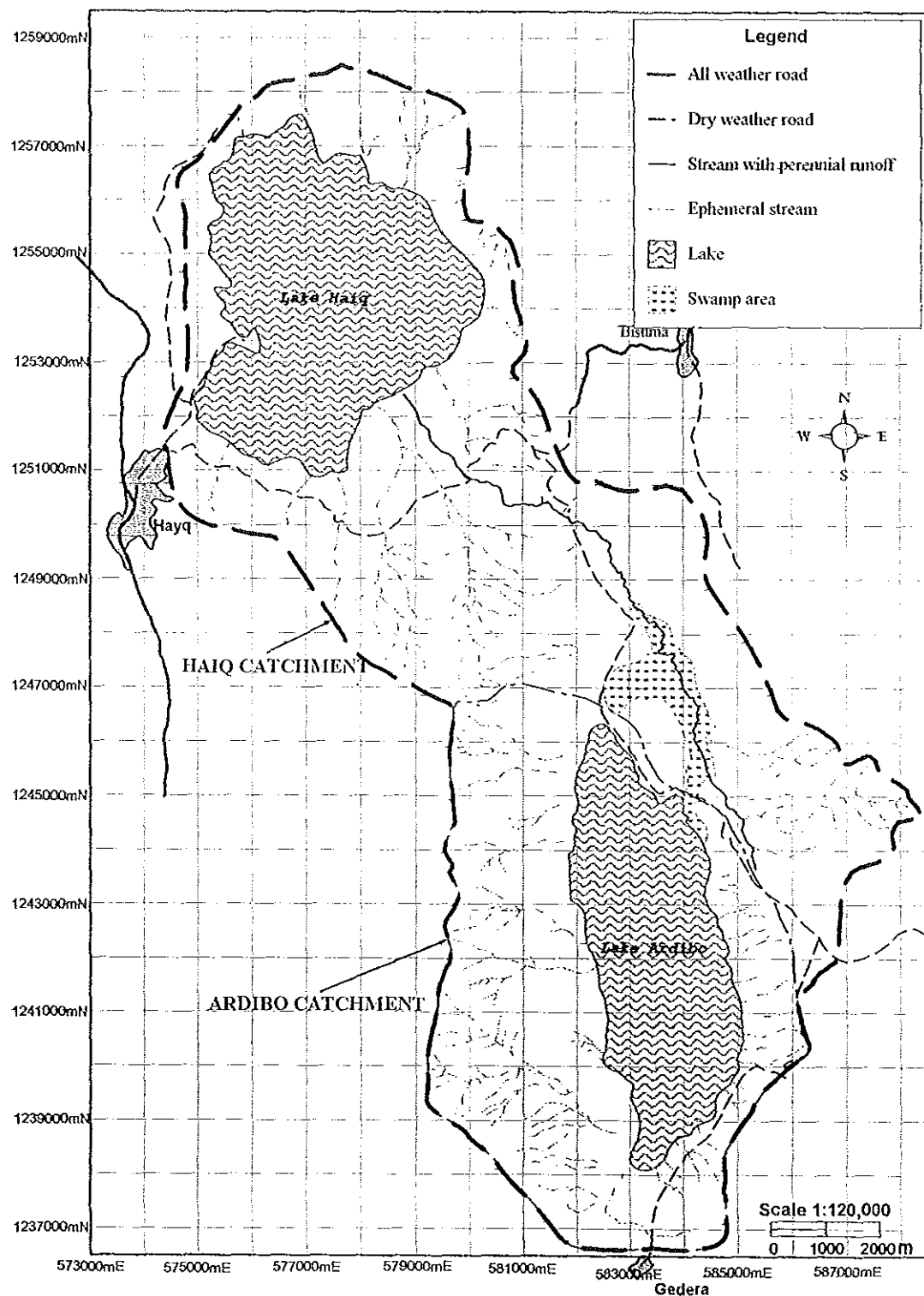


Figure 2.2 Drainage map of the Haiq-Ardibo Catchment

2.3 Land use and land cover

Broadly, four land use/land cover classes were identified:

1. Intensively cultivated land covering the gently sloping and flat areas of the catchment.
2. Scattered cultivation on moderately steep slopes with scattered bushes and grass land.
3. Bush, shrubs and grass land covering steep escarpments, hill tops and closed areas (aforested).
4. Areas covered by water bodies (lakes).

No.	Land use/land cover	Areal proportion of Haiq subcatchment (km ²)	Areal proportion of Ardibo subcatchment(km ²)	Total area
1	Intensively cultivated land	42.6	16.5	59.1
2	Scattered cultivation with some bushes, shrubs, and grass	9.4	5.9	15.3
3	Bush, shrub, and grass land	13	14.1	27.1
4	Water bodies (lakes)	22.8	15.8	38.6

Table 2.1 Area proportion of the different land use/land cover units

Due to the high population pressure that increases rapidly, the major land use is cultivation including very steep marginal areas. The population pressure has changed the land use and land cover patterns. Areas that were left affronted and for grazing are now deforested and cultivated (Fig.2.3).

The major corps grown are; wheat, maize, tee, beans, millet and peas. The main vegetation types are different acacia species, Bissana (corotoe),

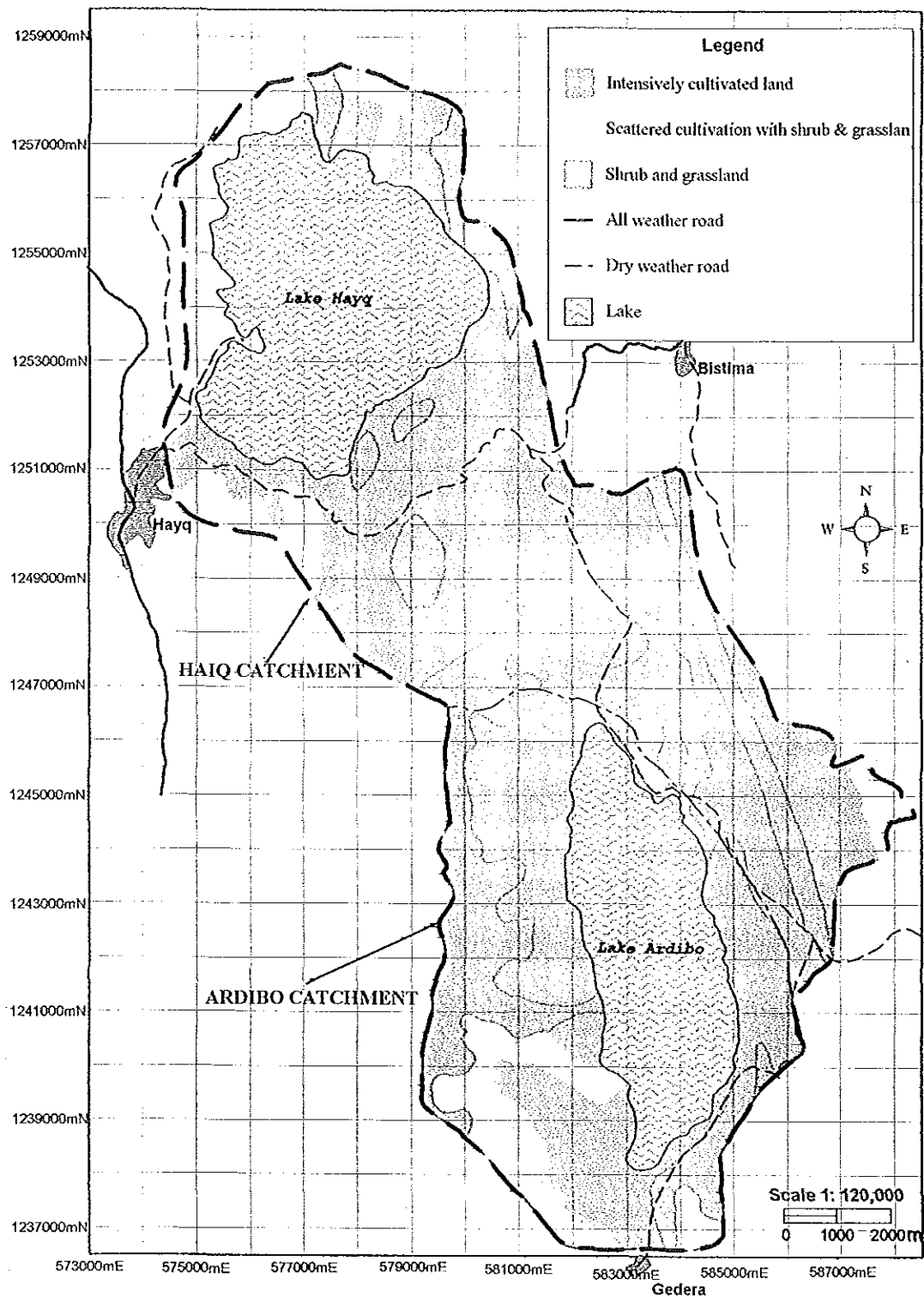
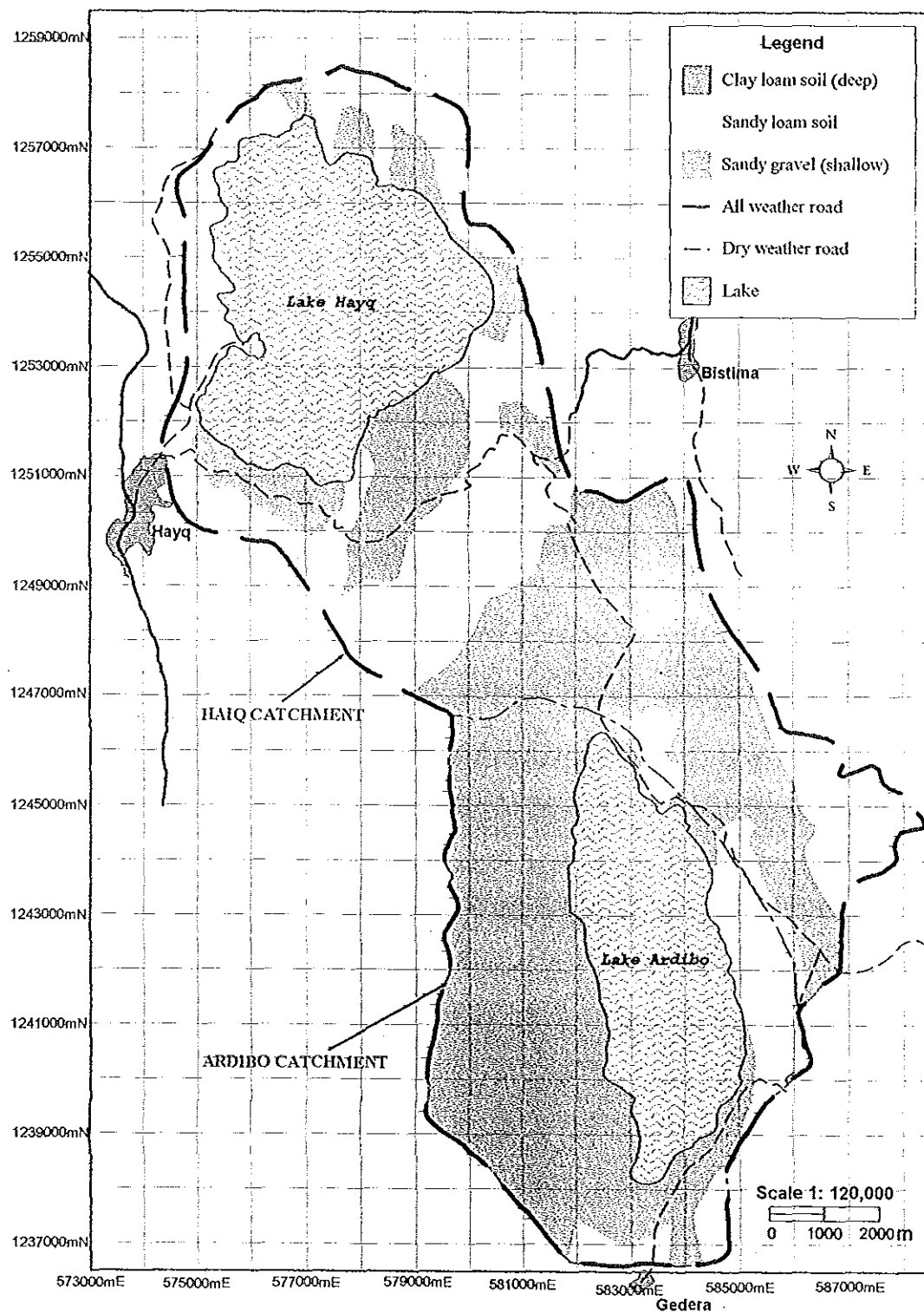


Figure 2.3 Landuse - Landcover Map of the Haiq-Ardibo Catchment

No.	Slope Class	Areal proportions (km ²)		Total
		Haiq subcatchment	Ardibo sub catchment	
1	<5%	8.8	5.4	14.2
2	5-12 %	12.7	0.3	13
3	12- 35 %	6.9	9.4	16.3
4	35 - 60 %	34.2	7.4	41.6
5	> 60 %	2.4	14.0	16.4

Table 2.2 Slope Classes of the Studied Catchment



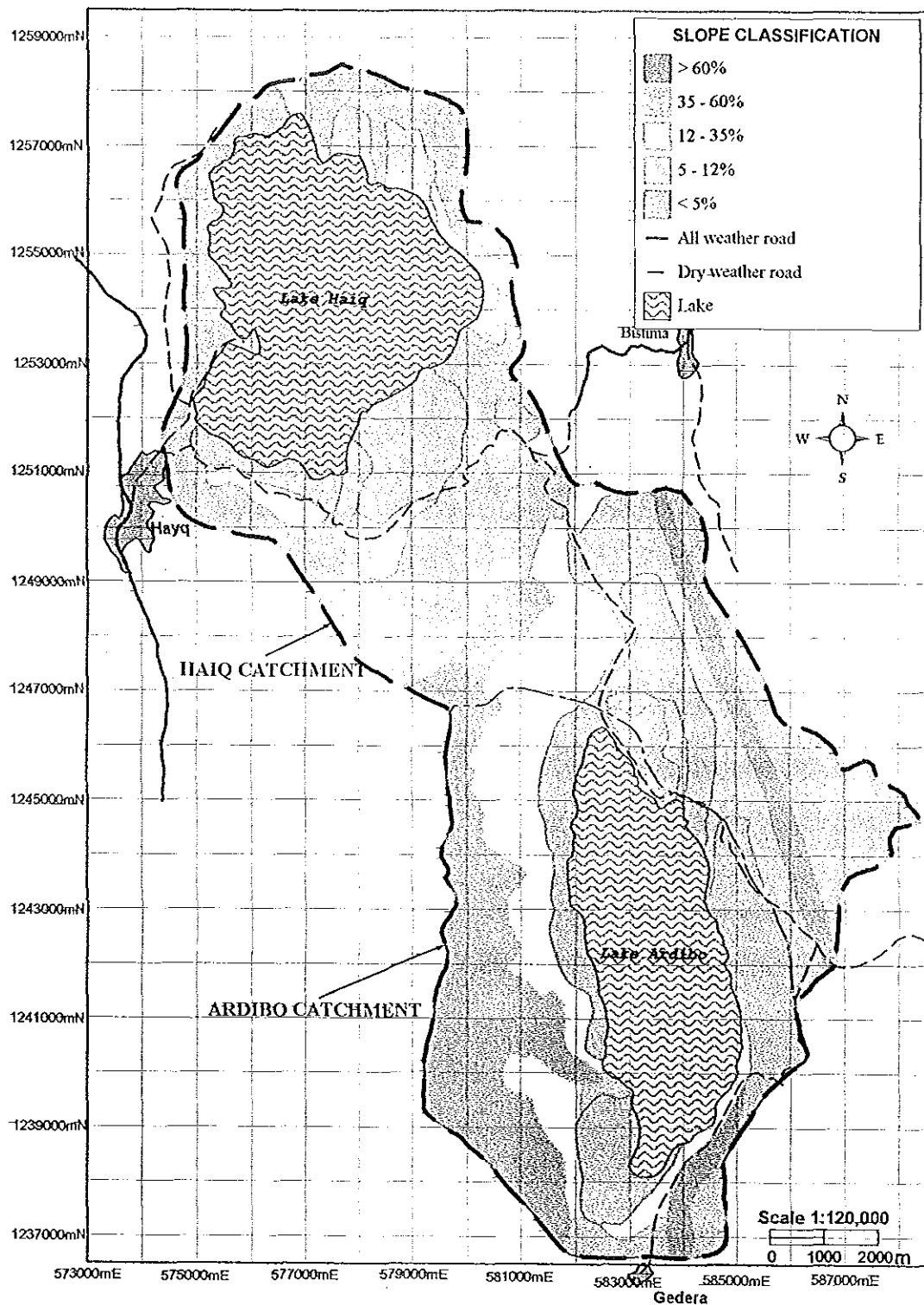


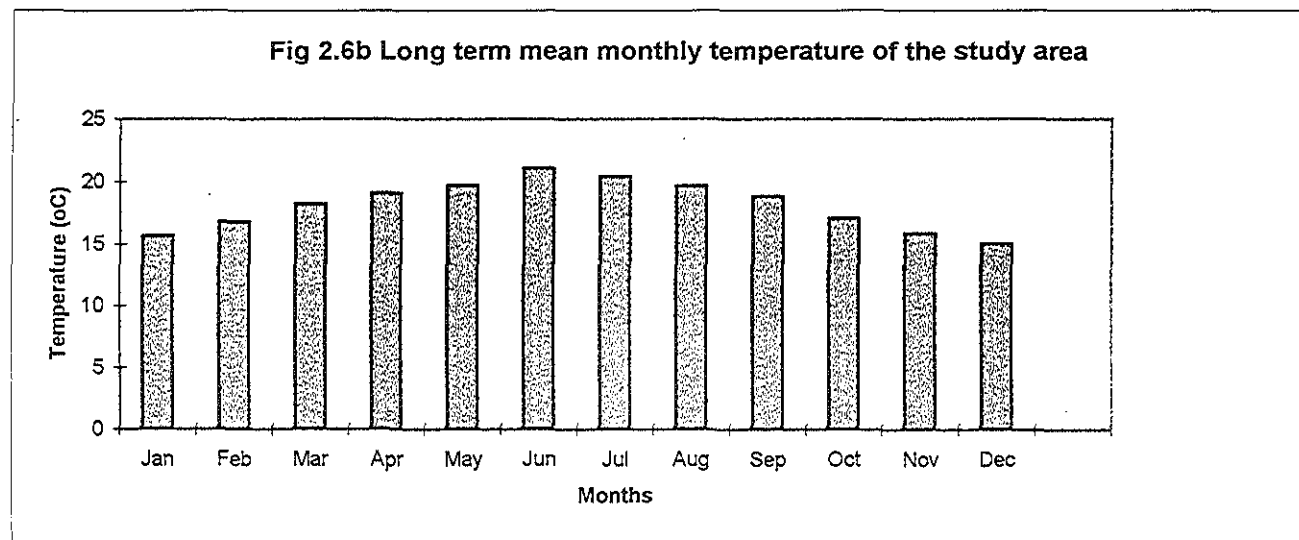
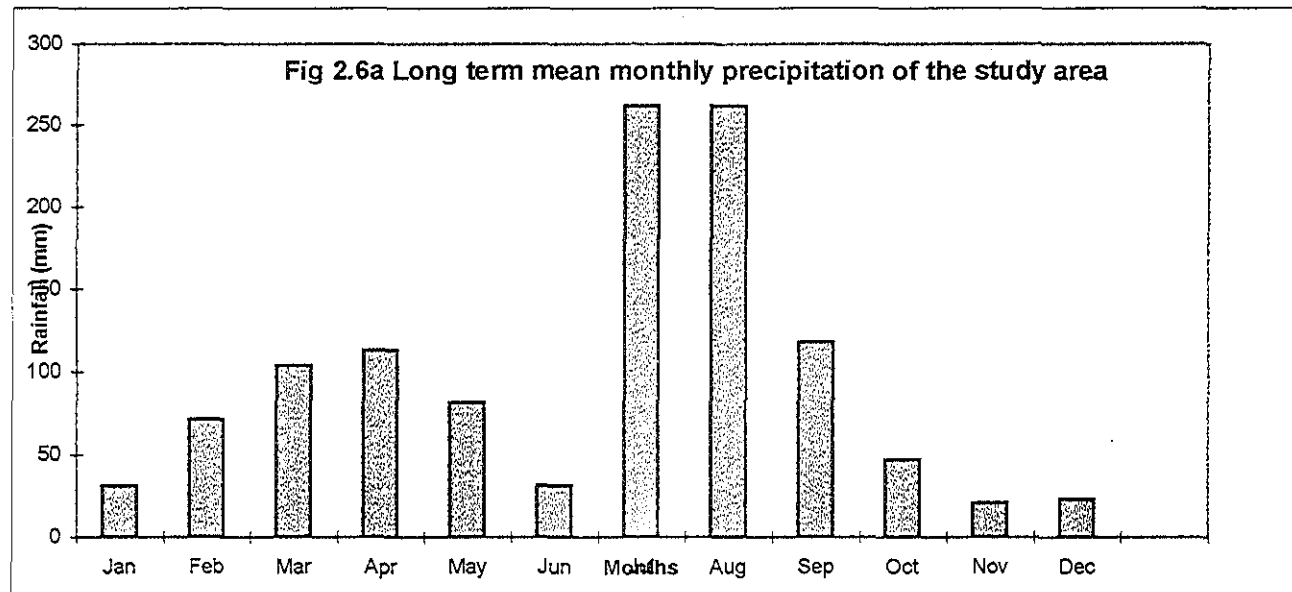
Figure 2.4 Slope Map of the Haiq-Ardibo Catchment

2.4. Climate

The study area exhibits a semi-arid subtropical climate traditionally classified as "Weina Dega" (Daniel Gemechu, 1977). The rainfall in the area is bimodal, that is, there are two maxima in the rainfall hydrograph of the area which are termed respectively as the "small rain" or "Belg" lasting from March to May and the "Big Rain" or "Kiremit" lasting from July to September (fig.2.6).

The amount of rainfall at any point in Ethiopia is influenced by the location of the point relative to the source of moisture, the direction of winds and topographical relief (Admasu Gebeyehu, 1996). In Summer a strong movement of air prevails from the south west to the north east direction, i.e., from the high pressure system over the Gulf of Guinea towards the low pressure center of Arabia, bringing the summer rain, during the summer months (June and July) the low pressure Inter-tropical convergence Zone (ITCZ) is located north of the country and the area will be under the influence of the Atlantic Equatorial Westerlies which ascend over the highlands from the south west and produce the big summer rain. The amount of this rainfall decreases from southwestern Ethiopia towards the study area due to orographic and altitudinal effects, since in the course of the long journey from the Atlantic to the East African highlands, the moisture of the winds decreases. The area gets moisture from the easterly and south easterly moist from the easterly and south easterly moist air currents in spring (Belg) when the ITCZ, is located south of the country. Therefore, the area gets moisture from two sources at two distinct time of the year. From the Atlantic equatorial westerlies during summer and from the southerly and easterly Indian Ocean air currents in spring. The long term mean annual rainfall for the study area is 1165.9 mm at station Haiq. The long term average minimum and maximum temperatures is 10.7 and 25.4 °c respectively

which gives a long term mean of 18.0 °c for the area. The average relative humidity is about 69%, minimum in the month of December and maximum in April.



Chapter 3

GEOLOGY

3.1 Regional Geologic Setting

The Cenozoic geologic history of Eastern Africa and Southern Arabia is remarkable in that a major uplift with a concomitant volcanic episodes took place in this region in the upper Mesozoic and early Tertiary times. The causes of this swell and volcanism has been a hot issue among earth scientists all over the world for the last forty years. According to Danielli & Azzoroli quoted in Mohr (1975), the first major uplift of the Ethio-Yemen Swell occurred in the Upper Eocene when the Western limit of the Mesozoic marine sedimentation retreated abruptly. The formation of the Red Sea, Gulf of Aden, and the East African Rift which are joined at the Ethiopian Afar (a triple junction of these three rifts) is attributed in the subsequent tectonic couples of the upper parts of the mentioned elongated dome and the north east drift of the Arabian plate in the Miocene. In this regard the Red Sea and the East African rift system were the major features recognized as having been produced by extension of the earth's crust (Mckenzie et al., 1970). Normal of awaiting along the sides of the rift valleys during earthquakes shows that this phenomenon still continues.

The development of the Afar Margin is summarized by Zanettin and Justin-Visentin (1975), and this margin was formed in two phases: in the Miocene, the drift of the Arabian plate brought about the formation of a shallow basin owing to the effect of crystal thinning, accompanied by "tilted blocks" structure of the Western Afar margin. In the Pliocene and Pleistocene, the united action of tensional movements and the injection of large magnetic mass along the foot of the escarpment and in the rift caused intense fracturing of the

escarpment itself with consequent large vertical throws, in this way the Afar margin is formed.

From tectonic point of view, the Afar margin turns out to have been formed (Zanethin et al., 1974) and Zanettin and Justin - Visentin, (1975) due to the effect of crystal dilation linked to the early stages of the drift of the Arabian in which the Western Afar margin was subjected to a series of sub-vertical and North-South trending fissures which caused the formation of blocks making up a complex system of horst and grabens, later the rocks became tilted towards the Afar. This margin was further complicated and modified by normal faults down thrown to the rift to which the difference in level now existing between plateau and Afar is attributes. Chorowicz et al., (1999) confirmed the above idea further in that, the margin is characterized by a series of north-south oriented basins, (as can be seen nowadays in Borkena and Corbetta) bordered by faults and are filled with sediments of plio-quaternary age.

Fracturing of the Afro-Arabian swell in the Early Tertiary in the Ethiopian side had produced the Ashanghi volcanism of the Western Ethiopian plateau. The tectonic uplift of Ethiopia has a major role in the geology of the country.

The volcanic stratigraphy of the Central eastern Ethiopian plateau and the Western Margin of Afar, and its tectonic evolution has been studied thoroughly by many geologists. Zanettin and Justin - Visentin, (1975) recognized three volcanic cycles in this area, namely: a first cycle; a pre-Oligocene volcanic activity giving rise to the out pouring of the Ashanghi basalts that covered the upper sand stone unit. After a long time of quiescence, the second volcanic cycle began to erupt in the lower middle Oligocene and cover the Ashanghi peneplain. This

cycle started first with flood basalts (Aiba basalts) and later by large quantities of ignimbrites (Alkaline rhyolites and Trachytes) with variable quantities of inter bedded basalts and collectively known as the "Alaji rhyolites", these units too are tilted towards the Afar. This cycle is concluded with the emission of large quantities of basalts termed the Termaber basalts that cover most parts of the preceding Alaji rhyolites. The third cycle confined more to the rift and its periphery and are termed as "Fursa basalts", "Balchi rhyolites", and "Bishoftu basalts" of plio-pleistocene age. The first two cycles clearly represent the "Trap series" of Blanford which are divided into a lower Ashanghi and an overlying Magdala groups (Gregnanin et al., 1973; Justin - Visentin and Zanettin, 1974). The third cycle is grouped to a more recent volcanic unit termed the rift series, (Zanettin et al., 1978).

Table 3.1 compares the volcanic stratigraphy described by Zanettin and Justin - Visentin, (1974) and Zanettin et al., (1978).

The above two stratigraphy and age of the rocks outcropping in the central eastern Ethiopian plateau and Western Afar are basically the same and therefore, the stratigraphy proposed by Zanettin et al., (1978) is adopted in this work. The Oligo-Miocene volcanic rocks in the Western Afar between 10°30' and 12°00'N divided into stratigraphic units of the Alaji rhyolites and basalts, and Termaber basalts. In fact, these units have a different time of eruption between the North and Southwestern Afar Margin. The trap series consisting of Ashanghi, Aiba, Alaji and Termaber formations make up the regional rock units from bottom to top respectively in the studied area. The Ashanghi formation is tholeiitic and/or alkaline basalts(Zanettin et al., 1978), low in Al_2O_3 and high in TiO_2 . The Aiba basalts, which overlay uncomfortably the lower Ashanghi basalts are transitional between tholeiitic and alkaline basalts(Zanettin et al., 1974).

The Alaji rhyolites and basalts, which are a product of fissural volcanism, are dominantly silicic and are made up of alkaline rhyolites and sodic ignimbrites intercalated with variable quantities of transitional basalts. Termaber basalts are products of central eruption and are alkaline in composition high in Al_2O_3 and low in TiO_2 .

The predominant trends of the fractures and fault tracers in the Western Afar are following the structural trend of the Red Sea rift system, which is NNW-SSE, and some follow the orientation of the East African rift system(SSW-NNE) to SW-NE (Kronberg et al., 1975). Less frequent WNW-ESE and WSW-ENE striking fault sets are also present. The area of study which marks the outer tectonic boundary of the Afar is basically characterized by NNW-SSE structures and rare E-W ones.

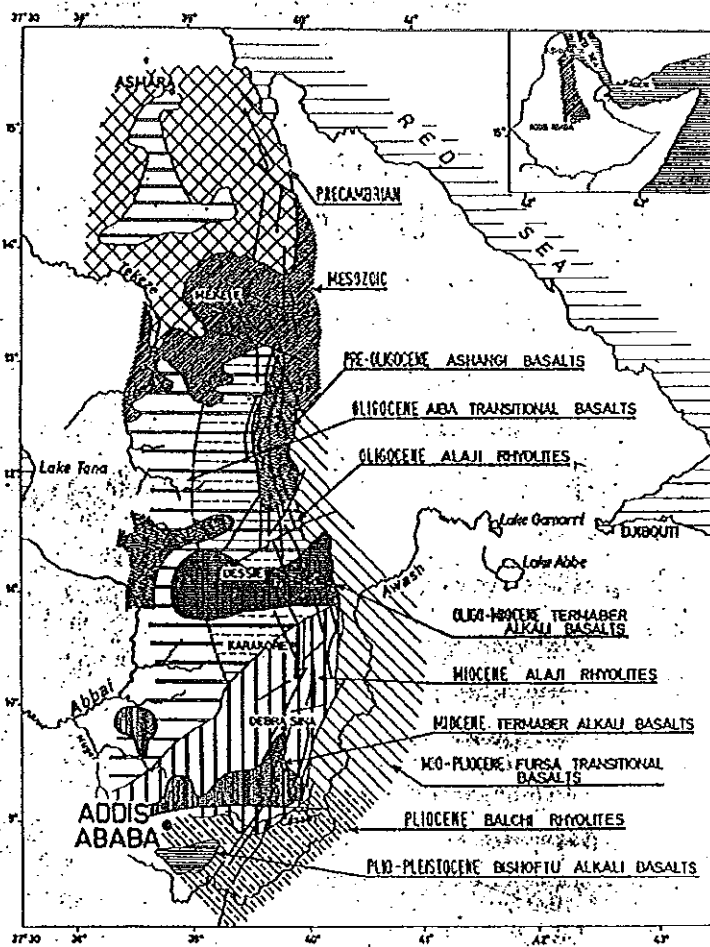


Fig. 3.1. Regional Geologic map of the central eastern Ethiopian plateau (after Zanettin et al., 1978)

3.2. Geology of the study area

3.2.1 General

The geology of the study area is prepared at a scale of 1:50,000 and then reduced to 1:100,000. The stratigraphy and age of the rocks were correlated to the regional stratigraphy and age the rocks outcropping in the central eastern Ethiopian plateau based on the works of Zanettin & Justin Visenttin (1973, 2974); Zanettin et al., (1974) and Zanettin et al., (1978). Based on the stratigraphic successions described by Zanettin et al., (1978), rocks

outcropping in the Haiq – Ardibo catchment belong to the Alaji rhyolites and inter-bedded basalts of Oligocene age (table 3.1).

Since the age of the Oligocene and Miocene volcanics become younger as one goes from North to South and Southeast, (Zanettin et al., 1974; Zanettin et al., & Justin Visenttin, 1974, 1975; and Zanettin et al., 1978), the Alaji rhyolites and basalts in the area belongs more specifically to the relatively older sub-unit of the northern sector, the “Alaji – Sirro” formation which has an age range between 32 – 26 m.y.

According to Zanettin and Justin Visenttin (1975), the Alaji rhyolites and basalts are considered to be a product of the second cycle of volcanism and are related to a N – S fissure system which were opened since the Oligocene at the Afar margin and feed the Alaji rhyolites. Zanettin et al., (1974) described these formations to be a product of fissural Silicic volcanism linked to an approximately N – S tectonic extensive crustal movement. With in the studied area, seven phases of eruptions were recognized, each having its own typical features (fig.3.2). These are, rhyolites with some ignimbrites, unwelded acidic units, thin ignimbrite bed, degraded and highly weathered basalt, thin basaltic flow, thick ignimbrite unit with small rhyolites at lower levels, and at the top most a basaltic flow unit rare ashes on top of it. Since the rhyolites and ignimbrites exist in association and since they have similar composition (field study), they are mapped as a single unit. On the other hand, since the thin ignimbrite layer and the thin basaltic flow are small (not mappable at the working scale), these are grouped into their chemical proxy, i.e., the unwelded acidic unit and degraded basaltic unit respectively. Therefore, the volcanic outcropping in the area are mapped into five units, namely, the rhyolites and ignimbrite unit, the unwelded acidic unit, the degraded basaltic unit, and the topmost basaltic flow unit. A recent formation composed of alluvial, lacustrine and

colluvial sediments is mapped covering an appreciable area of the catchment overlying one or more of these volcanic units.

3.2.2 The rhyolite and ignimbrite unit (T_{SV})

These units outcrop at different parts of the catchment in different stratigraphic positions. It outcrops south and southeast of lake Haiq and at this position it is the lowest and probably the oldest unit in the catchment. When present above the degraded basaltic unit, the rhyolite becomes rare and the ignimbrite dominates and the unit gets thick (maximum thickness of more than 200m is observed northeast of lake Ardibo). It is fine grained and sometimes glassy in texture, reddish to gray in color. Feldspar phenocrysts are observed in coarse-grained varieties of some exposures. Justin Visentin & Zanettin (1974) reported that the same rock unit localized in the Kombolcha – Eloa road is found to be highly glassy with a porphyritic texture, and composed of variable amounts of phenocrysts of plagioclase (18 – 22% anorthite) and anorthoclase and with rare quartz. On the other hand, the ignimbrite unit is smaller at the bottom of the succession when associated the rhyolite and in the middle it occurs distinctly individually as a thin bed extending horizontally with almost same thickness. There are rare trachytes in association with this rhyolitic and ignimbritic unit, probably with similar composition. The ignimbrite unit is much more dominant when compared with the other rock types. High degree of fracturing due to wide spread faulting characteristic. This will assist higher infiltration circulation of water within this unit. As compared to other rock outcrops in the study area, this unit is less affected by weathering.

3.2.3 Unwelded acid (pyroclastic) unit (T_{UPS})

The unwelded acidic unit is composed by various ash and fragmental acidic volcanites which are loose and are highly weathered and dislocated by faults. This unit is likely a product of explosively erupted acidic magma. No welding and flow structures were observed. In most instances, it overlies the acidic rhyolitic-ignimbritic rocks and underlain by the basic degraded rock unit. Rare basic pebbles and gravel sized materials were observed. Due to its loose and incoherent nature, high infiltration capacity is expected but due to its position is hydrogeologically unfavorable (chapter 5) it probably serves as a recharge media than as an aquifer.

3.2.4 Degraded basaltic unit (T_{BV})

This unit is composed of thick degraded, deeply weathered. Typical spheroidally weathered is characteristic of basaltic boulders. These boulders have a porphyritic texture where lithic fragments are present as phenocrysts within the ground mass. Like other units in the mapped area, this unit is also highly affected by tectonic disturbances. Which will enhance the hydraulic properties of the unit. There is no observable flow structure in this unit. The weathered pebbles and boulders show alterations probably of the olivine into a green mineral matter. This basic degraded unit in all areas is immediately overlain by a thin fine-grained basaltic flow characterized by columnar jointing and fracturing. The columnar joints end at the contact line of the underlying unit. This basaltic unit grades upward to a slightly lighter intermediate rock, which also shows extensive fracturing and weathering.

3.2.5 Upper basaltic unit (T_{BF})

This is probably the youngest unit in the Haiq - Ardibo catchment. It is a fine grained dark colored basaltic unit characterized by columnar jointing. Like other units, this unit too is affected by high degree of fracturing. In some outcrops, this unit is associated with rare tuffaceous and volcanic ash units. The thickness and areal coverage of this unit is very small.

3.2.6 Recent (Quaternary) unconsolidated sediments (Q_{AC})

It is the most recent unit mapped in the study area. It includes recent sediments that occupy depressions, the foot of hills and major escarpments, the flood plain of the Ankerka river and the shores of the lakes. The composition ranges from colluvial talus cones to alluvial and lacustrine deposits, and from fine clay fractions to alluvial gravel and sands. This quaternary sediment covers one or more of the above volcanic unit and cover a large proportion of the studied area.

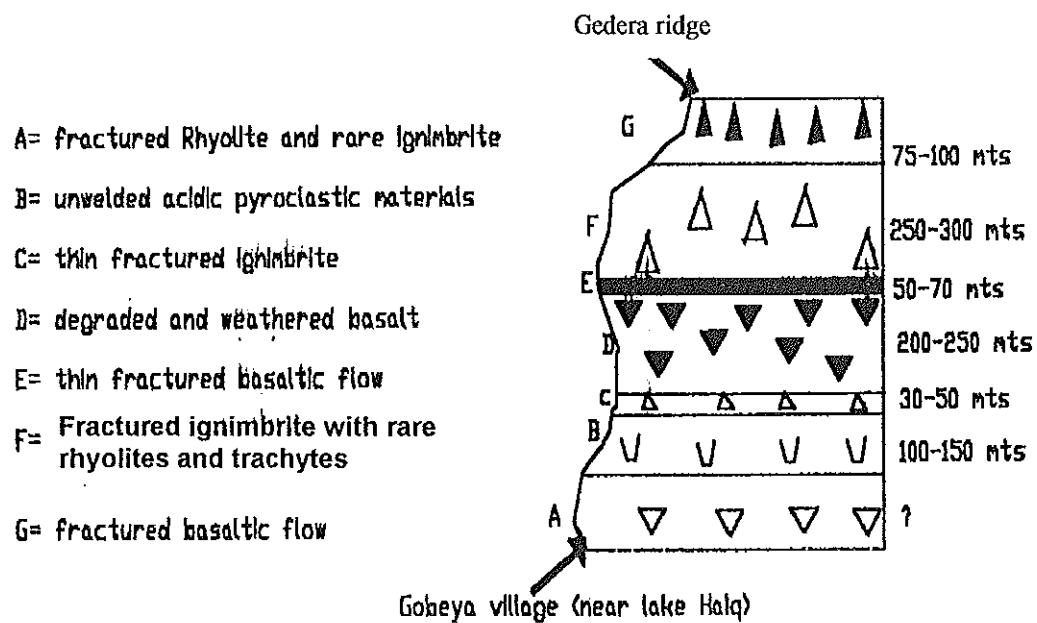
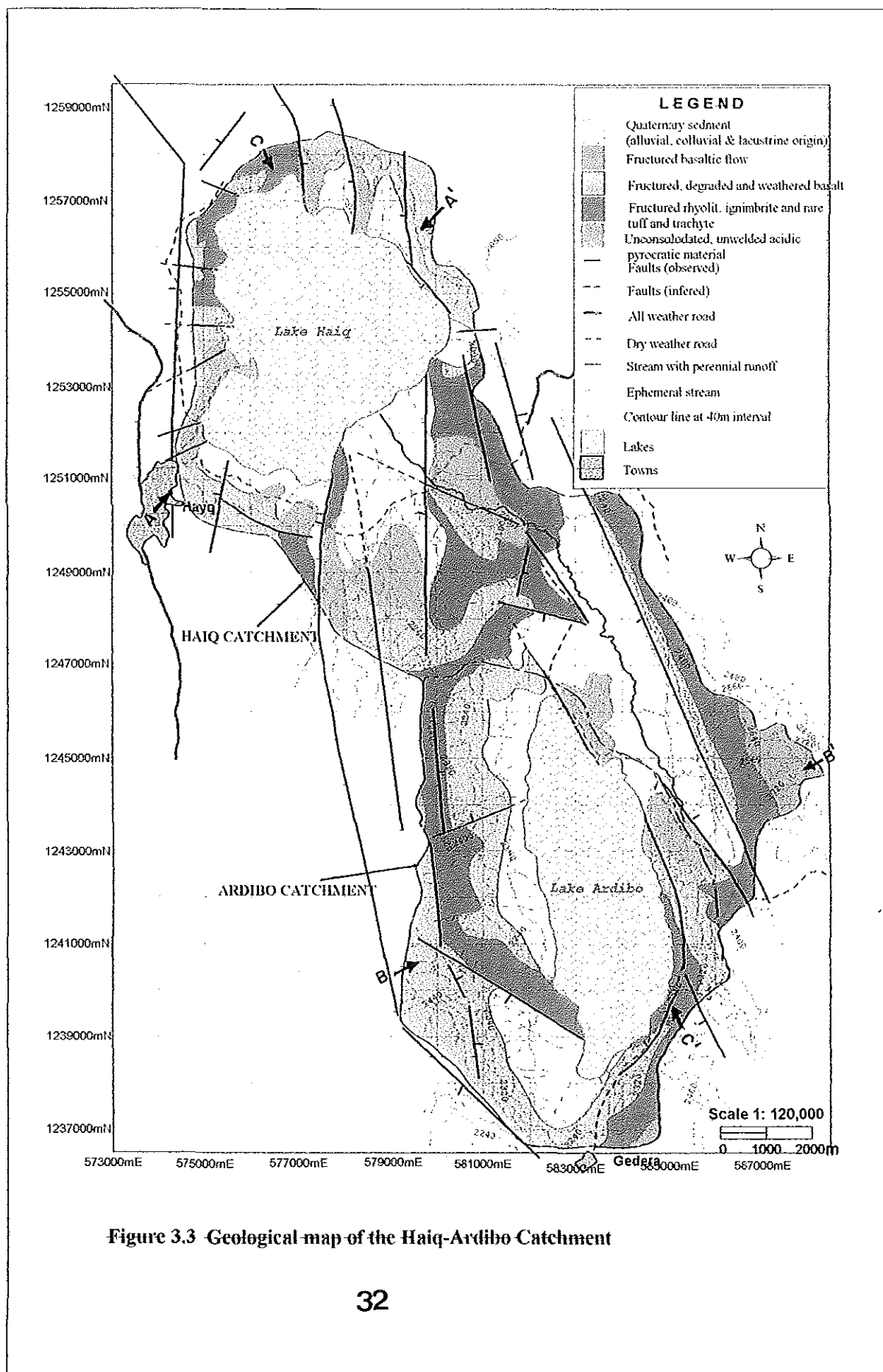
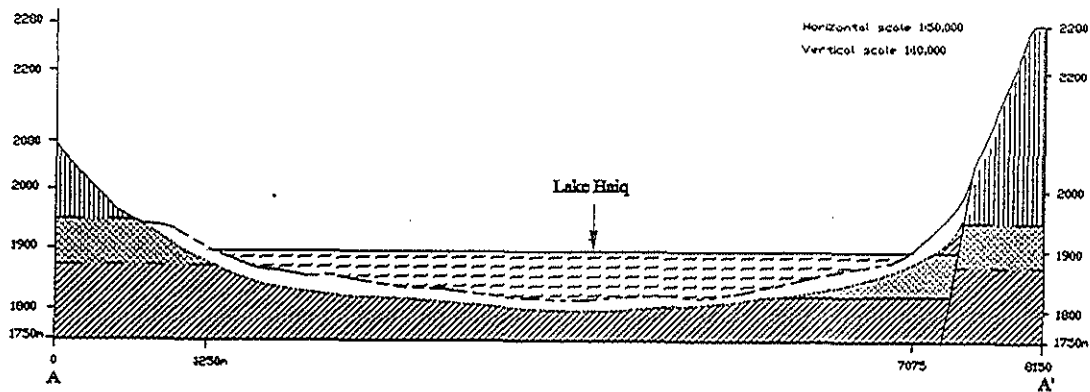
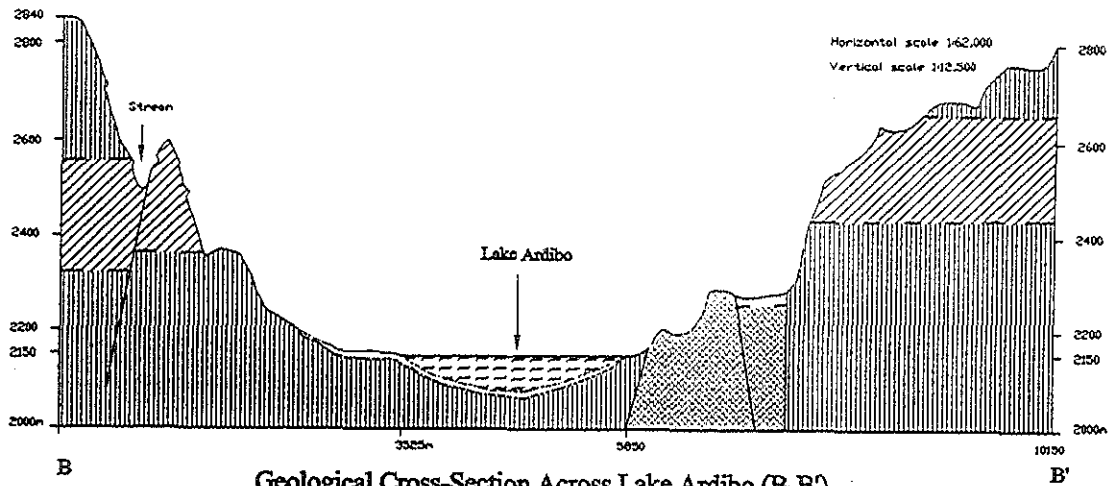


Fig. 3.2 A sketch of the volcanic successions from Gobeya village near lake Haiq to Gedera ridge (west of lake Ardibo)





Geological Cross-Section Across Lake Haiq (A-A')



Geological Cross-Section Across Lake Ardibo (B-B')

LEGEND

-  Quaternary sediments
-  Fractured basaltic flow
-  Fractured rhyolite ignimbrite and rare tuff & trachyte
-  Unconsolidated, unwelded acidic pyroclastic material

Figure 3.4 Geological Cross-Sections

3.3. Geologic Structures

It is well understood that the central western margin of the Afar rift is a tectonically dislocated area, where one can observe without difficulty major structures that run NNW or nearly N-S. In this area, there are N-S elongated ridges which are related probably to the regional extensional rift tectonics.

Three sets of faults are mapped in the area, having a trend of N30°W, S70°W or nearly E-W, and NNE respectively. The dominant ones are the NNW trending sets (Fig.3.4), which have affected all the rock units and cross in some cases the entire study area. The E-W trending fault sets are found to cut the NNW trending ones and are probably younger from the cross cutting relationship. The importance of the E-W faults in this hydrogeologic study will be discussed later. The major NNW sets are trending parallel to the trend of the Red Sea rift (Kroberg et al., 1975), where as those trending NNE are due to the influence of the Ethiopian rift system or interaction of the Afar and main Ethiopian rifts. The E-W trending ones are probably associated with the rift of the Gulf of Aden. According to the interpretation by Zanettin et al., (1978), these transverse faults are mainly situated between 11°00'N and 12°00'N, parallel to the "pre-Oligocene rift of Ashanghi" and are a rejuvenation of an old major tectonic lineament extending from the Gulf of Aden.

There are also two dominant joint sets mapped in the study area trending on average N25°W, and E-W. The spacing and aperture of these joints vary from outcrop to outcrop and are important from the perspective of water circulation with in these jointed rocks.

Chapter 4

HYDROLOGY

Water found in the earth is under continuous movement in a hydrologic system known as the water cycle. This movement involves a change from one state to the other and from one part of the earth to the next. In this continuous movement of water, solar energy and gravity plays the central role in the whole system. In this chapter some aspects of the hydrologic cycle such as precipitation, evaporation, evapotranspiration, infiltration runoff and some of the meteorological factors controlling them will be analyzed. The study of the hydrologic cycle for a given drainage basin is based on the water balance, which makes use of the law of conservation of mass. The water balance equation states that:

$$\text{In flow} = \text{Out flow} \pm \text{Change in storage}$$

The quantitative evaluation of each input, output parameters and change in storage for a given drainage area is the concept of water budget (balance) for that particular drainage area. Evaluating the water balance of a given basin or/catchment, therefore, needs each hydrologic input and output of the catchment well understood. In this regard, measurements related to each parameter must be done. For those parameters in which direct measurements are absent, some empirical techniques involving meteorological and other related hydrologic data are used. Records of precipitation, run-off and evaporation can be made from a network of meteorological and gauging stations disposed systematically within and around the basin. The remaining input-output parameters are evaluated on the basis of a thorough study of the vegetation, soil, geology and other hydrologic variables. In the mean time, meteorological

variables are necessary.

4.1. Hydrometeorological Data

For the analysis of the different hydrologic inputs in the studied catchment, long-term meteorological data were collected from the National Meteorological Service Agency for five selected stations located around the studied catchment. These are; Haiq, Wuchale, Dessie, Kombolcha and Bati. The nearest station is that of Haiq, which is found at the western watershed boundary of the studied catchment, followed by Kombolcha then Dessi, Wuchale and Bati. Data records include precipitation, temperature, wind speed, relative humidity, sunshine hours and pan evaporation data. Of these meteorological data, temperature, and wind speed, relative humidity and pan evaporation are considered exclusively from the Haiq station.

Sunshine hours data is taken from Kombolcha station, since it is missing at Haiq station.

A fourteen year period mean, min. and max. air temperature data is available for station Haiq, and the average monthly values are obtained (table 4.1) are one used for computing evaporation and evapotranspiration using different method.

Jan	Feb.	Mar	Apr.	May	Jun.	Jul.	Aug	Sep.	Oct.	Nov.	Dec.	Mean
15.5	16.7	18.1	18.9	19.6	20.7	20.3	19.7	18.8	16.8	15.6	14.9	18.0

Table 4.1 Mean monthly air temperature for the study area.

Since there is no measured kinetic surface temperature data for the lakes (Haiq and Ardibo), the average surface temperature from four rift valley lakes (Ziway-Shala basin) is transferred

to the studied area with a fair approximation using the data of Tenalem Ayenew (1998) found from the analysis of thermal image data. (TM-band six). The transferring was done using a factor found by way of simple approximation based on proportioning.

Thus, the result is tabulated as follows:

Month	Jan	Feb.	Mar	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Factor	1.2	1	1	1	1.2	1.1	1.1	1	1.2	1.3	1.4	1.4
Surface Temp.	18.6	16.6	18.4	21.3	23	22.4	21.4	22.2	21.6	21.8	21.6	21.9

Table 4.2 Mean monthly surface temperature of the studied lakes transferred from the rift lakes.

Relative Humidity and wind speed data at station Haiq is found for a very short period, respectively two and four years. This data is used in the computations, since data found the near by stations having a long period record are found to differ from that found from Haiq with a considerable amount due to significant contrast in site characteristics (degree of shelter, altitude and distance).

Incoming solar radiation data was not recorded in all of the near by meteorological stations. Therefore, the measured average short wave radiation at Addis Ababa Geophysical observatory at an altitude of about 9° N is compared with that found at standard tables (Dune & Leopold, 1978; Shaw, 1988) of average solar radiation received on a horizontal plane at the upper edge of the atmosphere (Annex.3). Solar radiation data obtained at standard tables for a 10°N latitude gave reasonable results and therefore, used in the computation of open water evaporation and evapo-transpiration.

Using the Thiessen polygon constructed over these stations in order to compute the areal rainfall of the catchment, only two stations namely, Haiq and Kombolcha influence the studied area. The areal proportion of each stations' influence were measured. The Thiessen areal proportion for station Haiq being 0.94 and that of Kombolcha 0.06.. The weighted average area precipitation (P) is then given by:

Where P is weighted average areal rainfall for the catchment,

A is the total catchment area in Km^2

a_i is areal influenced by the i^{th} station (km^2), and

P_i is the mean annual precipitation of the i^{th} station.

Thus P is found to be 1158.7mm. The third method used is the Isohyetal method, which makes use of drawing lines of equal precipitation. Isohyetes were constructed only using the relevant station mean annual precipitation's. Area between each isohyetes were measured. The areal catchment precipitation is therefore the weighted average of the area bounded by each isohyete. That is;

Where, P is average annual catchment precipitation

a_i is isohyetal area

P_i is mean annual precipitation for the i^{th} station

A is total catchment area

Isohyetal range	Mean rain fall between isohyetes (mm)	Inter isohyetal area (Km ²)	Proportion from the total area (%)
1160 - 1150	1155	3.1	2.2
1150 - 1125	1135.5	22.3	15.9
1125 - 1100	1112.5	37.4	26.7
1100 - 1075	1087.5	38.1	27.2
1075 - 1050	1062.5	27.5	26.5
1050 - 1046.5	1048.25	1.7	1.2

Table 4.4 Isohyetal ranges, inter isohyetal areas and mean rainfall.

From table 4.4, mean annual areal rainfall computed through the isohyetal method is therefore, 1096.5 mm. It is necessary to note that this isohyetal method has undermined the mean annual rainfall of the study area. This is due to the influence of the Bati station which has relatively low mean annual rainfall and relatively far from the study area, but without which, construction of the isohyetes is difficult.

The areal mean annual rainfall for the Haiq – Ardibo catchment using nearby meteorological stations is 1158.2, 1158.7, and 1096.5 mm for the arithmetic mean, Thiessen polygon and isohyetal methods respectively. From a detailed observation of the catchment characteristics, rainfall pattern between the stations considered and other near by gauging stations, the mean annual areal rainfall for the studied catchment is taken as the average of the arithmetic mean and Thiessen weighted average, which will be 1158.5 mm. The monthly areal rainfall is computed in the same way as for the annual and is tabulated in table 4.5 below.

Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Arithmetic mean	33.9	51.8	91.8	104.9	79.5	35	265.8	271.8	125.6	49.1	25.6	23.4
Thiessen polygon	30.5	69.7	102.3	111.2	80.3	31.6	261.6	261.2	118.6	46.8	20.9	23.2
Average	32.2	60.8	97	108.5	79.9	33.3	263.7	266.5	122.1	47.9	23.3	23.3

Table 4.5. Mean monthly areal rainfall in mm

4.2.2 Rainfall – Altitude Relationships

One of the major factors determining climatic conditions in the Region is altitude (UN, 1965). It affects rainfall, temperature and evaporation. In most areas of the world mean annual precipitation increases uniformly with altitude (Dune & Leopold, 1978; Dingman, 1994). But, in the study area, this increase of precipitation is further complicated by the prevailing direction of moisture-laden winds & topographical features. Around and probably in the studied catchment, the relation between altitude and rainfall is evident in the four stations, that is Haiq, Wuchale, Kombolcha,, and Bati, in which rainfall and altitude correlate linearly quantitative. But, local conditions such as gauge exposure, and probably wind direction has reduced the precipitation and Dessie located at an altitude of 2500m. On the other hand, Urgessa station has receives 1445.3 mm rainfall at an altitude of 2000 m and a few kms north of Wuchale, which is an exceptionally large annual mean precipitation. This is probably data errors Generally, rain fall increases with altitude around the studied area.

4.2.3 Temporal and Spatial Variability of Rainfall

In addition to the variation observed with altitude, rainfall in the area found to vary also temporally and spatially. The rainfall is found to be decreasing in a Southwest to Northeast or east direction from an observation of a limited data. It is also found to increase locally

from south to north considering the altitude. This is most probably explained by the topography of the area. Dessie at an altitude of 2500 m in the south gets 1182.4 mm mean annual rainfall, where as Wuchale at an altitude of 2000 m in the north gets a mean annual rainfall of 1238.9 mm.

On the other hand, it is possible to observe from the long term rainfall data that both extreme wet and extreme dry years in the rainfall record in most of the stations around the studied area. The wettest year being 1964 and the exceptionally driest being 1984. For the details (fig .4.1).

Fig. 4.1a. Long term mean annual precipitation at Haiq station

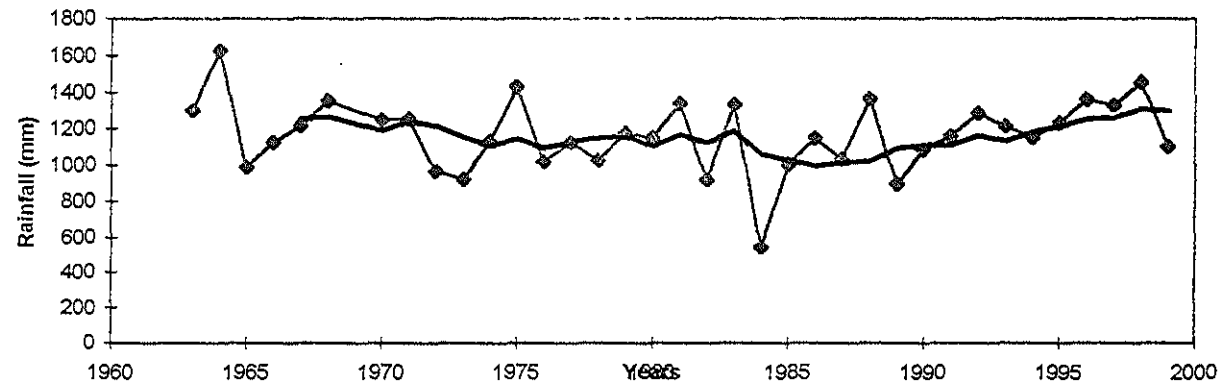
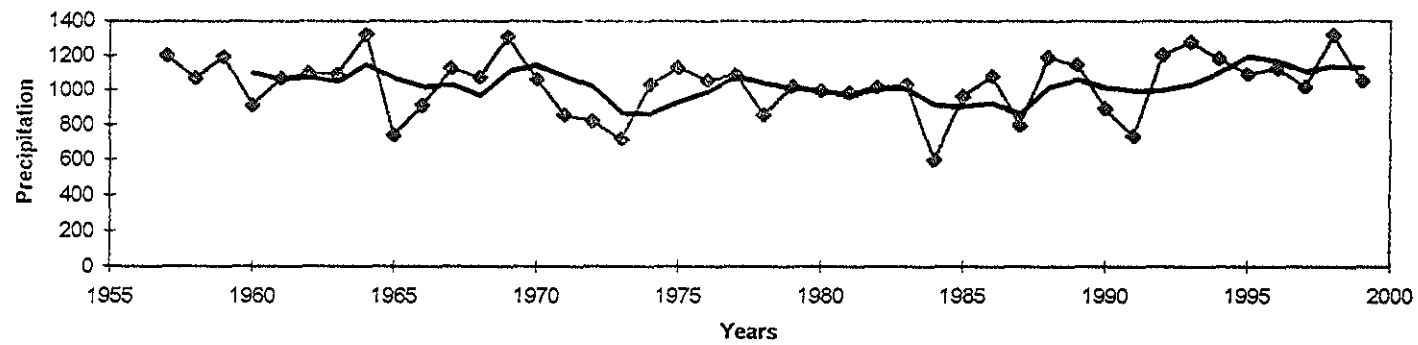


Fig. 4.1b. Annual precipitation variability at station Kombolcha .



4.3 Evapotranspiration

Evapotranspiration is a collective term for all the processes by which water in the liquid or solid phase at or near the earth's surface becomes atmospheric water vapor. It includes both evaporation from open water bodies and from the land, and transpiration by plant leaves or vegetation. Among the many phases of the hydrologic cycle, evapotranspiration is one of the most difficult to quantify. Both evaporation and transpiration are physical processes and are affected by physical conditions such as solar radiation, temperature of the evaporating surface and the air above, wind speed, atmospheric pressure, water vapor capacity of the air and supply of moisture at the evaporating surface. In the following section, open water evaporation and transpiration rates for the Haiq – Ardibo catchment will be estimated through different methods.

4.3.1 Open water evaporation

Water in lakes, reservoirs and ponds suffer loss from evaporation and therefore, evaporation from these water bodies is an important consideration in their water budget.

A. Estimation of open water evaporation from pan data.

Free water evaporation is measured quite simply from pan data record found from a pan installed at appropriate sites. For the catchment of Haiq – Ardibo, a seven year pan evaporation data (Annex.1) were found at station Haiq. The mean annual evaporation of this class A pan recorded data is found to be 1455.9 mm. But, in contrast to a lake, the class A pan receives large quantities of energy from radiation and conduction through its base and sides (Dune & Leopold, 1978; Shaw, 1988; Fetter, 1994). Usually evaporation from the pan will therefore be larger than from the lakes. Thus, observed pan evaporation should be multiplied by a factor less than one which is termed as the pan coefficient, to estimate the lakes evaporation.. For the lakes under study, there is no pan coefficient determined so far experimentally. UN(1973); HALCROW(1989) and Tenalem Ayenew(1998) used a pan

coefficient of 0.83 for the Ethiopian rift lakes. Therefore, taking in to consideration these values, and suggestion given by Dune & Leopold (1978) for areas without experimentally determined pan coefficient; a coefficient of 0.80 is considered for these lakes which are intermediate both in area and depth and found at the rift margin. From this, the lake evaporation will be 1164.7 mm annually.

B. Mass transfer (Vapor flux) method.

This method is sometimes called the vapor flux method (Shaw, 1988), which calculates the upward flux of water vapor from the evaporating surface to the atmosphere. The method makes use of the bulk aerodynamic equation found by Dalton (Dingman, 1994). It has the form:

$$E_o = (b_o + b_1 v_a) (e_s - e_a) \dots \dots \dots 4.1$$

E_o = rate of open water evaporation

b_o & b_1 = empirical constants

e_s = vapor pressure of the evaporating surface

e_a = vapor pressure of the air above

V_a = wind speed (at 2 meter height unless and otherwise stated)

Another form of equation 4-1 (Dingman, 1994) as:

$$E_o = K_E v_a (e_s - e_a) \dots \dots \dots 4.2$$

where K_E is a constant

Harbeck in Dingman (1994), has shown that K_E is dependent on the size of Lake Area and given by:

$$K_E = (1.69 \times 10^{-4}) (AL)^{-0.05} \dots\dots\dots 4-3$$

where AL is lake area in Km^2 .

Therefore, E_o will be:

$$E_o = 1.69 \times 10^{-4} (AL)^{-0.05} \cdot V_a (es-ea) \dots\dots\dots 4.4$$

In which V_a is in km/day, e in mb, K_E in $cmkm^{-1}mb^{-1}$ and E_o in cm/day

The vapor pressure terms in equation 4-4 is found from the relation;

$$es = 6.11 \exp[(17.3 T_s) / (T_s+237.7)] \dots\dots\dots 4.5$$

$$ea = W_a \times 6.11 \exp [(17.3 T_a) / (T_a+237.3)] \dots\dots\dots 4.6$$

Where T_s and T_a are Lake Surface and air temperatures respectively in °c, and W_a is the relative humidity of the area. Thus, the annual evaporation values for Lake Haiq and Ardibo after inserting the required variables, was found to be 464.5, and 472.6 mm respectively. From these values, one can understand that as the surface area of a lake increases, up to some area, $50m < A^{0.5} < 100$ km, evaporation decreases (Shuttle Worth, 1993)

C. Energy budget method

Evaporation from a water body (lake, reservoir) could be calculated by taking into consideration the heat or energy required for the evaporation process. The method is based on heat balance by considering the principle of conservation of energy that come into and go out of the system in the form of heat or radiation. The energy budget of a lake on an annual basis is given by:

$$Q_{co} = Q_s - Q_{rs} - Q_{lw} - Q_h \pm Q_g \pm Q_v \dots\dots\dots 4.7$$

Where,

Q_{Eo} = energy utilized for evaporation (Cal/cm²)

Q_s = incoming solar radiation (Cal/cm²)

Q_{rs} = reflected solar radiation (Cal/cm²)

Q_{lw} = net longwave radiation from the water body

Q_L = sensible heat transfer to the air (Cal/cm²)

Q_g = change in stored energy (Cal/cm²)

Q_v = energy transfer b/n water and bottom sediments

Since Q_L (sensible heat term) in eq- 4.7 could not be measured directly, it is incorporated in to the dimensionless Bowen's ratio (B), (Dune and Leopold, 1978).

$$B = Q_L/Q_{Eo} = 0.00061P[(T_s - T_a)/(e_s - e_a)] \dots\dots\dots 4.8$$

Where P is atmospheric pressure at the altitude of interest and varies with altitude. Hence,

$$P = 101.3[(293 - 0.0065Z)/(293)]^{5.256} \dots\dots\dots 4.9$$

Where Z = elevation above mean sea level, and P is in kpa. Since the altitude of the studied area varies from 1900 m to 2850 mm, for Haiq and Ardibo respectively a mean value of 2000m is assumed and the pressure becomes 79.8 Kpa which is equivalent to 798 mb.

The energy used for evaporation (eq. 4.7) can be further written as,

$$Q_{Eo} = [Q_s - Q_{rs} - Q_{lw} \pm Q_v \pm Q_g] / (1 + B + c(T_s) / \lambda) \dots\dots\dots 4.10$$

Where c is the specific heat of water (cal/gm⁰c) and λ is Latent heat of vaporization of water (590 cal/gm)

Q_{Eo} is converted to the depth of evaporation E_o by the equation :

$$E_o = Q_o / \lambda \rho \dots\dots\dots 4.11$$

Thus,

$$E_o = [Q_s - Q_{rs} - Q_{lw} \pm Q_r \pm Q_g] / \rho [\lambda [1 + B] + c(T_s)] \dots\dots\dots 4.12$$

E_o in cm/day.

The different terms in the energy budget calculation of evaporation is evaluated as follows:

Q_s (mean monthly solar radiation) is calculated (Dune & Leopold, 1978) as,

$$Q_s = I_o (0.803 - 0.34C - 0.458C^2) \dots\dots\dots 4.13$$

Where,

Q_s = is the mean daily solar radiation for the month,

I_o = is solar radiation per day received on a horizontal surface at the exterior of the atmosphere found tabulated in standard tables depending on latitude (Annex. 3)

C = Mean monthly cloudiness (decimal fraction) computed from the measured sunshine hours in the meteorological station under consideration

$$Q_{rs} = \alpha Q_s \dots\dots\dots 4.14$$

Where α is the albedo of water, which is assumed to be 0.06 in most studies.

Net long wave radiation is estimated from the empirical relation (chang, 1968 cited in Dune & Leopold, 1978),

$$Q_{lw} = \delta T_a^4 (0.56 - 0.08 \sqrt{e_a} (0.1 + 0.9n/N)) \dots\dots\dots 4.15$$

Where,

δ = The stefan – Boltz man constant ($1.17 \times 10^{-7} \text{ Cal/cm}^2 / ^\circ\text{K}^4/\text{day}$)

T_a = air temperature ($^\circ\text{F}$)

e_a = vapor pressure of the air

n = observed duration of sun shine (hours)

N = maximum possible duration of sun shine (hours) given is standard meteorological tables

Thus, assuming that the change in heat storage be Zero when energy budget is computed on annual basis; and the energy transfer between water and the bottom sediments is zero, since sediments are assumed to be no conductive of heat for most practical purposes. This reduces eq 4.12 to :

$$E_o = [Q_s - Q_{rs} - Q_{lw}] / \rho [\lambda [1 + \beta] + c(T_s)] \dots\dots\dots 4.16$$

Evaluating all the terms using available meteorological data gives as a lake evaporation of 1714 mm of water annually for Lakes Haiq and Ardibo.

D. Penman (Combination) Method

This method combines both mass transfer and energy budget approaches to compute open water evaporation. Penman, by combining the aerodynamic and energy budget method found out an equation, which do not require a surface temperature measurement of the water body. Since it gives satisfactory results, it has a theoretical foundation, and it requires meteorological inputs that are widely available or can be reasonably well estimated from available data, the combination method has become the standard hydrologic method for

determining free water evaporation (Dingman, 1994)

The basic Penman equation (formula) for open water evaporation is:

$$E_o = [(\Delta/\gamma)H + E_a] / [\Delta/\gamma + 1] \dots\dots\dots 4.17$$

Where E_o is evaporation rate in cm/day, H is net radiation in units of cm/day of evaporation, Δ (mb/°C) is the slope of the curve relating saturation vapor pressure to temperature, γ is psychrometric constant both can either be calculated or found from standard tables, and E_a is a term describing the contribution of mass transfer to evaporation.

The net radiation can be obtained from the relation;

$$H = [Q_s(1-\alpha) - Q_{lw}] / \lambda \dots\dots\dots 4.18 , \text{ and}$$

$$E_a = (0.013 + 0.00016V_a)(e_{sa} - e_a) \dots\dots\dots 4.19$$

Where, E_a in cm/day, V_a is the wind speed (km/day) measured at a height of two meters, e_{sa} (mb) is the saturation vapor pressure of the lake surface at the air temperature and e_a (mb) is the atmospheric vapor pressure. Using the relevant meteorological variables in to equation 4.17 gives the evaporation from lakes Haiq and Ardibo to be 1516.5 mm of water annually.

Methods		Annual evaporation in mm	Remark
1. Pan evaporation		1164.7	Using a pan coefficient of 0.8
2. Mass Transfer	L. Haiq	468.8	
	L. Ardibo	473.4	
3. Energy budget		1714	
4. Pen man (Combination)		1516.5	

Table 4.6 Summary of the results of open water evaporation for Lakes Ardibo and Haiq through different methods

From table 4-6, the mass transfer method highly undermines the annual evaporation of lakes Haiq and Ardibo, this is probably due to the low wind speed measured in the area on which the mass transfer equation is dependent, and the small vapor deficit observed because of the small differences in value between air and lake surface temperatures. In addition to these, the mass transfer approach of open water evaporation needs wind speed measured at two different heights where it is absent in the meteorological stations around the study area and probably in the country as a whole. Therefore, this value will not be considered in further analysis. The pan evaporation also gives relatively lower value as compared to the energy budget and Penman methods. The energy budget gives higher values among all the methods used. For further analysis and evaluation of the water balance of the studied area, the mean of pan evaporation, energy budget and penman values will be taken. Therefore, the annual evaporation over lake Haiq and Ardibo is found to be 1465.1 mm.

4.3.2. Potential Evapotranspiration

Evapotranspiration is a collective term of evaporation from the soil surface and transpiration from vegetation. In addition to those factors that affect (influence) open water evaporation, it is influenced by the supply of moisture at the evaporating surface. The evaporation that would occur from a well-vegetated surface when moisture supply is not limiting is termed as potential evapotranspiration (PET).

The actual evapotranspiration over the catchment is then obtained from the potential evapotranspiration by accounting actual soil moisture content. Penman developed two methods of potential evapotranspiration computation over a catchment.

Pen man(1): In this method, the potential evapotranspiration from a vegetated land surface is related to the evaporation of open water calculated through equation 4.17. Penman suggested a coefficient of 0.7 for semi-arid tropics (Dune & Leopold, 1978) that relate the open water evaporation to potential evapotranspiration over the catchment. Using this coefficient for the study area gives 1061.6 mm of potential evapotranspiration over the study catchment, provided that, when moisture supply is not restricted.

Penman (2): In this method, penman has modified his open water evaporation to account for evapotranspiration processes. The basic penman equation for evapotranspiration is given by (Shaw, 1988)

$$PET = [(\Delta/\gamma)H_T + E_{at}]/[(\Delta/\gamma) + 1] \dots\dots\dots 4.20$$

Where,

PET is the rate of evapotranspiration,

H_T is the net radiation term given by;

$$H_T = Q_s(1-\alpha) - Q_{lw} \dots\dots\dots 4.21$$

in which α is the Albedo of the vegetation cover of the studied catchment, and is taken to be an average value of 0.21.

Therefore,

$$H_T = 0.79Q_s - Q_{lw} \dots\dots\dots 4.22$$

$$Q_s = 0.79I_o(0.16 + 0.62n/N) \dots\dots\dots 4.23$$

$$Q_{lw} = \delta(T_a)^4(0.47 - 0.75\sqrt{ed})(0.17 + 0.83n/N) \dots\dots\dots 4.24$$

And E_{at} is the mass transfer term given by:

$$E_{at} = 0.35(1 + V_a/100)(e_a - e_d) \dots\dots\dots 4.25$$

Where, e_d is the vapor pressure of the air at the dew point temperature. Air temperature ($^{\circ}C$), vapor pressure (mm of mercury), wind speed in miles per day, Q_s , Q_{lw} , H_T , I_o are in mm/day expressed in equivalent evaporation.

Inserting appropriate variables from the Haiq-Ardibo catchment into equation 4.20 gives an annual PET value of 1200 mm of water. For the details of the computation Annex.1. When Penman (1) and Penman (2) values of PET are compared, a clear disagreement of values is observed. This may be explained by an under estimation of the factor that transform open water evaporation into PET in the first method of Penman. Therefore, modified Penman PET value is accepted in this work and will be used for further analysis of AET.

4.3.3 Actual evapotranspiration

The computation of potential evapotranspiration (PET) from available meteorological data is much simpler than computing actual evapotranspiration (AET) from a vegetated catchment. Since PET is dependent on a continuous supply of moisture, AET does not always proceed at the potential rate due to moisture restrictions in dry seasons.

AET is computed from PET values by considering the available moisture in the root depth. When ever moisture is unlimited in the soil, the two rates become equal. Under limiting conditions of moisture supply, the two rates vary. AET is, therefore, computed based on the computed values of PET considering moisture conditions in the soil. In order to compute AET in the Haiq-Ardibo catchment, the monthly water balance model developed by Thornthwaite and Mather (1955) as applied by Dingman (1994) was used. This method makes use of a simple bookkeeping procedure that needs the monthly values of effective precipitation and PET. The soil type in different parts of the catchment and its accompanying maximum moisture capacity should be mapped and known. PET values can be computed in any method suitable for the study area. For the Haiq Ardibo catchment, PET value is computed using the formula of modified penman (section 4.3) and soil types in the catchment were mapped and the maximum moisture capacity of each soil, class is correlated with published values. The relation between land use-land cover and soil types are shown in Table 2-3.

The Thornthwaite method of computing AET for each month ($m = 1 \dots 12$) for the Haiq-Ardibo catchment using the procedure of Alley (1984) cited in Dingman (1994) is done in the following way:

For a month m , when $P_m > PET_m$, the value of soil moisture at the end of that month S_m is found using;

$$S_m = \min\{[(P_m - PET_m) + S_{m-1}], S_{max}\} \dots\dots\dots 4.26$$

Where,

S_m is soil moisture for month m , P_m is the effective precipitation of month m , PET_m is potential evaporation of the same month, S_{m-1} is the soil moisture of the preceding month, and S_{max} is the maximum soil moisture capacity of that particular soil type (soil moisture value at field capacity); The values of S_{max} for different soil and vegetation type are listed by Dune & Leopold (1978) When $P_m < PET_m$, there is an increment in soil moisture deficit and the soil moisture in this case is given by:

$$S_m = S_{m-1} \exp\{-(PET_m - P_m)/S_{max}\} \dots\dots\dots 4.27$$

Where all the terms are as the terms are as mentioned before.

Thus, monthly actual evapotranspiration, AET is found

$$AET_m = PET_m, \text{ when } P_m > PET_m \dots\dots\dots 4.28$$

$$AET_m = P_m + S_{m-1}, \text{ when } P_m < PET_m \dots\dots\dots 4.29$$

Using equations 4.26 through equation 4.29, AET values for three soil types and corresponding vegetation (land cover) is computed from annex .4, for the two sub catchments (Haiq and Ardibo). The weighted average annual AET of the different vegetation- soil complexes is summarized in table 4.8.

Land use /land cover	Soil type	Haiq subcatchment			Ardibo subcatchment			Entire catchment	
		Areal proportion	AET	Surplus (mm)	Areal proportion	AET (mm)	Surplus (mm)	AET (mm)	Surplus (mm)
Intensive cultivation of cereals, corn and related crops	Clay loam	0.4	855.5	13.6	0.4	811	-		
Scattered cultivation of cereals; shrub and grass land	Sandy loam	0.4	814.4	54.7	0.2	783.4	27.6		
Shrubs, bushes, and grass land	Gravely sand soil	0.2	767.7	101.4	0.4	736.2	74.8		
Weighted average		1	821.5	47.6	1	775.6	35.4	805.0	43.2

Table 4.7 Relation between soil type, vegetation, AET and moisture surplus in the Haiq-Ardibo catchment.

A. Haiq subcatchment: The actual evapotranspiration obtained for this subcatchment as a weighted sum of the areal proportion of each soil and vegetation type is 821.5 mm with a surplus of 47.6 mm annually. From annex .4 the soil moisture surplus is concentrated in the month of August; this is one of the inherent characteristic drawback of the soil-water balance of Thornthwaite and Matter. The method lumps all the surplus contribution of the other months to the main rainy month. Therefore, The surplus found in the month of July and August is contributed also by other rainy months. The value of AET vary according to soil type and vegetation (Annex.5).

B. Ardibo subcatchment: The value of AET and moisture surplus computed for this catchment is 775.6 mm and 35.4 mm respectively. This value is less than that calculated for the Haiq subcatchment due to differences in the effective rainfall and soil-vegetation complex. The soil moisture surplus is concentrated in one month only, that is, August; due to the nature of the model that lumps the contribution of other rainy months. For the clay loam soil type no surplus was obtained because of the high moisture capacity of the soil which inhibits percolation so that soil moisture that stayed in the root zone is lost by evapotranspiration.

In the same way, AET and moisture surplus is computed for the entire study area as a weighted sum of the two subcatchments. Thus, Catchment actual evapotranspiration is 805.0 mm, and the annual moisture surplus that recharges the ground water is found to be 43.2 mm depth of water over the entire catchment area.

4.4 Runoff Characteristics of the Catchment.

Runoff is that portion of the precipitation that makes its way towards stream channels and lakes as a surface and subsurface flow. But, it is commonly referred to surface flow and will be used in this section with this context. Runoff in a given catchment or basin is influenced by rainfall related factors such as duration, intensity and areal distribution; and other watershed factors like size of watershed, shape, orientation, topography, geology and land use (Schwab et al., 1993).

In basins where there is a gauging station at the outlet of the stream, the measurement of the amount of runoff is not difficult. From the measured runoff data the concentration of surface

runoff and base flow can be analyzed. In area where there is no stream gauging stations like the Haiq-Ardibo catchment, quantification of channelized flow is difficult. When runoff data is needed for a watershed for which there are no records of runoff, estimates can be made using alternative methods. Among which the rational method, extrapolating the values from near by similar gauged catchments and water balance method are some and will be used for the quantification of the runoff in the Haiq-Ardibo catchment.

In order to understand the runoff characteristics of the studied catchment, landuse-landcover, slope and soil mapping was done which will later help for the quantification of the runoff coefficients for the two subcatchments (Haiq and Ardibo). The result of the mapping is summarized in table 4.8

No.	Landuse/land cover	Soil type	Slope class	Haiq subcatchment (km ²)	Ardibo subcatchment (km ²)	Total
1	Intensively cultivated land	Clay loam	2-35%	28.4	15.1	43.5
2	Intensively cultivated land	Sandy loam	35-60%	14.2	1.4	15.6
3	Scattered cultivation with bushes and grass	Sandy loam	35-60%	9.4	6	15.4
4	Bushes, shrubs, and grass land	Shallow gravely sand soil	35-60%	10.6	-	10.6
5	Bushes, shrubs and grass land	Shallow gravely sand soil	> 60%	2.4	14	16.4
6	Lakes	-	0	22.8	15.8	38.6
			Total	87.8	52.3	140.1

Table 4.8 Relation between land use-land cover, slope, and soil type

As can be seen from the table, the water shed characteristics of the Haiq-Ardibo catchment are diverse. Slope ranges from zero close to the lake to more than 60% at steep fault escarps. The land use/land cover and soil also varies depending on the physiography. The land cover on which cultivation is not practiced is well grown shrubs and bushes with moderate coverage. On the other hand, forest cover is nearly absent and cultivation of lands as steep as 60% is observed, that favors more runoff than infiltration. Because of the tectonic activities that affect the whole rock formation in the study area (intense faulting), together with deep weathering, the geology favors infiltration than runoff. Soil type and depth in the studied area follows the slope condition. Where there is gentle to flat area, the soil type is clay loam. Where as at steeper slopes, the soil grades into sandy loam, sand and weathered gravel in that order. The thickness also follows the same trend. Due to steep slope, intensive cultivation, small and compact nature of the two subcatchments, shallow soil depth and the proportion of the catchment covered by vegetation (shrubs, bushes, grass), the runoff is assumed to be dominant over the infiltration. Even though there is locally high infiltration, due to morphology and rock stratification, the infiltrated water will join the runoff as through flow.

4.4.1 Quantification of annual runoff into the lakes

A. Using runoff coefficient: In this method of runoff computation, a runoff coefficient of each subcatchment is determined based on soil, landuse/landcover and slope characteristics of the catchment. The runoff coefficient is the ratio of the peak rate of direct runoff to the average intensity rainfall in a given storm. The runoff coefficient is most commonly applied to storm rainfall and runoff; but, it can also be used for monthly and annual rainfall and stream

Chapter 5

HYDROGEOLOGY

5.1 General

Hydrogeological mapping at the scale of 1:50,000 was made for the study catchment. This mapping was done based on areal photo interpretation and field geologic and hydrogeologic data interpretation. Based on field investigation of hydrogeologic properties such as infiltration capacity of the surficial materials, permeability of the rocks outcropping in the study area, degree of weathering and fracturing, topographic and morphologic positions and the primary hydrologic features, the lithostratigraphic units discussed in section 3.2 are transformed into hydrostratigraphic units (Fig.5.1). Data on the transitivity, storativity and hydraulic conductivity of the different rock out crops and sediments within the study area are lacking due to the absence of borehole information in the catchment.

Based on field hydrogeologic data interpretation and mapping, lithostratigraphic units showing similar hydrogeological characteristics are grouped together. Thus, two broad hydrostratigraphic units are mapped. These are, the various Fractured volcanics, and the quaternary sediments

5.2 Fractured volcanic rocks

This hydrostratigraphic unit comprises both acidic and basic rocks found in the study area, i.e., rhyolites, ignimbrites, basalts, pyroclastic acidic materials and rare trachytes and tuffs. All these lithostratigraphic units show homogeneity in hydrogeological characteristics such as degree of fracturing, weathering and accompanying infiltration capacity of overlying

superficial materials and the permeability of these rocks. When comparison is made between the different lithologic units within this hydrostratigraphic units, the ignimbrites and rhyolites are relatively less permeable than the degraded basaltic and acidic unwedded pyroclastic units. This might probably be confirmed by the emergence of small contact springs at a number of points at the contact between the underlying rhyolite/ or ignimbrite and other overlying volcanic units. From field observation of the different lithologic units of the volcanics, primary hydrologic features are subdued by secondary processes of faulting, jointing, and weathering. As can be seen from the structural map of the area, different sets of faults have dissected the area which has contributed to the secondary porosity and permeability of the volcanics. Faults in the study area have, therefore, played the major role in the infiltration and subsequent groundwater circulation in the volcanics which could be evidenced by the emergence of widespread fault controlled springs.

Well data on the volcanics of the study area is not available, while, wells drilled in the Borkena river basin on similar volcanic units show very low yields as compared to the alluvial aquifers (Ketema Tadesse, 1980). On the other hand, wells drilled southwest of the catchment for the supply of Haiq town has a static water level at 3.4 m yielding 5.6 l/s with a drawdown of 7.9m.

Due to the steep topography that these volcanics are outcropping, the morphologic characteristics have controlled the water bearing property of these rocks and are poor aquifers. Had the morphologic and topographic conditions been suitable, the volcanics would have been good aquifers, owing to their degree of fracturing, weathering, jointing and faulting, particularly in the low lying plains. Almost all the volcanics are located at the

uplifted parts of the catchment and hills and therefore, they are mapped as poor aquifers in the study area.

5.3 Recent Sediments

Quaternary sediments in the study area are composed of gravel, sands, silt and clay size ranges. They originated from alluvial, colluvial, and lacustrine processes. From field observation and investigation of this hydrostratigraphic unit, alluvial and colluvial materials cover wider areas as compared to the lacustrine deposits which are confined to the shores of the lakes. This hydrostratigraphic unit occupy considerable area of the catchment at the low lying fault bounded graben like sector and around the lake shores. The unit occupy at morphologically suitable positions for the recharge, infiltration, storage of significant amount of groundwater. This is favored by the primary granular permeability and porosity of the sediments except in some points where the fine fractions dominate. Field observation of the texture, areal extent, and thickness of these sediments show that this unit constitute probably the major unconfined aquifer in the catchment. Since these sediments are located within the discharge area of the catchment, this aquifer gets recharge from direct precipitation, from the volcanics that lie upcatchment and in addition from topographically controlled springs that emanate at the foot of hills and fault controlled springs that emerge along the fault plane at the foot of most fault escarpments.

A number of shallow hand dug wells with submersible pumps were installed previously, with in this unit, but most of them are out of use due to lack of maintenance. Data on hydraulic properties such as transitivity, storativity, and hydraulic conductivity of this aquifer is lacking. Data in near by areas in Dessie and Kombolcha probably on similar sediments

showed that, at Dessie, using Jacob's non-equilibrium formula, a transmissivity of $94 \text{ m}^2/\text{d}$, a hydraulic conductivity of $3.58 \times 10^{-3} \text{ cm/s}$ at. At Kombolcha, a transmissivity of $28.1 \text{ m}^2/\text{d}$, a hydraulic conductivity of $1.25 \times 10^{-3} \text{ cm/s}$ was reported by Ketema Tadesse (1980).

Since the sediments have good recharge, because they occupy hydrologically favorable position, and since they can store and transmit ample amount of groundwater, they are referred in this study as very good aquifers.

5.4 Recharge and Discharge Conditions

Recharge of groundwater can be defined as the entry in to the saturated zone of water made available at the water table surface, together with the associated flow away from the water table with in the saturated zone. On the other hand, ground water discharge is the removal of water from the saturated zone across the water table surface, together with the associated flow toward the water table with in the saturated zone (Freezes & cherry,1997). In recharge areas, there is often a rather deep unsaturated zone between the water table and the land surface, conversely, the water table is found either close to or at the land surface in discharge areas.

Toth (1963) cited in Fetter (1994) showed the possibility of mapping recharge and discharge areas on the basis of field observation using the basic indicators such as topography, piezometric pattern, hydrochemical trends, environmental isotopes, and soil and land surface features such as seeps and springs.

From topographic point of view, discharge areas are topographically low, where as, recharge areas are topographically high. Even though geochemical interpretation requires a large

number of chemical analysis carried out on water samples, systematic samples representing the area along surface and ground water flow paths tells recharge and discharge area, since it is a well understood fact that moving groundwater through a flow system undergoes a geochemical evolution. Generally, salinity either in terms of electrical conductivity (EC) or total dissolved solids (TDS) increases along the flow path. Therefore, recharge areas are usually with fresh water, while water in discharge areas is often relatively saline.

A. Ardibo-subcatchment: since the studied area is divided into two subcatchments, it seems logical to describe the recharge-discharge relations separately. Ardibo subcatchment gets its recharge only from direct precipitation. The volcanic ridges and the fault escarpments that surround lake Ardibo and the surrounding low lying areas are recharge areas. While the lake and surrounding foot hill areas are discharge areas. The groundwater discharge is manifested by springs such as spring numbers CS-5,21,22,23 (Annex.6) and seepage zones southwest of lake Ardibo are some. Since Ardibo subcatchment is superficially a closed drainage system, there is no perennial stream with a well defined channel that enters the lake. It is possible to estimate the annual recharge for this catchment using the soil-moisture balance method of Thornthwaite & Mather (1957). Approximation of the annual recharge from precipitation is therefore, 35.4 mm depth. In the Ardibo subcatchment, due to geology and morphologic controls, groundwater inflow into this catchment may not be possible.

B. Haiq sub-catchment: Unlike Ardibo, Haiq sub-catchment gets its recharge from irrigation loss, from stream seepage and seepage from canal in addition to direct precipitation. Probably there is a possibility of cross catchment water transfer due to the NNW faults also, but this will be considered later (Chapter-6). Haiq subcatchment can also

get recharge from lake Ardibo and from Ardibo subcatchment, this could be confirmed through the presence of relatively large and constant discharge spring (CS-18 in Annex.6) some 500 meters north of lake Ardibo. The continuous seepage zone that once in the pluvial times, this lake was overflowing, is a sign of hydraulic interconnection between the two catchments and hence between the two lakes (fig.5.1). This seepage zone begins at the northern shore of lake Ardibo and reaches up to the Ankerka river upper course.

The amount of recharge from lake Ardibo, canal loss, river seepage loss and irrigation is difficult to quantify due to lack of data on each specific recharging process. On the other hand, a first estimation of recharge from precipitation is made for this catchment using the method of soil-moisture balance (Thornthwaite and Mather, 1957), and a value of 46 mm depth of water is obtained.

The catchment area contributing recharge to this catchment is the ridges that surround the lake and surrounding low-lying flat areas. The topography of the catchment, geology including structures such as the eastern major fault (Hara fault) and other faults control recharge processes by directing infiltrated water towards the discharge areas. As described in section 5.5, the recharge areas of Ardibo subcatchment also have some contribution in recharging the Haiq subcatchment, since it is assumed that the two lakes and their catchments are hydraulically interconnected. That is, in the local groundwater flow regime, flow is towards local low spots (that is towards the lakes) but in the intermediate flow condition, groundwater flow is from Ardibo catchment to the Haiq catchment implying recharging of Haiq.

As compared to the recharge areas, the discharge area of Haiq sub-catchment is small. This consists of the area north of lake Ardibo, including the seepage zone (swamp) and the line of springs that emerge due to the NW trending Hara fault, and the flat alluvial plane south of lake Haiq. Lake Haiq itself is a point of least elevation in the catchment therefore, it is also a discharge area like lake Ardibo. Major manifestation of discharge in the Haiq sub-catchment are springs Cs-1,2,3,4 (Annex. 6), line of springs following the fault trace of Hara and other seepage zones. Generally, faults have played a significant role in the discharge of groundwater by controlling lateral and vertical movement of water in the catchment

5.5 Springs

The catchment of Haiq-Ardibo is magnificent in two respects; the first is the surface water bodies (lakes) that covers more than 38 km² area, the second is the manifestation of groundwater in terms of springs in many places and some times when controlled by faults, makes a line. This catchment has more than 30 springs in which some of the springs and their field description is given in Annex .6 These springs emerge in different modes: some are controlled by faults (fault springs), others are due to the topographic slope break in which the water table crosses the surface (depression springs), and still other are developed due to the contact between two lithologic units of relatively differing permeability (contact spring). They range in discharge from a mere seepage zone to more than 4 liters per second, and have temperatures less than 20 °c to more than 28°C but no thermal springs are found within the catchment suggesting shallow circulation of groundwater. Most of the springs have a fairly constant discharge and drain from acidic to basic rocks and from unconsolidated colluvial sediments to pyroclastic materials.

Springs that emerge due to major faults are characterized by large and constant discharge, on the contrary springs that owe their origin to lithologic contact have low and variable discharges. Depression type springs are in between the two extremes. Springs that are aligned in NW- SE direction north of lake Ardibo could mark the fault trace of the major NE-trending Hara fault in the catchment and seems to control the settlement patterns of the area .

In other parts of the catchment where there is a sharp drop in elevation, springs are observed at the topographic low spots.

The common practice in this area is the utilization of springs for irrigation. All the springs in the study area are completely used for irrigation implying that they are fresh. This groundwater utilization for irrigation is a major part in the water balance of the area, since it is comparable to pumping ground water. The chemistry of these springs is discussed in chapter-8. Most of the major springs are developed using plane concrete division boxes, sometimes with small-reinforced concrete reservoirs.

From the water budget point of view, there are two groups of springs, the first group are those that enter the lakes and constitute groundwater influx. The second group are those that leaks out of the lakes representing groundwater outflow. In this regard, the inflow springs into lake Ardibo are CS-5, 21,22,23, and the out flow is CS-18; for lake Haiq the inflow springs are CS-1,2,3,4,6 and others are far up stream; and outflow is through the E-W faults that cut across the western crater rim and are CS-7, 8, 9, 26, 27, 28 (Annex .6).

5.5 Groundwater flow and Surface water-Groundwater Interactions.

From the detailed field observation of the geology, topography, the discharge, chemistry and distribution of springs; two groundwater flow systems are conceptualized. These are the intermediate and local flow systems. The local flow system is developed following the surface water divide of the two subcatchments, that is, Haiq and Ardibo. The two local systems are developed as a result of the local topographical relief that gave rise to the two lakes and the surrounding geology. In these systems, groundwater flow is towards the respective lakes and the flow is shallow. According to Fetter (1994), if the surface topography has a well defined local relief, local groundwater flow systems can form. This is because of the undulation of the water table influenced by the topographic relief. As discussed in sections 5.4, a local groundwater flow system has its recharge area at topographic high spots and its discharge area at an adjacent topographic low.

For the entire catchment, due to the topography and drainage area geometry, an intermediate groundwater flow is expected. In this system of groundwater flow in the Haiq-Ardibo catchment, groundwater circulation depth is not shallow and the residence time of the recharged water is intermediate. In the intermediate flow system, groundwater flow is towards the topographically low spot, that is, towards lake Haiq. With this system, the two lakes are connected hydraulically, Lake Ardibo flowing into Lake Haiq. This north ward movement could be evidenced by an elevation drop of 250 m from Ardibo to Haiq. The development of relatively large discharge and perennial springs in between the two lakes, and by the chemical evolution of ground and surface waters in the direction of the proposed

groundwater flow direction (chapter-8). Due to lack of piezometric data, construction of a groundwater flow map for the flow system and subsequent quantitative evaluation of this intermediate flow system is not possible.

The interaction between surface and groundwater in the study area is evident in that both lakes and groundwater recharge interact one another. In relatively elevated areas where lake Ardibo is situated, due to the influence of hydrogeology (both structure and permeable rock units) groundwater is recharged through the lake in its north eastern shore probably for the contribution of the intermediate flow system (regional system with in the catchment). There is also shallow groundwater input to this lake but the amount of groundwater that enters the lakes is influenced by irrigation activities in the catchment. In topographically low area like lake Haiq, the lake-groundwater interaction is such that the groundwater contributes to these lakes with, and the groundwater table is not below the lake bed.

An interesting surface water-groundwater interaction is observed on the course of the a systematic discharge measurement of the Ankerka river. Systematic flow measurements were made following the flow direction of the river at four appropriate points. In addition to the river discharge measurement, samples for chemical analysis were collected. From discharge measurement, and chemical data the following is observed.

point of measurement	At the canal outlet near lake Ardibo	Point. 1	Point. 2	Point. 3
Discharge	0.462 m ³ /s	0.249m ³ /s	0.184 m ³ /s	0.0957m ³ /s
Field EC (μs/cm)	510	606	528	526
Lab. EC.	581	613	560	550
Lab. TDS	529.1	525.7	491.4	499

Table 5.1 Discharge and EC measurements of Ankerka river along the flow path.

From table 5.1 it is clear that the river loses water to the subsurface, that is, discharge has decreased from 0.462 m³/s to 0.095 7 m³/s following the flow path with a significant human interference. This implies that the groundwater table is depressed far below the bed of the Ankerka river and the Ardibo canal. Much of the loss has occurred in the first and last segment of measurement exactly coinciding with the alluvial- colluvial aquifer mapped in fig.5.1. Therefore, the Ankerka river is a losing stream. The chemistry also shows variation of EC and TDS along the flow path probably due to the interaction of the river water with groundwater, but this variation is not systematic. This may be attributed to the effect of evaporation and /or local human interference.

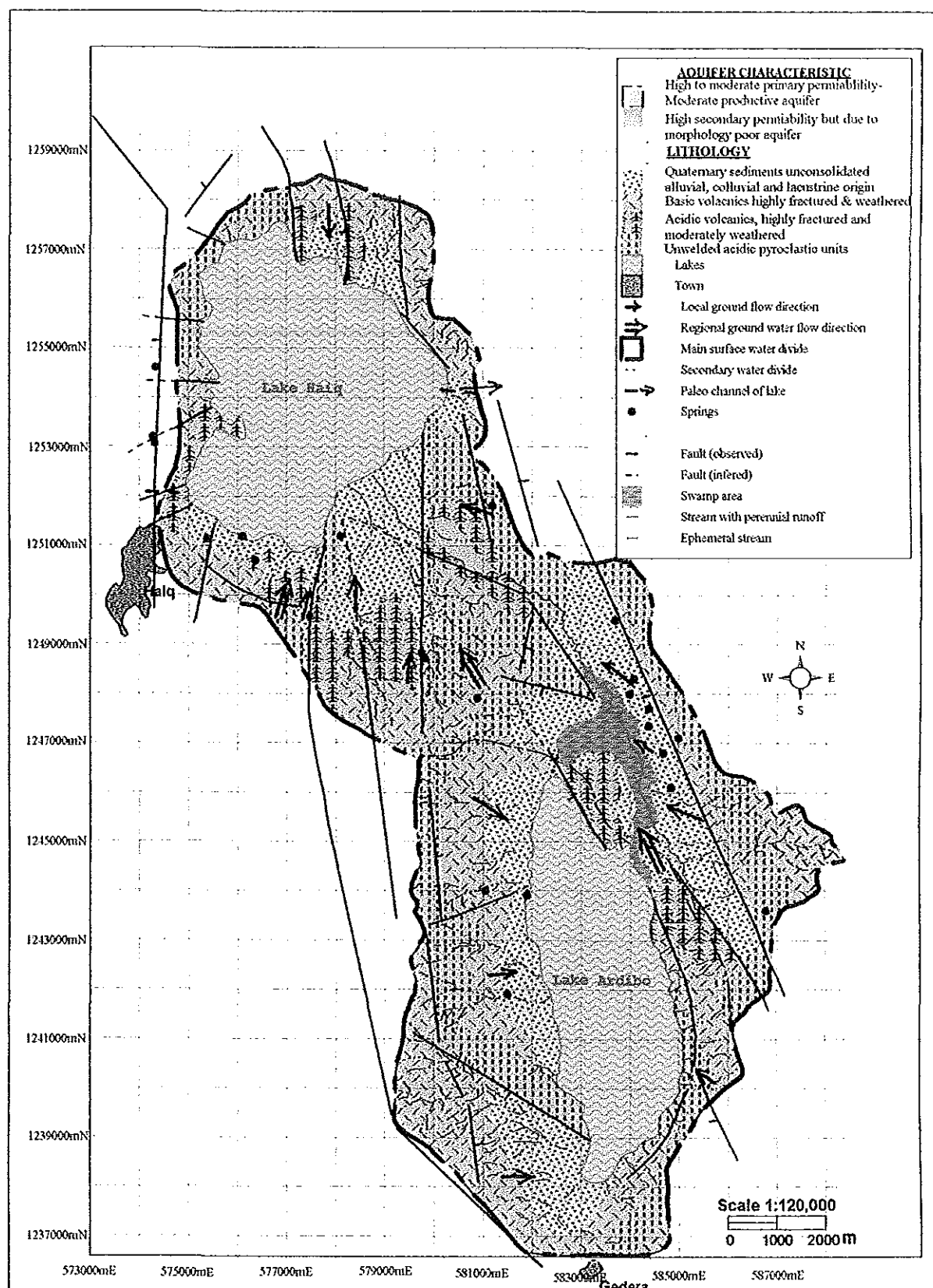


Figure 5.1 Hydrogeological map of Haiq-Ardibo Catchment

CHAPTER 6

WATER BALANCE

6.1 General

The study of water balance of river basins lakes and other reservoirs including groundwater basins is a basis for the rational use, management and control of water resource. On the basis of the water balance, it may be possible to make a quantitative evaluation of water resources and their change under the influence of human activities (UNESCO, 1974).

The water balance of a given hydrologic system, such as a water body (lake) or drainage basin follows the principle of conservation of mass often referred to as the continuity equation; which states that total input minus output will be balanced by the change in storage of water in the system. Therefore, use of a water balance technique implies measurement of both storage and rates of influx and out flux for a given period of time for a given area.

The analysis of the water balance of the Haiq-Ardibo catchment is one of the main objectives of this research work. To accomplish this, the catchment is divided in to two closed independent subcatchments from surface water point of view. For each subcatchment, water balance is done independent of the other, and finally the water balance of the entire catchment is treated. Abstraction of water for domestic purposes is neglected in all of the water balance analysis.

6.2 Ardibo subcatchment

The water balance for any water body or hydrologic system for any given time interval is generally represented by:

$$P_i + S_i + G_i - E - S_o - G_o \pm A = \Delta s \dots\dots\dots 6.1$$

Where, p is precipitation

S_i = Surface water inflow

G_i = Groundwater inflow

E = Evapotranspiration

S_o = Surface water outflow

A = Groundwater outflow

Δs = Change in storage

Whenever the groundwater divide coincide with the surface water divide, equation 6.1 takes the form:

$$P - E - A = \Delta s \dots\dots\dots 6.2$$

In the Ardibo subcatchment, there are geologic, morphologic , and hydrogeologic evidences that the catchment is not closed from groundwater point of view. Therefore, there is a groundwater outflow component in the water balance. But, We can safely assume that there is no groundwater in flow from other basins to this catchment. The water balance equation is given by:

$$P - E - A - G_s = \Delta s' \dots\dots\dots 6.3$$

And $\Delta s' = G_o + \Delta v$, where G_s is groundwater outflow through springs (estimated), G_o groundwater outflow other than the observed springs, Δv surface water storage changes if there is any, and $\Delta s'$ is the residual term.

In the water balance computation, all the input and output parameters are annual values over the Ardibo catchment and is given in million meter cube. The various computed values of the water balance terms are summarized in table 6.1.

Drainage area (km ²)	Water balance components of the Ardibo subcatchment					
	Volume in million cubic meters (mcm)					
	Precipitation (P)	Evaporation from lake(Eo)	Evapotranspiration from land area	Abstraction (A)	Groundwater outflow through springs (Gs)	Residual (s')
52.3	60.6	23.15	28.3	3.15	0.095	5.905

Table 6.1 Mean annual water balance for Ardibo subcatchment

In the Ardibo subcatchment, the only input is precipitation over the catchment. From detailed studies of the geology and hydrogeology, groundwater inflow is negligible. Outflow from this catchment includes evapotranspiration from the catchment and evaporation for lake Ardibo, Groundwater out flow through springs and calculated as a residual in the $\Delta s'$ term, and abstraction of water for the irrigation through a subsurface canal. The abstraction amount is measured using a current meter and a float at the canal outlet and this measured value 462 l/s but about, it is highly exaggerated from the actual value. While designing the canal, its capacity is fixed to be 300 l/s (Aragaw Addis, personal communication). Therefore, the abstraction at present is less than 300 l/s. Taking 100 l/s the present abstraction rate, the annual volume 3.15 mcm. groundwater out flowed through springs is estimated to be (field result) 3 lit/s which is about 0.095 mcm annually.

The groundwater storage change in the catchment on annual basis can be considered as zero (Freeze & Cherry, 1979). The residual $\Delta s'$ value found therefore, is either the groundwater outflow or the change in surface water storage change or both. But, from field observation of lake Ardibo, (no recent lake level data found), the lake does not show significant rise in level, therefore, the residual term in table 6.1 that is 5.905 mcm. could be considered as a component of groundwater outflow.

6.2.1. Water balance for Lake Ardibo.

The water balance equation for a closed basin lake where the surface water divide coincide with the groundwater divide of the watershed and with only ungauged surface runoff (unchannalized flow) is:

$$Pl + Sr + Gi - Eo - Go \pm A = \Delta v \dots\dots\dots 6.4$$

Where, Pl = precipitation on the lake surface

Sr = surface runoff from the watershed

Gi = Groundwater inflow

Eo = Evaporation from the lake surface

Go = Groundwater outflow from the lake

A = Abstraction

Δv = Change in volume for the water balance period.

Equation 6.4 is valid for lake Ardibo, since there is no channelized flow that drain in to the lake and from hydrogeologic observations, groundwater inflow and outflow could be

possible. Since G_i and G_o are difficult to quantify, the two terms are lumped with the Δv term and therefore, equation 6.4 becomes:

$P_i + S_r - E_o - A = \Delta v'$ 6.5 where $\Delta v'$ is the residual for the groundwater flux and change in storage volume.

Lake Ardibo		Water balance components in mcm				
Area of the lake(km ²)	Area of the catchment with out lake(km ²)	Surface inflow (Sr)	Precipitation on the lake surface (Pi)	Evaporation of the of the lake (Eo)	Abstraction from the lake (A) for irrigation	Residual ($\Delta v'$)
15.8	36.5	12.68	18.3	23.15	3.15	4.68

Table 6.2 Mean annual water balance of lake Ardibo

The residual term in the water balance of lake Ardibo is 4.68 mcm. From observation of the lake, lake level rise have not been observed on Ardibo. Therefore, the residual in equation 6.5 represent the annual net groundwater flux of this lake. The value is positive implying the groundwater outflow is dominant over the groundwater inflow component.

From the water balance in table 6.2 it can be interpreted that the lake maintains its level fairly constant at this abstraction rate. If the abstraction is increased, for example from approximately 100 l/s at present to 300 l/s (the designed discharge capacity of the Ardibo canal), the residual will be reduced to -1.72 mcm. If this is distributed over the surface area of the lake, it will be 108.54 mm depth of water. That means the lake level will be reduced by 10.9 cm each year. The commutative of this lake level reduction has an adverse effect both on the ecology of the lake as well as on the life of the irrigation project (lake will retreat away from the outlet canal). Therefore consideration of each water balance elements is needed before applying additional abstraction.

6.3 Haiq subcatchment

Following equation 6.1, the water balance for the Haiq subcatchment is:

$$P - E + G_i - G_s + A = \Delta s' \dots\dots\dots 6.6$$

where, G_i is the groundwater inflow in to the catchment from the Ardibo subcatchment
Neglecting the ground water inflow into this catchment (the geology supports this); G_s is
ground water outflow through springs (spring numbers, CS-7,8,9,26,27,28 in Annex.6). $\Delta s'$
is the residual including the net groundwater out flux and change in surface water storage; A
is water imported from the Ardibo subcatchment and added to Haiq subcatchment (measured
using a current meter) is about 60 l/s.

The water balance for the catchment therefore is given in table 6.3

Drainage area (km ²)	Precipitation over the Catchment (P)	Evaporation from the lake surface (Eo)	Evapotranspi ration from the watershed (Et)	Imported water (abstracti on) (A)	Groundwa ter outflow through springs (Gs)	Groundwater inflow into the catchment (Gs)	Residual $\Delta s'$
87.8	101.7 mcm	33.4 mcm	53.4 mcm	3.15 mcm	0.134 mcm	5.905 mcm	23.82

Table 6.3 Mean annual water balance of Haiq subcatchment.

The water balance of Haiq subcatchment (table 6.3) shows that there is a residual value of 23.8 mcm of water which accounts for the groundwater outflow and the change in storage change. Therefore, Since the change in surface water storage is small, the result shows the large amount of annual groundwater outflow from this catchment. If additional abstraction is made on this catchment the surface water storage will be affected highly.

6.3.1. Water Balance of Lake Haiq.

A valid water balance equation for Lake Haiq is written as:

$PL + Sr + Gi - Eo - Go \pm = \Delta v$ (equation 6.4), but since the groundwater flux components are difficult to measure directly, it will be lumped with the Δv term in the equation above. Therefore, the equation is one in the form of:

$$Pl + Sr - Eo + A = \Delta v' \dots\dots\dots 6.7$$

solving for $\Delta v'$ gives table 6.4 below:

Lake Haiq		Water balance components in mcm.				
Area of the catchment (km ²)	Area of the lake (km ²)	Pl	Sr	Eo	A	$\Delta v'$
65	22.8	26.4	18.83	33.4	1.6	13.43

Table 6.4. Mean annual water balance of Lake Haiq

The inflows into lake Haiq are direct precipitin on the lake surface, surface runoff from the watershed, groundwater inflow, and imported water from the Ardibo subcatchment. The out flows are evaporation and groundwater outflow. The residual; the difference in ground water in flow and out flow plus change in the storage in the lake is 13.43 mcm. Since the change in volume of lake is in significant, the residual is the net groundwater flux. The positive sign of this residual implies that the groundwater out flux is greater than the groundwater inflow.

Considering the subsurface hydraulic relation between the two lakes, lake Haiq and Ardibo can be related using a simple Darcian relation as follows:

$$Q = W \times b \times K \times i \dots\dots\dots 6.8$$

where, w = is the width of the aquifer

b = saturated thickness of the aquifer

K = hydraulic conductivity of the aquifer

i = hydraulic gradient between the two lakes

Taking an average width of the aquifer 2 km, a saturated thickness of 50 m, average hydraulic conductivity of the aquifer is taken as 3.5×10^{-5} m/s (as computed by Ketema Tadesse, 1980 for Dessie area), and the hydraulic gradient between the two lakes is 2.9×10^{-2} . Solving for Q gives $0.1 \text{ m}^3/\text{s}$, the annual value then becomes 3.3 mcm. The annual groundwater inflow into lake Haiq from lake Ardibo is 3.3 mcm. The water balance result (section 6.2) shows that there is a net groundwater flux of 4.68 mcm. Therefore, the computed value using equation 6.8 is reasonable and could be taken as the annual groundwater outflow from lake Ardibo. In this regard the groundwater inflow can be found by deducting the groundwater outflow from the residual (net flux) and is 1.38 mcm annually.

6.4 Water balance for the entire study area.

Following equation 6.1, the water balance equation valid for the catchment of Haiq-Ardibo is:

$$P - E_o - AET - G_{so} = \Delta s' \dots\dots\dots 6.8 \text{ where,}$$

P = precipitation over the studied catchment

E_o = open water evaporation in the lakes

G_{so} = groundwater outflow through springs associated with E-w trending faults

AET = Actual evapotranspiration over the watershed.

$\Delta s'$ = difference of ground water inflow and outflow plus change in storage of surface water bodies.

Drainage area(km ²)		Water balance components in mcm				
Lakes	Watershed	P	Eo	AET	Go	$\Delta s'$
38.6	101.5	162.3	56.6	81.7	0.134	23.87

Table 6.5 Mean annual water balance of the Haiq - Ardibo catchment

Since the study area is a closed basin, there is no surface water outflow. The only measured inflow is direct precipitation. The $\Delta s'$ term is a commutative of net groundwater flux (ΔG) change in storage of surface water bodies, because these the surface water bodies do not change much volume, it can be said that the residual term in equation 6.8 is the net groundwater flux. Still we can safely assume that the groundwater inflow from the near by catchment is negligible. Therefore the residual term is the groundwater outflow from this catchment.

Actual field observation of the area shows that appreciable amount of groundwater is lost:

1. by evapotranspiration through irrigation of the springs
2. A small increase of lake level, especially lake Haiq For the past three years is reported
3. Ground water loss out of the catchment is also observed due to the high tectonic activity in the area, specially due to E-W trending faults.

These all contribute loss to the residual term of the 23.87 mcm of water. Since the water balance for the catchment is dominated by the groundwater out flow term than the groundwater inflow term, the catchment will be sensitive to a small addition and abstraction of water. the main groundwater outflow from our catchment is through the Haiq

subcatchment. The net groundwater flux of the Haiq subcatchment is almost the same as the groundwater outflow of the entire catchment.

CHAPTER 7

BATHYMETRY OF THE LAKES

Bathymetry refers to the measurement of depth of a water body through various sounding procedures. Bathymetric survey of rivers and lakes provides important information on the configuration of the bed which will be of good help for navigational purposes. Bathymetric data serves also for water management and sound water resources utilization. Continuous bathymetric measurement of lakes also provides information on the lake level change and rate of sedimentation. In light of this, the bathymetry of the two lakes were established through free sounding procedures using a sounding line.

7.1 Lake Haiq

The bathymetry of lake Haiq was first measured by Morandini (1941). At that time, the lake was much more above the level that we observe during the field visit. The Monastery of Haiq Istefanos was an island during the time of Morandini's visit of lake Haiq (fig.7.1a). Morandini measured a maximum lake depth of 88.8 m. Currently the maximum depth measured is 81 m. This shows a lake level reduction of approximately 7.8 m for the past 60 years. The present bathymetric measurement (limited data points) shows that the lake has retreated from the original. For comparison purposes, the bathymetric map prepared by Morandini (1941), and the present work is given in Fig. 7.1 for comparative assessment. The maximum surface area of this lake is 22.8 km².

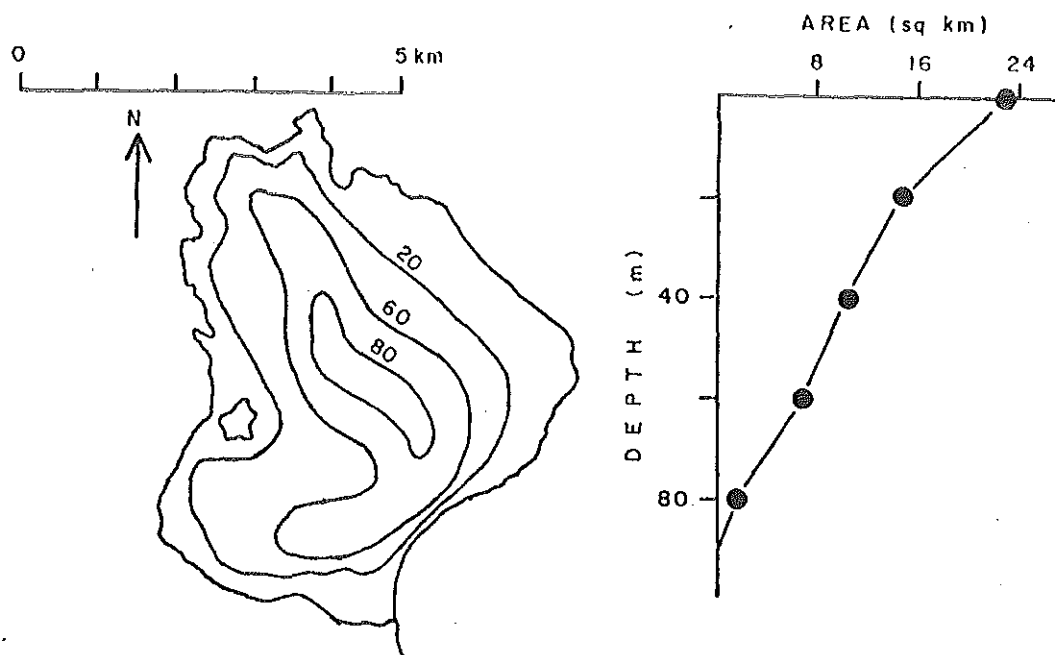


Fig 7.1a Bathymetric map and profile of lake Haiq (Brunelli et al., 1941; Morandini, 1941 in Baxter and Golobitsh, 1970).

7.2 Lake Ardibo

The bathymetry of lake Ardibo is prepared for the first time by this work. The lake is elongated approximately N-S and the depth contours also follow this trend (fig.7.2). The depth increases towards the center in all directions, the deepest point being almost at about the geographic center. The maximum depth measured is 64 m. The surface area of the lake calculated from topographic maps prepared in 1992 is 15.8 km².

Lake Ardibo like lake Haiq has experienced significant amount of lake level reduction (local information and observation of wave marks).

From the bathymetric data and observation of local geological features, lake Ardibo represents a volcanic crater later modified by NW trending parallel normal faults.

7.3 Lake level fluctuations

Lake level fluctuation on both lakes is observed from field wave mark studies and local information. As indicated in section 7.1, lake Haiq has experienced a minimum lake level reduction of about 8 meters for the last 60 years, which is evident on the bathymetric map of Morandini (1941).

A preliminary suggestion as to the cause of the lake level reduction could be attributed to local and regional climatic changes in which rainfall is the major one, neotectonics that might have formed subterranean fractures and disturb the water balance of the lakes, and local land use changes that may affect runoff, infiltration and groundwater recharge. Long term mean annual four years moving average rainfall observation at four stations around the study area (section 4.2) shows that the moving average has a decreasing trend from 1967 to 1989 and an increasing trend from 1990 to present.

The last 10 years increasing trend has increased the level of the lakes about half a meter (Personal communication). Lake Haiq, especially has a pronounced lake level rise due to the addition of extra-water from lake Haiq through a canal constructed for irrigation. Since no significant effect is induced by the abstraction in lake Ardibo, it is probably compensated by the small increase in the trend of the rainfall.

Lake Haiq		Lake Ardibo	
Area (km ²)	Depth (m)	Area (km ²)	Depth (m)
0.15	> 80	0.86	> 60
3.81	70-80	3.31	50-60
3.11	60-70	2.44	40-50
2.94	50-60	2.51	30-40
2.45	40-50	1.57	20-30
2.85	30-40	1.67	10-20
2.83	20-30	12.36	< 10
2.30	10-20		
2.36	<10		

Table 7.1 Present day Depth-area relation of lake Haiq and Ardibo.

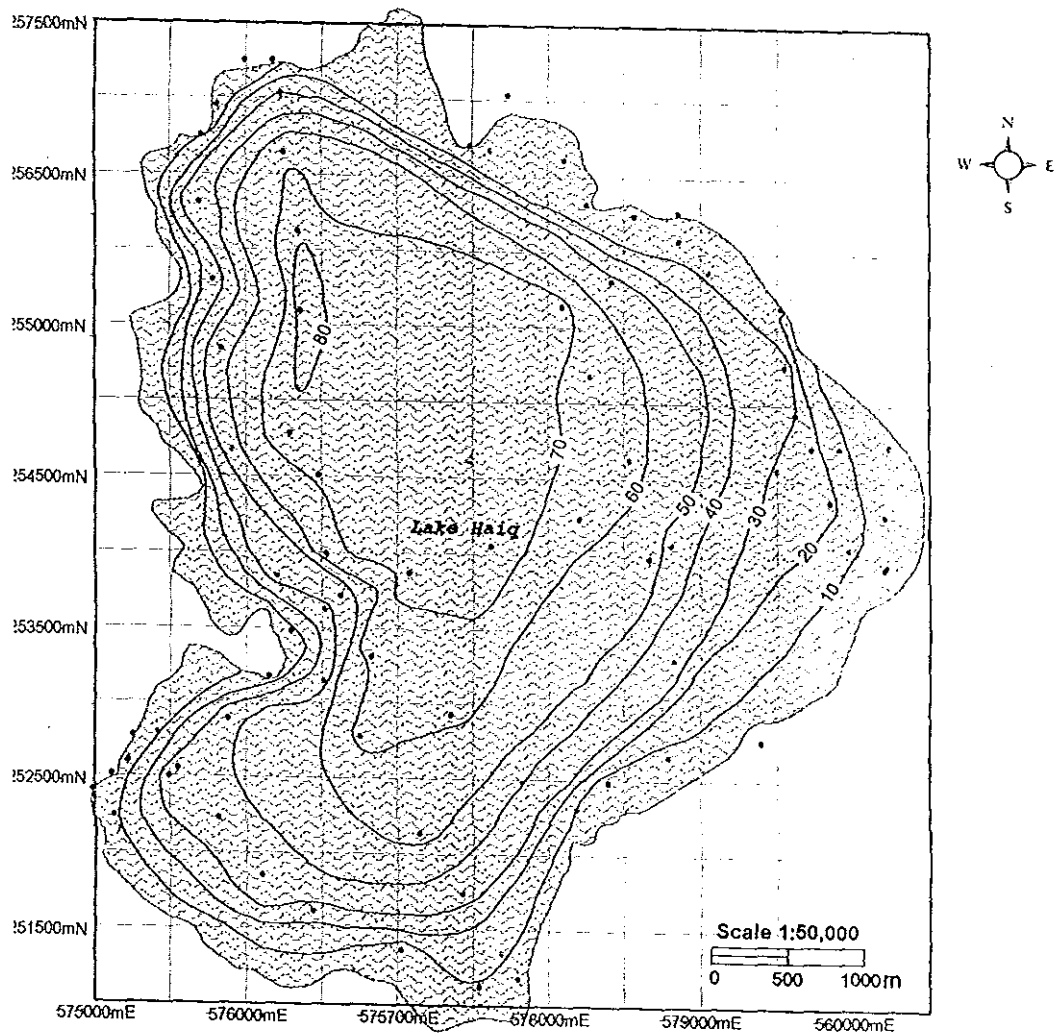


Figure 7.1 Bathymetric map of Lake Haiq

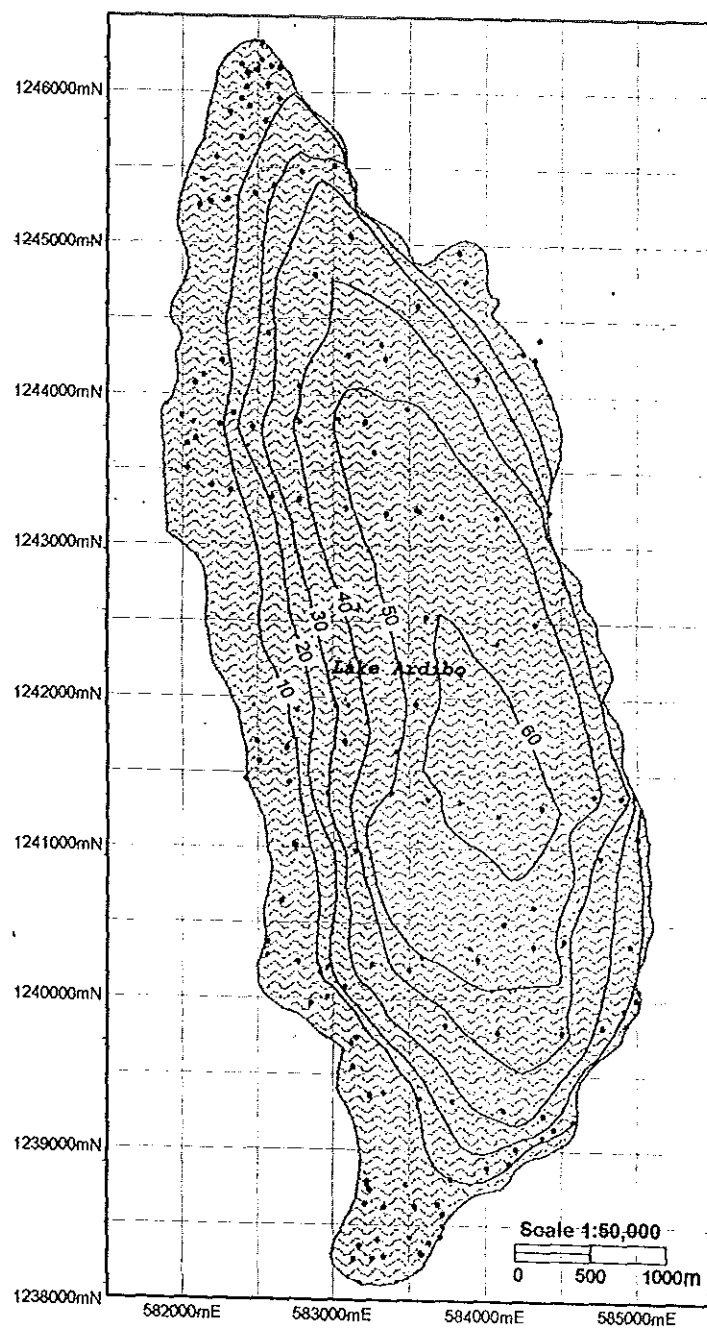


Figure 7.2 Bathymetric map of Lake Ardibo

CHAPTER 8

HYDROCHEMISTRY

8.1 Introduction

The chemical quality of water is as important as its quantity. Chemical constituents in both surface and groundwater determine its usefulness for domestic, agricultural, and industrial purposes.

Dissolved constituents in water provide clues on its geologic history and its mode of origin in the hydrologic cycle (Freeze & Cherry, 1979). Hydrochemical data also reveals information that is encoded into the water during its circulation.

In this chapter, an attempt is made to provide chemical information of the waters of the study area and interpretations are made on the quality of surface and groundwater resources. Comparison and preliminary interpretation is also made with data of previous works.

8.2 Water sampling and analysis.

Samples of water for Hydrochemical analysis were collected from different water bodies, that is, lakes, rivers, springs, borehole, and rainfall.

Lake water samples were taken both from Haiq and Ardibo. The samples in these lakes were collected both at the surface and at the bottom of the lakes so that possible chemical stratification can be assessed. The river samples were taken at three positions following the flow path of the Ankerka river. Spring samples collected includes those with in the study

catchment and outside, so that possible groundwater inflow-outflow conditions could be studied. A single rainfall sample was taken at Dessie town to approximate in general the chemistry of precipitation in the study area and compare it with those of surface and groundwater samples. one groundwater sample was taken from Dessie Tannery located in Haiq town. This borehole sample represents the water supplied to the Haiq town and the Tanning factory.

Certain properties of water such as electrical conductivity (EC), temperature, and pH, are closely related to the environment of the water, therefore, they are likely to be altered by sampling and storage. Hem (1980) strongly recommended insitu tests of these parameters. Hence, EC, temperature, pH, and dissolved oxygen was measured in the field.

The samples collected were analyzed in the Ethiopian Geological Survey's laboratory. The analysis include, major anions, and cations, EC, pH, and some trace elements.

8.3 Water type classification.

Before chemical analysis results are interpreted, the accuracy of the laboratory result has to be checked. A simple method of accuracy checking is done by calculating the reaction error given by:

$$\text{Reaction error} = [\text{Sum of cations} - \text{Sum of anions}] / [\text{Sum of all ions}]$$

where, the concentration is expressed in milli equivalent per liter. The reaction error is assumed to be caused by the analytical error of the individual parameters analyzed, in some

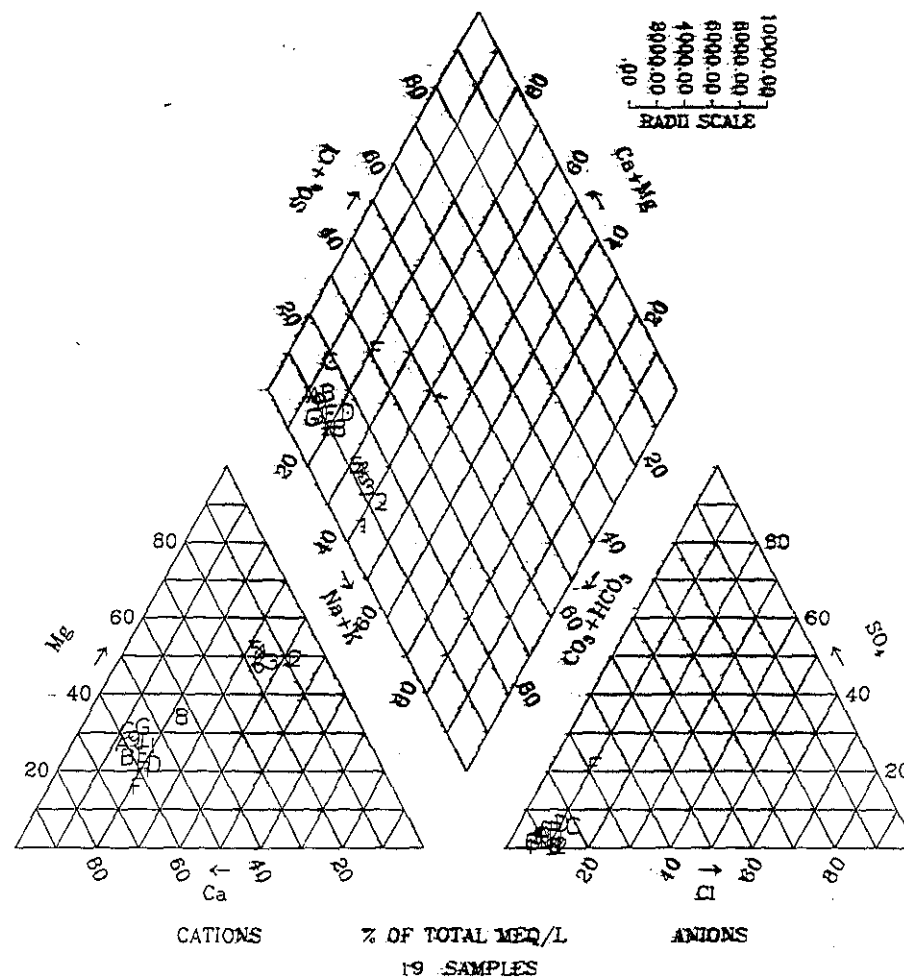
cases if there is UN measured ion in the sample this also contribute to the reaction error. In waters of moderate concentration, a reaction error between 1-2 % is acceptable (Hem, 1970). Maser (1997) recommends an acceptable range of a reaction error between 2 % to 5 %.

Water samples results reported from the laboratory are found to have less than 5 % reaction error and therefore accepted for further interpretation except for the rainfall sample which has a reaction error of about 44 %.

Plotting of the chemical analysis results of the water samples from the study area on a trilinear diagram using Plotchem computer program shows two major water groups (Fig.8.1) based on the cation compositions. As can be seen from the trilinear plot, the first group of waters, is the river and lakes samples. In this group the cation triangle contains about 50 % of magnesium and nearly 30 % sodium plus potassium. The calcium concentration is less than 20 %. The spring and groundwater samples show calcium dominance. The calcium percentage is more than 50 %, about 30 % magnesium and 20 % sodium plus potassium. Sample number eight on the plot stands alone at about equal 40 % Mg and Ca ions and 20 % K and Na ions showing the influence of groundwater on the Ankerka river . On the other hand all the samples plot at the HCO_3^- and CO_3^{2-} apex showing the predominant anion which is more than 80%.

Based on the few samples analyzed, except the groundwater samples all the waters can be classified as Mg- HCO_3 type On the triangular plots, the river and lake waters are Mg type and the groundwater samples are Ca type. From the anion plot all the waters in the study area are HCO_3^- type. From the piper trilinear plot, the waters in the study area are classified in to two water types. The lake and river samples are Magnesium-Bicarbonate type and the ground water samples (springs and borehole) are Calcium Bicarbonate type.

- 1 LH-1
- 2 LH-2
- 3 LA-1
- 4 LA-2
- 5 AC-1
- 6 RS-2
- 7 RS-3
- 8 RS-4
- 9 CS-1
- A CS-2
- B CS-3
- C CS-5
- D CS-6
- E CS-7
- F RafS
- G BH-1
- H DCS-1
- I DCS-2
- J CS-4



8.4 Chemical composition of different water samples

The chemical composition of different water bodies analyzed is given in Annex.7 The piper trilinear plot in fig. 8.1 shows that the different water bodies plot in a group with out any significant clustering. Those in one group therefore, is interpreted to have similar chemical history (origin).

8.4.1 Lake and river water samples

Table 8.2 shows chemical composition of lakes and river water samples. The TDS of all the lakes and river waters shows that these water bodies are dilute. Bicarbonate is the dominant anion in all the lakes and the river followed by chloride. Sodium is the dominant cation followed by magnesium. But, water in which magnesium being a predominant cation is uncommon, and in most natural fresh water, the magnesium concentration is much lower than the calcium and usually lower than sodium. Despite this, the concentration of magnesium in the lakes Haiq and Ardibo is much more than the concentration of calcium (Annex.7). Exceptional magnesium enrichment of these lakes was also reported by Baxter & Golobitsh (1970). The high magnesium concentration in the lakes is interpreted in terms of the lithology in which the feeder water of the lakes is draining. That is, reaction of with magnesium silicate minerals such as forsterite is the dominant mineral in the degraded basalt mapped. Hem (1970) pointed out that magnesium has a very long residence time compared to calcium. This implies that magnesium precipitates less readily than calcium. This might be also the cause of the low concentration of calcium with in these lakes. High calcite precipitation in the form of travertine is observed in the field specially at lake Haiq.

Comparison of the chemistry of lake Haiq at the surface and at the bottom shows that (limited data), the lake is not stratified at the time of sampling and is considered well mixed. A slight difference in pH changes the concentration of CO_3 with depth; the same is true for lake Ardibo too. Baxter et al., (1965) cited in Baxter & Golobitsh (1970) reported that the Ethiopian highland lake's chemical stratification is at a minimum in January and February.

When the chemistry of lake Haiq and Ardibo is compared, lake Ardibo is more dilute than Haiq, which can be interpreted as the later is a terminal lake which is true. They have a TDS of 497 and 795 mg/l, and an EC of 580 and 917 $\mu\text{S}/\text{cm}$ respectively. The chemistry of the Ankerka river is highly influenced by lake Ardibo since the irrigation return flow and springs that originate from Ardibo contribute to base flow of this river. For these reason, the two waters have similar chemistry except some modifications due to river water - groundwater interactions that takes place in the course of travel of the river.

8.4.2 Groundwater samples (springs)

The chemistry of the springs that represent the groundwater of the Haiq-Ardibo catchment show variation in chemistry depending on the position of the springs relative to each other. The TDS varies from 442 mg/l to 588 mg/l, EC from 417 to 606 $\mu\text{S}/\text{cm}$. The chemistry of these springs are more related in terms of EC and TDS to lake Ardibo than to lake Haiq (more concentrated). This implies that the springs get recharge from lake Ardibo except few springs out of the catchment that get recharge from lake Haiq.

The dominant cation in the groundwater in all of the springs is calcium in contrast to the lakes, followed by magnesium and sodium. The relatively higher concentration of magnesium

in the groundwater supports the previous idea of the lithologic control of the concentration of this ion. Where as calcium is precipitated to the lake bed forming a travertine deposit.

The dominant anion is bicarbonate followed by nitrate, chloride and then sulfate. has Silica has high concentration in the groundwater compared to the lakes, this could be because of the biologic activity in the lakes that deplete silica. The same is true for sulfate and nitrate.

Springs that are expected to originate from lake Haiq have relatively high EC and TDS values compared to other springs found with in the catchment. These springs differ from others in that they have high concentration of Na & HCO_3^- . The borehole sample has a fairly similar chemistry with the springs.

The pH of the lake and groundwater differs markedly. The lakes are alkaline having a pH of 9.1 on average for both lakes. Where as, the groundwater have a pH range of 7.2 to 8, which is the natural pH range for groundwater.

The fluoride content of both surface and groundwater's of the study area are small (less than one) as compared to the waters of the rift valley that contains between 1.9 to 250 mg/l for the lakes and 2 to 150 mg/l for hot springs. (Tenalem Ayenaw, 1998)

8.5 Temporal Variation of the Chemistry of the Lakes

Table 8.4 compares the chemistry of lake Haiq and the Ankerka river analyzed by Baxter & Golobitsh (1970) in 1969 and at present. From the Lake it is possible to observe that sodium has increased nearly by one unit. K^+ , Ca^{2+} and Mg^{2+} have decreased both at the surface and at depth. Total cation has increased, total anions, silica pH and EC has increased through time.

The increase in the chemical species is interpreted as the evaporative concentration of the ions in the lake as explained by the change in volume of the lake from 1969 to the present. The ionic concentration decreased through time, this may be as a result of precipitation, ion exchange, and coprecipitation .

Comparison of the river water chemistry between these two time limits is influenced by human interference in the area where the river drains (agricultural activities) and therefore, comparison is difficult.

8.6 Oxygen and temperature profiles of the lakes

Temperature measurements at an interval of 15 m were taken in lake Haiq to see the temperature variation with depth. The result shows that the variation is erratic (table 8.2).

Depth (m)	Oxygen (mg/l)	Temperature (°C)
0	6.4	21.9
15	1.5	23.5
30	1.3	21.4
45	1.01	21.3
60	0.5	20.8
72	0.3	20.6

Table 8.2 Oxygen and temperature profile of lake Haiq

On the other hand the oxygen profile is well depicted and as is usually the case decreases downward. In the first 15 meters of depth the oxygen concentration drops sharply. After that it gets decreasing steadily reaching 0.3 mg/l at a depth of 72 m. Lake Ardibo also do not show temperature stratification at this time .

8.7 Water quality

The quality of water is determined by the concentration of solutes in the water. This quality of water is determined by analyzing a sample of it both in the Lab. or in the field. Water quality is equally important as its quantity, since poor quality of water in excess amount either may need lots of investment for quality upgrading or not good for different purposes.

8.7.1 Water quality criteria

The usefulness of water for different purposes such as drinking, irrigation and industry is determined by its quality. One basic measure of water quality is TDS, which is the amount of

solids dissolved in water. As the amount of TDS increase, the quality of the water for utilization for drinking and irrigation degrades, as it changes from fresh to saline in some cases to brine. In the study area all the water samples analyzed have a TDS less than 800 mg/l implying both the surface and groundwater to be fresh.

Another water quality criteria is its hardness; which is a result of the presence of divalent metallic cations in which calcium and magnesium are the most important. Because of the adverse action with soap, hard waters are not satisfactory for household purposes.

The total hardness of water is given by (Todd, 1980):

$$H_T = 2.5Ca^{2+} + 4.1Mg^{2+}, \text{ where } Ca^{2+} \text{ and } Mg^{2+} \text{ are in units of meq/l.}$$

A. Drinking water quality: The inorganic constituents that were analyzed for the different water samples conforms well with the national and international quality standards. The pH of the lakes is above the Guide line value of the World Health Organization (1984).

All the waters sampled in the study area have a total hardness below 30 (table 8.3) implying they are soft according to the hardness classification of Dufour and Becker cited in Tenalem Ayenew (1992). Nitrite concentration is high in spring and ground water samples but small in the lake and river samples. In both cases the concentration is below the WHO guide line value. Fluoride concentration in waters of the study area is with in an acceptable limit, the maximum being one mg/l. The trace metal's concentration analyzed are also below the national and international drinking water standards (Table 8.7)

Sample	NO ₃	F	Fe(tot)	MN	BA	Zn	pH	TDS	Hardness
Lake Haiq	2.38	1	< 0.1	< 0.1	< 0.1	< 0.1	9.2	804.2	24.1
Lake Ardibo	0.92	0.5	< 0.1	< 0.1	< 0.1	< 0.1	9.1	490.2	14.3
Ankerka river	0.26	0.38	< 0.1	< 0.1	< 0.1	< 0.1	8.9	499.3	14.3
Spring(CS-1)	38.3	0.37	< 0.1	< 0.1	< 0.1	< 0.1	7.2	578.1	16.6
Spring(CS-7)	36.1	0.45	< 0.1	< 0.1	< 0.1	< 0.1	7.7	668.9	17.3
Borehole	17.6	0.26	< 0.1	< 0.1	< 0.1	< 0.1	7.3	570.1	16.6

Table 8.3 Water quality of samples in the Haiq-Ardibo catchment

B. Irrigation water quality: The suitability of water for irrigation depends on the effect of the chemical constituents of the water on both the plant and the soil. The most important characteristics of irrigation water are: total concentration of soluble salts, proportion of sodium to other cations, concentration of potentially toxic elements to plants, and bicarbonate concentrations as related to the concentration of calcium plus magnesium. The total soluble salts are commonly indexed by the electrical conductivity and TDS of the water. The sodium hazard (when the concentration of sodium far more greater than the concentration of the other major cations affect the structure of the soil by reducing its permeability) is expressed by the sodium adsorption ratio (SAR)

$$SAR = Na^+ / [\sqrt{((Ca^{2+} + Mg^{2+})/2)}] , \text{ where the cations are in units of meq/l.}$$

Sample	SAR	EC (μ S/cm)	Boron(HBO ₃)	HCO ₃ (mg/l)	% Na*
Lake Haiq	2.41	914	< 0.15	508	42
Lake Ardibo	1.58	581	< 0.15	326	37.8
Ankerka river	0.85	550	< 0.15	339	22.8
Spring (CS-1)	0.51	578	< 0.15	333	14.2
Spring (CS-7)	0.77	703	< 0.16	403	18.8
Borhole	0.53	601	0.31	268	14.7

Table 8.4 Water quality for irrigation of representative samples in the study area.

Wilcox (1955) referred by Todd (1980) has classified quality of water for irrigation as shown in table 8.5. Table 8.4 is compared to the quality classification of Wilcox (Table 8.5).

Water class	% Na	EC ($\mu\text{S}/\text{cm}$)	Boron (mg/l)		
			sensitive crops	Semi tolerant crops	Tolerant crops
Excellent	< 20	< 250	< 0.33	< 0.67	< 1
Good	20-40	250-750	0.33-0.67	0.67-1.33	1-2
Permissible	40-60	750-2000	0.67-1	1.33-2	2-3
Doubtful	60-80	2000-3000	1-1.25	2-2.5	3-3.75
Unsuitable	> 80	> 3000	> 1.25	> 2.5	> 3.75

Table 8.5 Wilcox water quality classification for irrigation

Boron , though essential to normal growth of plants, it is toxic under some conditions in concentrations as low as 0.33 mg/l (table 8.5). But, this depends on plant type. The concentration is very low in the study area, below 0.16 except at the bottom of lake Haiq and borehole samples where the concentration reached 0.31 mg/l.

Bicarbonate ions under high concentration may result in precipitation of calcium and magnesium bicarbonates from the soil solution, increasing the relative proportion of sodium and this leads to sodium hazard. In the Haiq-Ardibo catchment, the concentration of both bicarbonate and sodium are relatively high in the lake water but lower in the groundwater. The SAR value is within the low range of sodium hazard, and EC from medium to high salinity.

Generally, the chemical species analyzed shows that , the surface and groundwater bodies are suitable for irrigation. But, Precautions may be needed while using the lake water

specially the terminal lake Haiq for irrigation, since the sodium and EC values are relatively high.

8.8 Water pollution

From the chemical analysis data obtained in the study area, nitrate and sulfate concentrations are found to be much more higher in the spring and borehole samples than in the lakes and river. This shows that there is a potential danger of pollution of the shallow groundwater most likely through agricultural activities. The very small concentration of nitrate and sulfate in the lakes and river water is interpreted in terms of the consumption of these chemicals by living organisms that reside in the water bodies.

Field observation of the Ankerka river shows the growth of algae in its lower course. Elizabeth et al., (1992) have reported eutrophication in lake Haiq and relate the Fish kill to loss of oxygen in the lake. The algal bloom that developed is probably as a result of the addition of nutrients from the catchment by way of high fertilizer utilization.

Chapter 9

CONCLUSIONS AND RECOMMENDATIONS

Geological, hydrological, and hydrogeological studies were conducted in the Haiq-Ardibo lakes catchment, northern Ethiopia. Geological mapping at the scale of 1:50,000 revealed seven distinct phases of volcanic eruptions ranging from acidic to basic in composition. Correlation with the regional stratigraphy sets these volcanic units in the Alaji rhyolites and interbedded basalts of Oligocene age. The major mappable units are fractured rhyolites and ignimbrites, unwelded pyroclastic units, and degraded and weathered basaltic rocks. Three sets of faults trending NNW, E-W, and NNE were mapped. All these sets of faults are widespread and made the area one of the intensively faulted parts of the rift margin.

Annual mean areal precipitation was analyzed for the Haiq-Ardibo catchment and it is estimated to be 1158.8 mm.

Two major hydrostratigraphic units are mapped based on field investigation. These are the quaternary unconsolidated sediments and fractured volcanic units. The former is found to be a good aquifer getting much of its recharge from the volcanics and is also characterized by wide spread springs controlled by topography and faults. The later is classified as poor aquifer due to morphologic setting. But, because of the high fracturing and weathering, the volcanic unit have a good hydraulic properties (secondary porosity, permeability and conductivity) that represent a good zone of recharge.

Groundwater flow direction from field observations is found to be towards the respective lakes locally and towards lake Haiq when observed at the scale of the study catchment.

Open water evaporation and potential evapotranspiration using different methods were done. For open water evaporation, the mean calculated by the method of Radiation, Pan and Penman was taken as 1465.1 mm depth. Potential evaporation calculated by the method of modified Penman was acceptable. The value obtained was 1200 mm depth over the study catchment.

Annual recharge and actual evapotranspiration was estimated using Thornthwaite & Mather (1957) soil-water balance method by dividing the study catchment into Haiq and Ardibo subcatchments. The results obtained were 821.5 mm and 775.6 mm of AET respectively for Haiq and Ardibo subcatchments. The annual groundwater recharge is 47.6 mm for Haiq Subcatchment and 35.4 mm For Ardibo subcatchment. The Weighted mean annual recharge and AET for the entire catchment is 43.2 mm and 805 mm respectively.

Water balance analysis for water bodies and the catchment was done. The result shows the following :

1. For Ardibo subcatchment, the total input computed is 60.6 mcm and output is 54.695 mcm. The residual of the balance is 5.905 mcm representing annual groundwater outflow into the Haiq subcatchment.

2. For lake Ardibo the total annual input is 30.98 mcm and the total annual output 26.3 mcm. The residual of the water balance is estimated to be 4.68 mcm. This residual value represents the difference between groundwater inflow and outflow. The annual groundwater outflow from lake Ardibo into lake Haiq was computed using simple Darcian relation and is estimated to be 3.2 mcm. From this annual groundwater inflow into this lake was estimated to be 1.48 mcm.
3. For Haiq sub catchment a total input of 103.3 mcm and a total output of 86.9 mcm were estimated. A residual of 23.82 mcm which represents the annual groundwater outflow from this catchment.
4. For lake Haiq an annual inflow of 46.83 mcm and a total outflow of 33.4 mcm were estimated. A residual of 13.43 mcm was obtained representing the change in groundwater inflow and outflow.
5. Water balance for the entire study area shows that a total inflow of 162.3 mcm and outflow of 138.4 mcm. A residual of 23.9 mcm was estimated representing the annual groundwater outflow from this catchment.

The bathymetric study shows that both lakes have undergone lake level reduction in the past. The small rise in level that is observed currently on lake Haiq is due to the imported water from lake Ardibo and a cumulative from the small general rise in the trend of rainfall for the last ten years.

Hydrochemical study of surface and groundwater's showed two distinct water types. The river and lakes are magnesium bicarbonate type and the groundwater is calcium bicarbonate type. The chemical analyses further revealed calcium depletion in the lake water and

enrichment in the groundwater. The low concentration of calcium in the lakes is attributed to carbonate precipitation whereas the high concentration in the groundwater may be due to the lithology with which the groundwater interacted.

The TDS of both surface and groundwaters is below 800 ml/l implying water in the catchment is fresh. Furthermore, the chemical quality of the lake and groundwaters satisfy the drinking water guideline of WHO (1984). Ground and surface waters also have permissible amounts of EC, SAR and boron. Consequently, it can be used for irrigation safely.

Based on the present study the following recommendations are given:

- ◆ Stable isotope mass balance techniques will be needed to separate the residual (net flux) in the water balance of the lakes into groundwater inflow and outflow.
- ◆ Further numerical modeling is important to understand the subsurface hydraulic connection between the two lakes and estimate the different fluxes.
- ◆ While planning development projects on these lakes, the impact of different abstraction scenarios on the water balance components should be analyzed before implementation.
- ◆ Nitrate and sulfate in the groundwater are high, indicating potential pollution. It is, therefore, important to minimize the sources of these pollutants.
- ◆ A potential alkali (sodium) and salinity hazard is expected while utilizing lake Haiq for irrigation. Therefore, further soil study is recommended before applying this water to crops.

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Annex. 1 Haiq station mentholy pan evaporation

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1985	123.4	116	122	121.8	127	124	125.4	124	121	129	123	125
1986	125.63	106	126	122	130	122	124.7	127	120	127	129	121
1987	128.56	109	118	115	123	131	125.5	126	123	127	122	125
1988	118.22	98	112	107	125	116	98.83	85.6	101	110	113	116
1989	120.92	102	105	98.3	113	116	115.9	103	115	119	116	116
1990	120.01	100	116	106.6	123	117	111.9	116	113	113	121	129
1991	146.02	130	147	140.7	135	146	141.7	127	129	146	152	154

Annex 2. Mean monthly rainfall data for the stations around the study area.

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Komb	30.36	43	76.4	95.5	60.1	31.7	263.6	249	123	27	19	17	1045
Dessie	26	38	80.1	95.2	77.8	40.1	285.3	293	151	51	25	20	1183
Wucha	48.5	55	107	116	98.4	36.5	252.8	283	110	62	37	33	1239
Bati	38.6	51	59.1	86.2	56.3	19	187	200	81	30	28	30	867
Haiq	31.5	71	104	113	81.6	31.6	261.5	262	118	47	21	24	1167
Ourg	64.8	82	127	164	89.3	42.6	291.8	318	122	63	40	42	1445

3.1 Relevant meteorological data summary

	Jan	Feb.	Mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec	
Va(km/day)	84.67	92	107	92.4	89	97.6	89.86	79.5	121	65	72	80	89.1 Mean annual wind speed in km/day
Ta	15.65	17	18.2	19.1	19.7	21.1	20.4	19.7	18.8	17	16	15	18.1 mean annual temperature
Ts	18.62	17	18.4	21.3	23	22.4	21.42	20.2	21.6	22	22	21	20.7 Surface temperature
Wa	0.707	0.7	0.72	0.72	0.71	0.67	0.681	0.72	0.7	0.7	0.7	0.6	0.69 Mean annual Relative humidity
N	11.6	12	12	12.3	12.6	12.7	12.6	12.4	12.1	12	12	12	Mean daily maximum possible sunshine hours
Sun.Hr.	7.4	7.1	6.8	6.9	7.9	6.3	5.1	5.7	5.8	7.8	8.5	8.1	6.95 Measured mean daily sunshine hours
C	0.383	0.4	0.43	0.43	0.34	0.48	0.575	0.53	0.52	0.4	0.3	0.3	Fraction of cloud cover
n/N	0.6379	0.6	0.57	0.561	0.63	0.5	0.405	0.46	0.48	0.7	0.7	0.7	
Kcs	755	820	870	895	885	870	870	855	880	830	770	730	Clear sky solar radiation at the top of the atmosphere
Kin	481	496	534	508	510	394	331.4	366	403	601	582	539	Measured incoming solar radiation (Addis Ababa)
(measured													
P	788.33	788	788	788.3	788	788	788.3	788	788	788	788	788	pressure in mb.
No of days	31	28	31	30	31	30	31	31	30	31	30	31	Number of days in a month
Z	2100	2100	2100	2100	2100	2100	2100	2100	2100	2100	##	2100	Mean altitude of the area
win(m/s)	0.98	1.1	1.24	1.07	1.03	1.13	1.04	0.92	1.4	0.8	0.8	0.9	Wind speed in m/s
Win(mil)	52.41	57	66.4	57.31	55.2	60.5	55.71	49.3	75	40	44	51	Wind speed in miles
Ta(F)	60.17	62	64.8	66.29	67.4	70	68.72	67.4	65.8	63	60	59	Mean monthly temperature in(F)
E pan	128.7	112	120	116	125	125	120.6	116	117	124	125	127	1456 Mean monthly pan evaporation

Annex 3.2 Evaporation computation summary

Io	755	820	870	895	885	870	870	885	880	830	770	730	Clear sky solar radiation for 10dg N .
C	4.2	4.7	5.2	5.4	4.7	6.4	7.5	6.7	6.3	4	3.1	3.4	Mean cloud cover
CF	0.3621	0.4	0.43	0.439	0.37	0.5	0.595	0.54	0.52	0.3	0.3	0.3	Fraction of cloud cover
Qs	467.99	488	496	506.1	542	448	381.4	430	442	527	523	484	
Qrs	28.079	29	29.7	30.36	32.5	26.9	22.88	25.8	26.5	32	31	29	
Qlw	151.15	143	128	123.8	135	111	95.14	104	112	157	174	174	
es(Ts)	21.512	19	21.2	25.45	28.2	27.1	25.59	23.8	25.9	26	26	25	
ea(Ta)	17.819	19	21	22.1	22.9	25.1	24.03	22.9	21.8	19	18	17	
ed	12.598	13	15	15.96	16.4	16.7	16.37	16.5	15.2	13	12	11	
R(BOWEN)	0.1602	-0	0.01	0.115	0.14	0.06	0.053	0.04	0.13	0.2	0.2	0.2	
Eo	127.3	148	170	155	168	144	127	147	133	147	130	119	1714 Openwater evaporation(energy balan)
Eo Penman	112.3	114	137	138	153	133	116.3	125	125	133	119	111	1516 openwater evaporation (combination)
A(LA)	15.8	16	15.8	15.8	15.8	15.8	15.8	15.8	15.8	16	16	16	15.8 Area of lake Ardibo
A(LH)	22.8	23	22.8	22.8	22.8	22.8	22.8	22.8	22.8	23	23	23	22.8 Area of lake Haiq
Eo HA	33.82	22	29.8	38.06	47.1	44	37.14	26	56.3	38	43	49	465 Lake Haiq
Eo LA	34.45	22	30.4	38.8	47.9	44.8	37.83	26.4	57.4	39	44	50	473 L Ardibo

Annex 3.3 Computation of Evapotranspiration using modified Penman

Ea	0.1386	0.2	0.18	0.171	0.18	0.24	0.21	0.17	0.21	0.2	0.1	0.2	
H	0.4894	0.5	0.57	0.596	0.64	0.53	0.446	0.51	0.51	0.6	0.5	0.5	
S(TA)/Y	1.7561	1.9	2.04	2.148	2.23	2.43	2.326	2.23	2.12	1.9	1.8	1.7	
Y	0.66	0.7	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.7	0.7	0.7	
U2	84.672	92	107	92.45	89	97.6	89.86	79.5	121	65	72	80	
Ht	0.3704	0.4	0.45	0.468	0.5	0.41	0.349	0.4	0.4	0.4	0.4	0.4	
Ea	0.1386	0.2	0.18	0.171	0.18	0.24	0.21	0.17	0.21	0.2	0.1	0.2	
Et	88.76	91	111	112	124	108	95.31	101	102	106	93	87	1220 Potential Evapotranspiration

Annex 4. Values of runoff coefficient for peak rates of runoff with rational formula (after Tripathi & Singh, 1993).

Soil condition	Land use		
	Cultivated	Pasture	Forest
General			
Soil with above average infiltration rates, usually sand or gravel*	0.29	0.15	0.1
Soil with average infiltration rates, no clay pans, loam and similar soils	0.4	0.35	0.3
Soil with below average infiltration rates, fine clays or soils with clay pan near the surface, shallow soils above impervious rock	0.5	0.45	0.4
Culturable land up to 4% slope	0.5	-	-
Rolling topography (5-10%) slope**	0.6	0.36	0.18
Hilly land (10-30% slope)**	0.72	0.42	0.21
Agricultural small water watersheds with bench terrace	0.22 (0.18-0.25)	-	-
Forest watersheds	-	-	0.25 (0.22-0.28)
Soil texture and slopes			
Sandy loam			
0-5%	0.3	0.1	0.1
5-10%	0.4	0.16	0.25
10-30%	0.52	0.22	0.3
Clay and silt loam			
0-5%	0.5	0.3	0.3
5-10%	0.6	0.36	0.35
10-30%	0.72	0.42	0.5
stiff clay			
0-5%	0.6	0.4	0.46
5-10%	0.7	0.55	0.5
10-30%	0.82	0.6	0.6

Annex 5.1 Computation of AET using Thornthwaite and Mather soil water balance method for Haiq subcatchment. Soil type is clay loam.

Vegetation's are cereals maize and related moderately deep-rooted crops. The maximum available soil moisture capacity is 200 mm.

Months	Jan.	Feb.	Mar.	April	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Year
P_m	24.2	45.6	72.8	81.4	59.9	25	197.8	199.9	91.6	35.9	17.5	17.5	869.1
PET	88.8	91.2	111.2	112	123.6	108.4	95.3	101.4	102.3	105.7	93.3	86.8	1220
P-PET	-64.6	-45.6	-38.4	-30.6	-63.7	-83.4	102.5	98.5	-107	-69.8	-75.8	-69.3	
S_m	46.8	37.2	30.7	26.3	19.1	12.6	115.1	200	189.6	133.7	91.5	64.7	
ΔS	-17.9	-9.6	-6.5	-4.4	-7.2	-6.5	102.5	84.9	-10.4	-55.9	-42.2	-26.8	
AET	42.1	55.2	79.3	85.5	67.1	31.5	95.3	101.4	102	91.8	59.7	44.3	855.5
Def	46.7	36	31.9	26.2	56.5	76.9	0	0	0.3	13.9	33.6	42.5	364.5
Sur	0	0	0	0	0	0	0	13.6	0	0	0	0	13.6

P_m = effective monthly rainfall found from the total monthly rainfall by subtracting the runoff.

PET = Potential evapotranspiration

S_m = Soil moisture

ΔS = Change in soil moisture storage

AET = Actual evapotranspiration

Def = Deficit

Sur = Surplus moisture

Annex 5.2 Haiq subcatchment computation of AET for a fine sandy loam soil, vegetation cover cereals, and shrubs pasture grass having a rooting depth of 1m. Available water at the root zone = 150 mm.

Months	Jan.	Feb.	Mar.	April	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Year
P _m	24.2	45.6	72.8	81.4	59.9	25	197.8	199.9	91.6	35.9	17.5	17.5	869.1
PET	88.8	91.2	111.2	112	123.6	108.4	95.3	101.4	102.3	105.7	93.3	86.8	1220
P-PET	-64.6	-45.6	-38.4	-30.6	-63.7	-83.4	102.5	98.5	-107	-69.8	-75.8	-69.3	
S _m	21.6	15.9	12.3	10	6.5	3.7	106.2	150	139.7	87.7	52.9	33.3	
ΔS _m	-11.7	-5.7	-3.6	-2.3	-3.5	-2.8	102.5	43.8	10.3	-52	34.8	-19.6	
AET	35.9	51.3	76.4	83.7	63.4	27.8	95.3	101.4	101.9	87.9	52.3	37.1	814.4
Def	52.9	39.9	34.8	28.3	60.2	80.6	0	0	0.4	17.8	41	49.7	405.6
Sur	0	0	0	0	0	0	0	54.7	0	0	0	0	54.7

Annex 5.3 Haiq subcatchment computation of AET for a fine sandy soil having vegetation with a rooting depth of 1m. (Pasture grass and shrubs). Available moisture at the root zone is 100 mm.

Months	Jan.	Feb.	Mar.	April	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Year
P _m	24.2	45.6	72.8	81.4	59.9	25	197.8	199.9	91.6	35.9	17.5	17.5	869.1
PET	88.8	91.2	111.2	112	123.6	108.4	95.3	101.4	102.3	105.7	93.3	86.8	1220
P-PET	-64.6	-45.6	-38.4	-30.6	-63.7	-83.4	102.5	98.5	-107	-69.8	-75.8	-69.3	
S _m	5.5	3.5	2.4	1.8	1	0.4	100	100	89.8	44.7	20.9	10.5	
ΔS _m	-5	-2	-11	-0.6	-0.8	-0.6	99.6	0	-10.2	-45.1	-23.8	-10.4	
AET	29.2	47.6	73.9	82	60.7	25.6	95.3	101.4	101.8	81	41.3	27.9	767.7
Def	59.6	43.6	37.3	30	62.9	82.8	0	0	0.5	24.7	52	58.9	452.3
Sur	0	0	0	0	0	0	2.9	98.5	0	0	0	0	101.4

Annex 5.4 Ardibo subcatchment computation of AET and surplus moisture for a clay loam soil and vegetation cover of corn, cereals and related crops. Rooting depth 0.8m and available water capacity of the root zone is 200 mm.

Months	Jan.	Feb.	Mar.	April	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Year
P _m	22.2	42.6	67.9	76	55.9	23.3	184.6	186.6	85.5	33.5	16.3	16.3	811
PET	88.8	91.2	111.2	112	123.6	108.4	95.3	101.4	102.3	105.7	93.3	86.8	1220
P-PET	-66.3	-48.6	-43.3	-36	-67.7	-85.1	89.3	85.2	-16.8	-72.2	-77	-70.5	
S _m	40.6	31.8	25.6	21.4	15.3	10	99.3	184.5	169.6	118.2	80.4	56.5	
ΔS _m	-15.9	-8.8	-6.2	-4.2	-6.1	-5.3	89.3	85.2	-14.9	-51.4	-37.8	-23.9	
AET	38.4	51.4	74.1	80.2	62	28.6	95.3	101.4	100.4	84.9	54.1	40.2	811
Def	50.4	39.8	37.1	31.8	61.6	79.8	0	0	1.9	20.8	39.2	46.6	409
Sur	0	0	0	0	0	0	0	0	0	0	0	0	-

Annex 5.5 Ardibo subcatchment computation of AET for the sand loam soil type and cereal crops and shrubs having a rooting depth of 1m.
Available water capacity of the root zone is 150 mm.

Months	Jan.	Feb.	Mar.	April	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Year
P _m	22.2	42.6	67.9	76	55.9	23.3	184.6	186.6	85.5	33.5	16.3	16.3	811
PET	88.8	91.2	111.2	112	123.6	108.4	95.3	101.4	102.3	105.7	93.3	86.8	1220
P-PET	-66.3	-48.6	-43.3	-36	-67.7	-85.1	89.3	85.2	-16.8	-72.2	-77	-70.5	
S _m	19.9	14.4	10.8	8.5	5.4	3.1	92.4	100	134.1	82.9	49.6	31.0	
ΔS	-11.1	-5.5	-3.6	-2.3	-3.1	-2.3	89.3	10.4	-15.9	-51.2	-33.3	-18.6	
AET	33.6	48.1	71.5	78.3	59	25.6	95.3	101.4	101.4	84.7	49.6	34.9	783.4
Def	55.2	43.1	39.7	33.7	64.6	82.8	0	0	0.9	21	43.7	51.9	436.6
Sur	0	0	0	0	0	0	0	27.6	0	0	0	0	27.6

Annex 5.6 Ardibo subcatchment computation of AET for the sandy soil with shrub and grass vegetation having a rooting depth of 1m, available soil moisture in the root zone is 100 mm.

Months	Jan.	Feb.	Mar.	April	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Year
P _m	22.2	42.6	67.9	76	55.9	23.3	184.6	186.6	85.5	33.5	16.3	16.3	811
PET	88.8	91.2	111.2	112	123.6	108.4	95.3	101.4	102.3	105.7	93.3	86.8	1220
P-PET	-66.3	-48.6	-43.3	-36	-67.7	-85.1	89.3	85.2	-16.8	-72.2	-77	-70.5	
S _m	4.8	2.9	1.9	134	0.7	0.3	89.6	100	84.5	41.0	19	9.4	
ΔS _m	-4.6	-1.9	-1	-0.6	-0.6	-0.4	89.3	10.4	-15.5	-43.5	-22	-9.6	
AET	27.1	44.5	68.9	76.6	56.5	23.7	95.3	101.4	101	77	38.3	25.9	736.2
Deficit	61.7	46.7	42.3	34.4	67.1	84.7	0	0	1.3	28.7	55	60.9	482.8
Surplus	0	0	0	0	0	0	0	74.8	0	0	0	0	74.8

Annex. 6 Spring data in the studied catchment

Spring	Local Name	Location (UTM)	Date of visit	T (C)	EC)pH (miS/cm	pH	mode of emergenc	eye	Rock type	Topography	Perennial/ Seasonal	Meinzer Scale	Discharge (l/s)
Cs-1	Mariam Woha	1251188N 576108 E	25/05/92	22.2	588	7.2	slope break	multiple	collivial deposit	gentle	Perennial	sixth	0.75
Cs-2	Abakundal	1250697 N 536362 E	25/05/92	23.1	415	7.2	slope break	single	collivial deposit	gentle	Perennial	sixth	0.5
Cs-3	Ulaula	1249573N 577475 E	25/05/92	23	481	7.4	fault controlled	single	collivial deposit	gentle	Perennial	fifth	2
Cs-4	Tigo	1251200N 578100E	25/05/92	25.4	586	7.3	fault controlled	single	rhyolite, ignimbrite	foot hill	Perennial	fifth	4
Cs-5	Chereti	1246930N 570550E	25/05/92	22.6	562	7.9	slope break	multiple	weathered basalt	foot hill	Perennial	fifth	2
Cs-6	Cheffe	1251143N 575392E	25/05/92	19.7	515	8.5	slope break	multiple	collivial deposit	gentle	Perennial	sixth	0.75
Cs-7	Abaduba-Cheffe	1254597N 574335E	26/05/92	24.4	616	7.4	fault controlled	multiple	collivial deposit	gentle	Perennial	fifth	2.5
Cs-8	Atomotie	1253065N 574322E	26/05/92	28.9	659	7.1	fault controlled	multiple	collivial deposit	flat	Perennial	sixth	0.25
Cs-9	Bedesso	1253194N 574288E	26/05/92	26.5	656	7.7	fault controlled	multiple	collivial deposit	flat	Perennial	sixth	0.5
Cs-10	Shollow	1248831N 579768E	30/05/92	-	-	-	contact	multiple	unwelded acidic unit	moderately steep	Perennial	sixth	0.25

Annex 6. Continued

Cs-11	Aelaw	1249500N 583700E	27/05/92	-	-	-	fault controlled	multiple	colluvial deposit	gentle	Perennial	sixth	1
Cs-12	Chegello	1248300N 584100E	27/05/92	-	-	-	fault controlled	multiple	colluvial deposit	gentle	Perennial	sixth	0.5
Cs-13	Cherit	1248000N 584000E	27/05/92	-	-	-	fault controlled	multiple	colluvial deposit	gentle	Perennial	sixth	0.5
Cs-14	Godguade	1247700N 584400E	27/05/92	-	-	-	fault controlled	multiple	colluvial deposit	gentle	Perennial	sixth	0.25
Cs-15	Wurebilie	1247350N 584400E	27/05/92	-	-	-	fault controlled	multiple	colluvial deposit	gentle	Perennial	sixth	1
Cs-16	Chomoch	1247100N 585000E	27/05/92	-	-	-	fault controlled	multiple	colluvial deposit	gentle	Perennial	sixth	1
Cs-17	Mumie	1246800N 584700E	27/05/92	-	-	-	fault controlled	multiple	colluvial deposit	flat	Perennial	fifth	3
Cs-18	Atekulfee	1246200N 584100E	27/05/92	-	-	-	fault controlled	multiple	alluvial	flat	Perennial	fifth	3
Cs-19	Abeku	1246100N 584850E	27/05/92	-	-	-	fault controlled	multiple	colluvial	gentle	Perennial	sixth	0.5
Cs-20	Hedo	1243608N 586779E	27/05/92	-	-	-	contact	multiple	weathered basalt	moderately steep	Perennial	sixth	0.75

Annex 6. continued

Cs-21	Sokawonz	1244200N 581050E	28/05/92	-	-	-	slope break	multiple	weathered basalt	gentle	Permian	fifth	2.5
Cs-22	Folekie	1243900N 581900E	28/05/92	-	-	-	slope break	multiple	weathered basalt	gentle	Permian	fifth	2
Cs-23	Ababissa Ager	1241900N 581500E	28/05/92	-	-	-	slope break	multiple	colluvial deposit	gentle	Permian	fifth	3
Cs-24	Zawya(Yaber awoha)	1247900N 580900E	28/05/92	-	-	-	slope break	multiple	colluvial deposit	gentle	Permian	fifth	1
Cs-25	Cheffe	1251800N 581200E	28/05/92	-	-	-	fault	multiple	rhyolite ignimbrite	gentle	Permian	fifth	2
Cs-26	Bishangura	1251850N 581280E	28/05/92	-	-	-	fault controlled	multiple	rhyolite ignimbrite	steep	Permian	sixth	0.5
Cs-27	Melequsit	1252000N 581290E	28/05/92	-	-	-	fault controlled	multiple	rhyolite ignimbrite	steep	Permian	sixth	0.25
Cs-28	Kebena	1251900N 581200E	28/05/92	-	-	-	fault controlled	multiple	rhyolite ignimbrite	steep	Permian	sixth	0.25

Annex .7 Hydrochemical data

	EC	pH	CO3	HCO3	Cl	SO4	F	NO3	Na	K	Ca	Mg	HBO3	SiO2	Ba	Li	Sr	Fe	Mn	Zn	Cr
Samples	mi.S/cm		Mg/l	Mg/l	Mg/l	Mg/l	Mg/l	Mg/l	Mg/l	Mg/l	Mg/l	Mg/l	Mg/l	Mg/L	Mg/l	Mg/l	Mg/l	Mg/l	Mg/l	Mg/l	Mg/l
LH-1	914	8.9	41	508	50	1.9	1	2.38	98	11	20	64	<0.15	7	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
LH-2	920	8.8	31	508	50	2.1	0.99	2.43	96	10	16	62	0.31	7	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
LA-1	581	8.6	20	326	29	< 0.4	0.5	0.92	50	5.3	17	36	<0.15	5	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
LA-2	579	8.4	7	346	29	1.2	0.48	0.92	48	5.3	20	41	<0.15	5	<0.1	<0.1	<0.1	<0.1	<0.1	0.1	<0.1
Remark			LH (lake Haiq)					LA(lake Ardibo)													
AC-1	581	8.2		371	30	<0.4	0.62	1.12	50	5.2	23	45	<0.16	3	<0.1	<0.1	0.1	<0.1	<0.1	<0.1	<0.1
RS-2	613	8.1		373	30	0.4	0.48	0.65	50	5	23	38	<0.15	5	<0.1	<0.1	0.2	<0.1	<0.1	<0.1	<0.1
RS-3	560	8.5	10	327	29	0.8	0.58	0.68	50	4.1	22	40	<0.16	7	<0.1	<0.1	0.2	<0.1	<0.1	<0.1	<0.1
RS-4	550	8.3		339	26	2.9	0.38	0.26	29	2.3	50	24	<0.15	25	<0.1	<0.1	0.2	<0.1	<0.1	<0.1	<0.1
Remark			RS(Ankerka river)																		
CS-1	578	7.5		333	17	10	0.37	38.3	19.6	2.4	74	22	<0.16	61	<0.1	<0.1	0.1	<0.1	<0.1	<0.1	<0.1
CS-2	417	7.4		257	11	9	0.35	17.6	12.8	1.2	59	16	0.16	53	<0.1	<0.1	0.1	<0.1	<0.1	<0.1	<0.1
CS-3	513	7.5		272	18	11	0.33	33.2	18.5	1.9	69	16	<0.16	61	<0.1	<0.1	0.1	<0.1	<0.1	<0.1	<0.1
CS-4	606	7.5		365	15	9	0.52	17.4	25	1.2	78	23	<0.16	52	<0.1	<0.1	0.1	<0.1	<0.1	<0.1	<0.1
CS-5	596	7.9		293	28	16	0.26	47	16.3	1.8	76	24	<0.16	62	<0.1	<0.1	0.1	<0.1	<0.1	<0.1	<0.1
CS-6	619	7.6		320	23	19	0.54	40.7	34	2.6	76	18	<0.16	56	<0.1	<0.1	0.1	<0.1	<0.1	<0.1	<0.1
CS-7	703	7.9		403	20	17	0.45	36.1	30	1.6	82	21	<0.15	57	<0.1	<0.1	0.3	<0.1	<0.1	<0.1	<0.1
BH-1	601	7.7		368	13	5	0.26	17.6	20	2.2	68	24	0.31	51	<0.1	<0.1	0.3	<0.1	<0.1	0.2	<0.1
Remark			CS (cold spring samples)																		
			BH(borehole sample)																		

Annex 8.1 Lake Ardibo Bathymetric data

X	Y	Z	X	Y	Z
1246326	582533	0.9	1243800	582249	23.1
1246344	582679	0.92	1243782	582467	34.5
1246399	582624	1.77	1243838	582758	45.7
1246147	582497	1.14	1243820	582776	47.22
1246122	582443	1.44	1243839	583031	53.26
1246178	582388	1.4	1243821	583213	52.07
1246122	582424	1.44	1243914	583485	50.3
1246141	582479	3	1244118	583939	35.8
1246215	582533	2.76	1244284	584248	5.5
1246289	582643	1.9	1244248	584321	1.75
1246271	582733	1.5	1244377	584357	0.9
1246252	582715	1.12	1245167	583500	8.16
1246160	582642	5.42	1245038	583555	9.3
1246172	582588	6.93	1244946	583664	2.06
1246030	582425	4.6	1244950	583828	3.6
1245956	582388	1.35	1244966	584137	1.25
1245864	582316	1.48	1244762	583865	15.24
1245901	582443	5.4	1244596	583556	35.1
1246049	582570	8.23	1244337	583320	45.2
1246142	582733	6.9	1244263	583103	47.4
1246179	582824	1.5	1244059	582775	43.9
1246105	582843	5.45	1243874	582339	27.15
1246068	582861	2.66	1243707	582085	12.63
1245994	582843	7.72	1243670	582030	2
1245957	582643	10.65	1243504	582031	2.44
1245809	582552	12.28	1243394	582195	1.54
1245698	582389	4.18	1243358	582322	16.2
1245569	582226	1.85	1243322	582595	32.83
1245421	582135	1.5	1243304	582777	43.27
1245255	582117	1.4	1243249	583087	52.09
1245274	582190	5	1243213	583342	56.54
1245293	582299	11.05	1243241	583542	56.73
1245330	582481	20.57	1243196	583706	56.72
1245386	582608	24.19	1243196	584069	54.9
1245478	582790	28.69	1243234	584415	36.6
1245516	583008	22.1	1243216	584524	4.05
1245535	583208	1.15	1243087	584543	4.16
1243618	583268	2.82	1242977	584634	7.16
1245332	583336	3.63	1242774	584507	41.37
1245055	583118	37.05	1242497	584326	53.83
1244797	582883	39.5	1242367	584072	59.13
1244409	582574	3203	1242164	583836	61.84
1244224	582266	17.4	1241960	583545	59.8
1244131	582138	5.85	1241831	583236	45.34
1244076	582084	1.7	1241663	582691	23.11
1243855	581994	1.66	1241709	582490	5.77
1243818	582067	5.95	1241710	583073	1.64

Annex 8.2 Lake Haiq Bathymetric data

X	Y	Z	X	Y	Z
1254021	576085	18.66	1253719	576621	41.72
1254678	576664	66.59	1253995	576529	61.46
1255534	577125	76.98	1254511	576474	71.35
1255627	577105	76.68	1254787	576291	78.72
1252150	575170	6.4	1255082	576345	80.05
1253868	577075	74.7	1255598	576362	81
1254053	577621	75.18	1256132	576342	79.84
1254239	578202	64.86	1256648	576250	66.1
1254068	578803	49.43	1257035	576231	40.72
1254574	579492	29.3	1257256	576176	18.22
1254722	579911	17.45	1257256	575994	10
1254741	580238	7.35	1256960	575813	14.2
1254281	580203	6.9	1256757	575704	32
1253949	580221	2.1	1256315	575687	47.58
1253931	580204	3	1255799	575780	34.47
1254059	579967	16.6	1255339	575835	55.36
1254372	579839	22.05	1254675	575909	59.62
1254722	579729	19.95	1253847	576202	43.1
1254943	579619	30	1253479	576294	18
1255256	579546	35.64	1253147	576513	32.8
1255643	579526	20.08	1252779	576751	61.98
1255808	578417	10.3	1252135	577134	52.76
1255881	579053	23.16	1251749	577426	37.62
1256083	578852	15.3	1251344	577682	19.85
1256268	578852	4.13	1251179	577791	5.2
1256321	578252	16.77	1251123	577537	10
1256248	578561	17.34	1251361	577027	8.37
1256616	578105	15.64	1251618	576444	24.47
1256670	577614	15.28	1251856	576098	37.6
1256707	577487	21.5	1252224	575824	33.55
1258040	577738	48.65	1252555	575551	33.05
1255639	578090	71.28	1252795	575423	19.63
1255179	578273	69	1252776	575259	5.84
1254627	578529	64.5	1252610	575223	6
1253982	578657	53.65	1252517	575114	9.33
1253300	578823	33.66	1252407	574987	3
1252767	579394	7.15			
1252655	578788	3.8			
1252489	578388	5.32			
1252304	578189	7.32			
1252487	577824	39.9			
1252928	577351	63.73			
1253314	576822	64.3			
1253627	576512	37.1			
1253183	576150	12.7			
1252888	575878	39.89			
1252500	575496	31.42			
1252241	575133	9			