HYDROLOGICAL AND HYDROGEOLOGICAL STUDY ON THE KULFO RIVER BASIN

A THESIS SUBMITTED TO THE
SCHOOL OF GRADUATE STUDIES
ADDIS ABABA UNIVERSITY

IN PARTIAL FULFILMENT
OF THE REQUIREMENTS FOR
THE DEGREE OF MASTER OF
SCIENCE IN GEOLOGY

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JUNE 1996

TO MY MOTHER

ACKNOWLEDGMENTS

I would like to express my sincere gratitude to my advisor Professor Peter Jeschofnig for his relentless supervision, guidance and unreserved comments in the preparation of this dissertation.

I extend my thanks to my previous advisor Prof. Antonio Vernier and I also thank Prof. Giulio Barbieri and Dr. Admasu Gebeyehu for their comments.

The writer wishes to thank the Ministry of Water Resource and the National Meterological Agency for providing me the necessary data of the study area. My thanks also go to Arbaminch water Technology Institute, Department of Geology and Geophysics of AAU and the staff for their support when I was following the course of this work. Special thanks go to Ato Paulos Gemechu for facilitating the stay in the field.

I am indebted to Ato Dessie Nedaw, W/t Aynalem Ali, Ato Seifu Kebede, Ato Asfawossen Asrat and Ato Dagnachew Legesse, for their comments and suggestion. Appreciation is also extended to Ato Ahmed Mustefa for the printing of this manuscript.

I would like to express my heartfelt appreciation to my friends and colleagues for their persistent encouragement throughout the preparation of this work. Some of them are Ato Asrat Sewit, W/t Tsige G/Mariam, Ato Yared Addis, W/t Selamawit Alem, Ato Asfaw Mirga, Ato Tilahun Aklog, Ato Binyam W/Mariam, Ato Kinfu Seyoum, Ato Senetebeb Gashu and Ato Tekabe Neway.

Last but not least, I express my thanks to my family for the advise and encouragement

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ABSTRACT

The study area, the Kulfo River basin, is located 500 km south of Addis Ababa. It is bounded on the basis of the surface divide of the Kulfo River. The area is composed of part of the rift floor and part of the western escarpment. More than 85% of the area is underlain by Oligocene basalt and the lowland areas by alluvium and Quaternary basalt.

Using three meteorological stations, the weighted mean annual rainfall of 1232 mm was computed by using the Thiessen Polygon method. The Thornthwaite method was applied to calculate the potential and actual evapotranspiration of the area , which are 971 mm and 940 mm, respectively. From the above data, the surplus water was obtained, which is 291 mm. The mean annual runoff depth of the Kulfo river is 361 mm which is less than the calculated surplus water. The reason might be that there is an inflow of groundwater from an adjacent basin.

Concerning the aquifer characterstics of the different rock units, the alluvium is more productive than the other rock units. One representative well from AWTI was taken to calcualte the hydraulic parameters of this unit.

Using the discharge data from Arbaminch Springs, the general hydrological conditions of the springs were computed. This includes the computation of the recession constants and the recession curve for the springs. The hydraulic volume which feeds the springs instant by instant were also computed. The study of the chemistry of the springs was based on data from WSSA's Arbaminch water supply project. This study confirms that the quality of the water is suitable for drinking and agricultural purposes according to international standards. However, the presence of E. coli bacteria indicates that the water needs to be chlorinated on a regular basis.

CHAPTER ONE

Introduction

1.1. Purpose of the study

The increase in population and the advancement of technology are associated with an increasing demand of water in the world. Protecting the surface and ground water from pollution, and the wise utilization of water are among the different elements which might help reduce the high demand of water in the world. Water is such an important resource that it needs detailed scientific research in all regions of the world.

In Ethiopia, several Masters' theses dealing with water problems of various regions of the country have been produced in recent years. The Arbaminch area is an important area of the Ethiopia which is experiencing tremendous population growth and whose water resources have not been formally studied.

Therefore, the purpose of this study is to analyze the water resources of this region from a geological, hydrological, chemical, and biochemical point of view. The Arbaminch springs, the Kulfo river and the ground water around the Kulfo river basin are some of the water resources in the study area. The water from these sources is used for drinking, agricultural and industrial purposes.

More than 95% of the Arbaminch town's water supply comes from a series of springs at the east edge of the town. (The name Arbaminch means forty springs in Amharic). The spring water is piped from the foot of the escarpment to the town, where it is used for all municipal purposes, including drinking water and industrial uses. Although at present the supply of spring water is adequate for the town's needs, in the near future the demand for water is expected to increase due to population growth and industrialization. Additional water, about 5%, is provided by the Kulfo river, as well as a few water wells which utilize the local ground water aquifer.

The main goal of the research is, therefore, to carry out a detailed investigation of the hydrogeological conditions of the Arbaminch springs and the water balance of the whole basin. Specifically, the objectives of the study include:

1. to identify the type of springs,
2. to determine the spring hydrogeology,
3. to identify the type of aquifers,
4. to analyze the different hydrologic parameters of the aquifers,
5. to analyze the water-budget of the basin,
6. to study the chemical and biochemical quality of the waters.

1.2. Location

The study area is located 360 km linear distance, south west of Addis Ababa, on the western side of the Rift Valley escarpment, near Lake Abaya and Lake Chamo. Its geographical coordinates are $5^0$56'N, 6^0 16'N latitude, and 37^0 18'E, $37^0$36'E longitude (see Fig 1 & 2). The study encompasses the watershed of the Kulfo River, and has an area of 439 km^2 and a perimeter of 115 km. The elevations range from about 3500 m above sea level (a.s.l.) to 1120 m a.s.l

The town of Arbaminch , the capital of North Omo Zone, is situated within the catchment area under investigation. It is connected to Addis Ababa via the town of Shashemene by a 505 km all-weather road, of which 390 km are asphalted.

1.3. Socio-economic conditions

According to the 1994 census made by Kebeles, the population of the town of Arbaminch is around 45,000, while the population of the rural areas within the basin is around 55,000. The average population density is 200 persons per square kilometer (WBISPP, 1995). The main ethnic groups in the area are the Gamo, with sub-groups being the Ocholo and the Genta. However, like the majority of towns in Ethiopia, the ethnic composition of Arbaminch town is heterogeneous. Gamo,

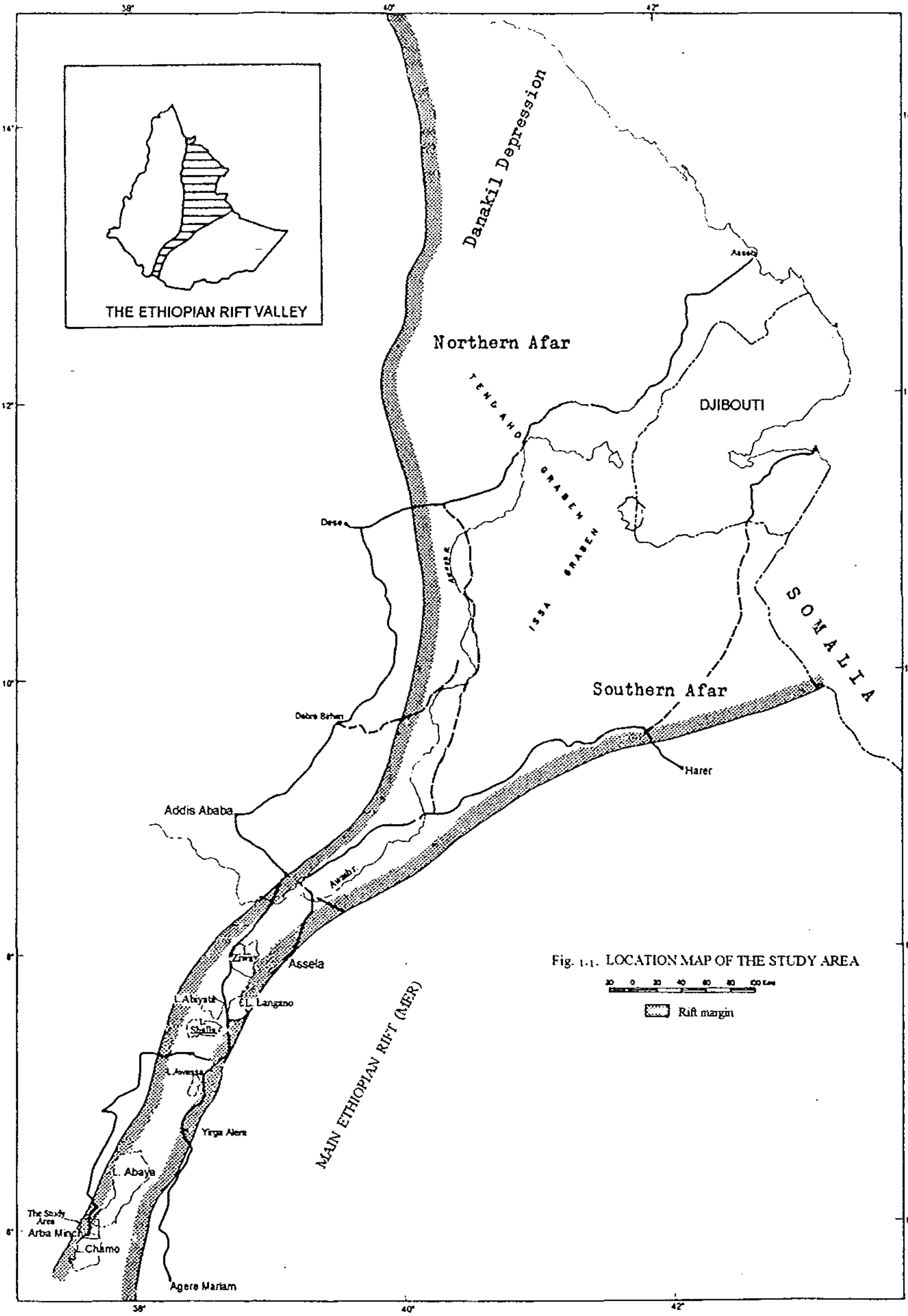


Fig. 1.1. LOCATION MAP OF THE STUDY AREA

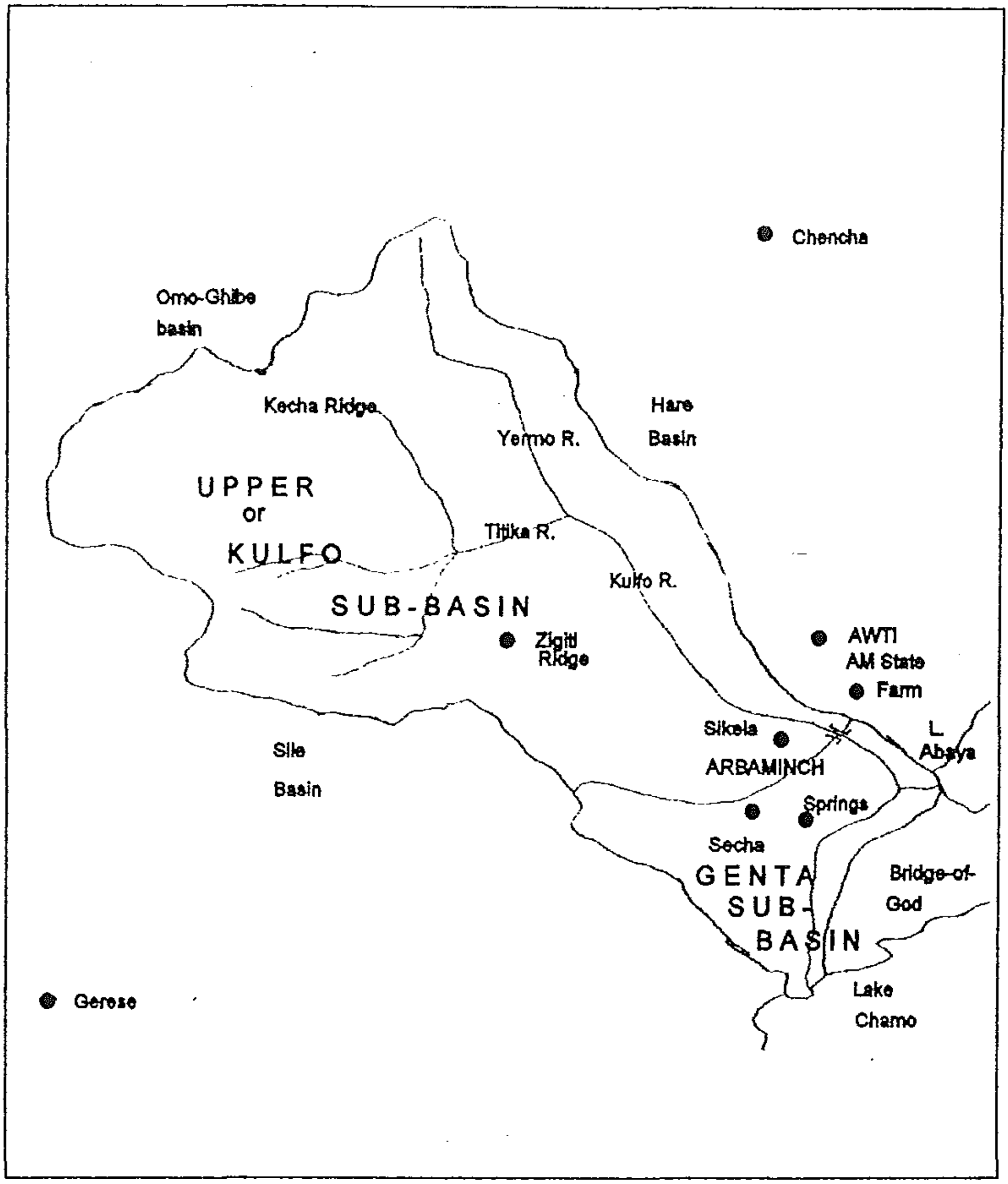


Figure 2: Map of the Study Area

Walayta, Amhara and Konso are the dominant ethnic groups in town.

The socio-economic background of the area is based mainly on subsistence agriculture, while livestock breeding, fishery, trade, and low level industrial activities are practiced at a low level of intensity. Enset is the dominant food plant found in most of the highland areas. Enset agriculture is based on natural rainfall only. Cereals like barley, wheat, and teff are of secondary importance, and are mainly found in the middle course of the Kulfo river. Kulfo river water is used for irrigation by the Arbaminch State Farm, which produces cotton, banana, and maize. Sheep farming is common, but the animals are of poor quality.

1.4. Topography

Due to the position of the basin on the western side of the escarpment of the Ethiopian Rift Valley, most parts of the basin are characterized by steep topography. The elevation varies from about 3500 m a.s.l. in the west of Arbaminch to 1120 m a.s.l. in the east of Arbaminch (Fig 3 & 4).

The prominent features of the basin are its numerous step-faults, which determine the different surface configurations of the basin, and of course, the flat topography in the valley. From this topographic contrast, the highest points, the Kecha ridge and Wisha ridge, are found at the western end of the basin having an elevation of 3500 m.a.s.l. In contrast, the lowest point, the rift floor, has an elevation of about 1120 m.a.s.l., and is located around the town of Arbaminch in the eastern part of the study area. Generally, the area around the town has a uniform, low-lying, flat topography. Also, the rift floor of the Ethiopian Rift Valley consists mainly of extensive flat lands, while the escarpment areas have mostly steep slopes and cliffs.

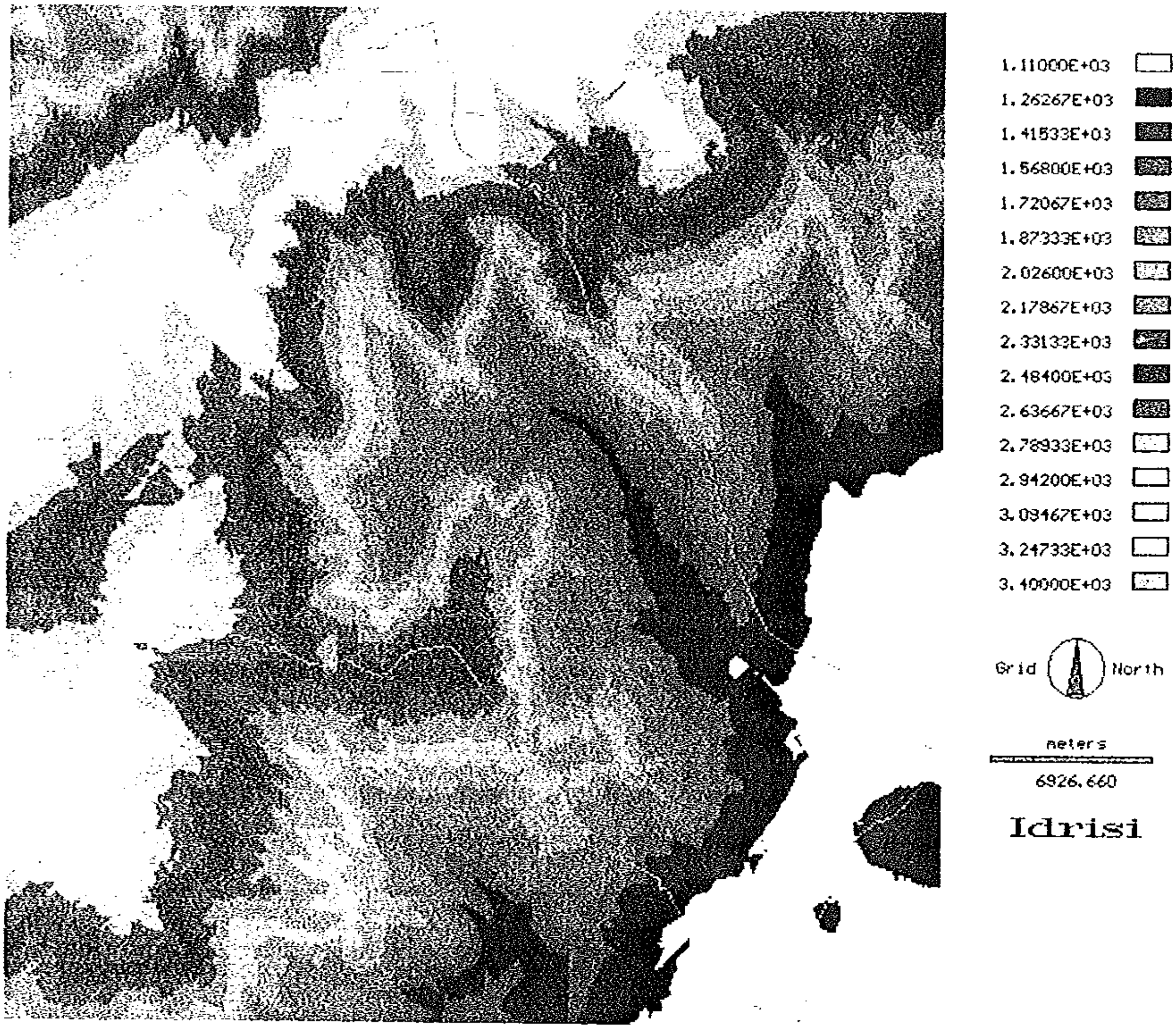


Figure 3: Topographic Map of the Study Area

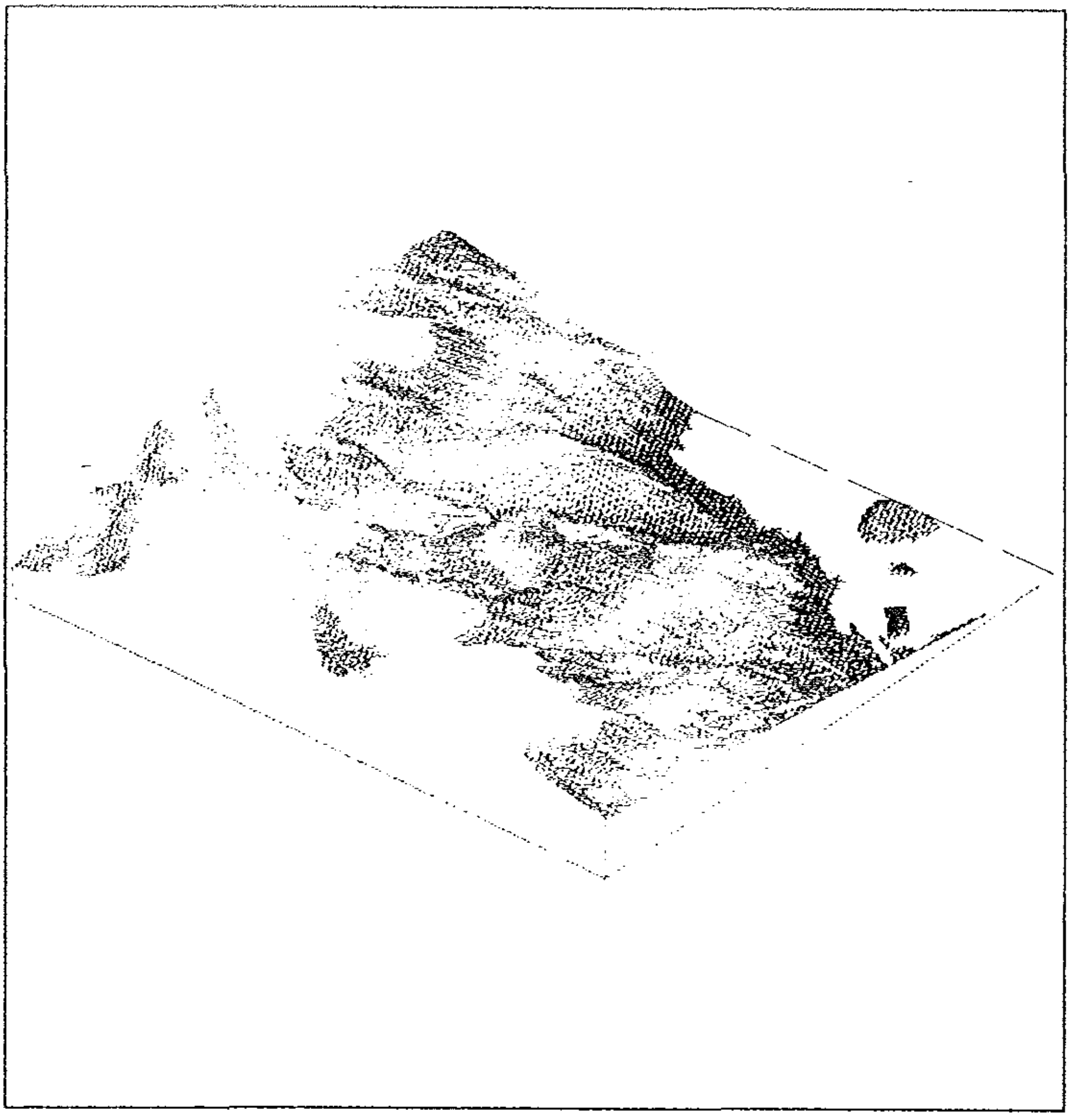


Figure 4: 3-D Digital Elevation Model of the Kulfo Basin

1.5. Drainage

The natural course of the Kulfo river follows the slope orientation of the area. Originating from the western highlands of the area, the river drains an extensive area to the east and perennially flows into Lake Chamo after joining the outlet channel from Lake Abaya.

The two main tributaries of the Kulfo river are the Toothache river and the Yermo river, which are tectonically controlled. Among the two, the drainage area of Yermo river is almost double that of the Toothache river (Fig 5).

The Yermo river drains most of the areas in the highlands of the southern part of the basin. It drains part of the Haringe ridge, Laka ridge, Kuyle ridge, Kecha ridge, Wisha ridge, Gacho ridge and Merzo ridge. The Toothache river drains part of the Merzo ridge and the Guye mountains. The rest of the small tributaries go directly to the main river. The main river unites with the river which comes from the outpouring of Abaya lakes at the rift floor and perennially flows into Lake Chamo. On the way to Lake Chamo, several tributaries from the Genta mountains and "Bridge-of-God" join the system.

Generally, the Kulfo river has steep channel slopes in the higher elevated areas where it starts mainly with perennial sources. On the rift floor, close to the two lakes, the river channel has low slopes. Most of the tributaries of the Kulfo river are tectonically controlled. They have a general trend of the faults of the East Africa rift Valley.

1.6. Methodology

The methods which have been used for the research project might be categorized as desk studies and field investigations. The desk study included preparatory study; such as conducting a literature search and a preliminary estimate on the basis of the available documents; and interpretation of data, which were

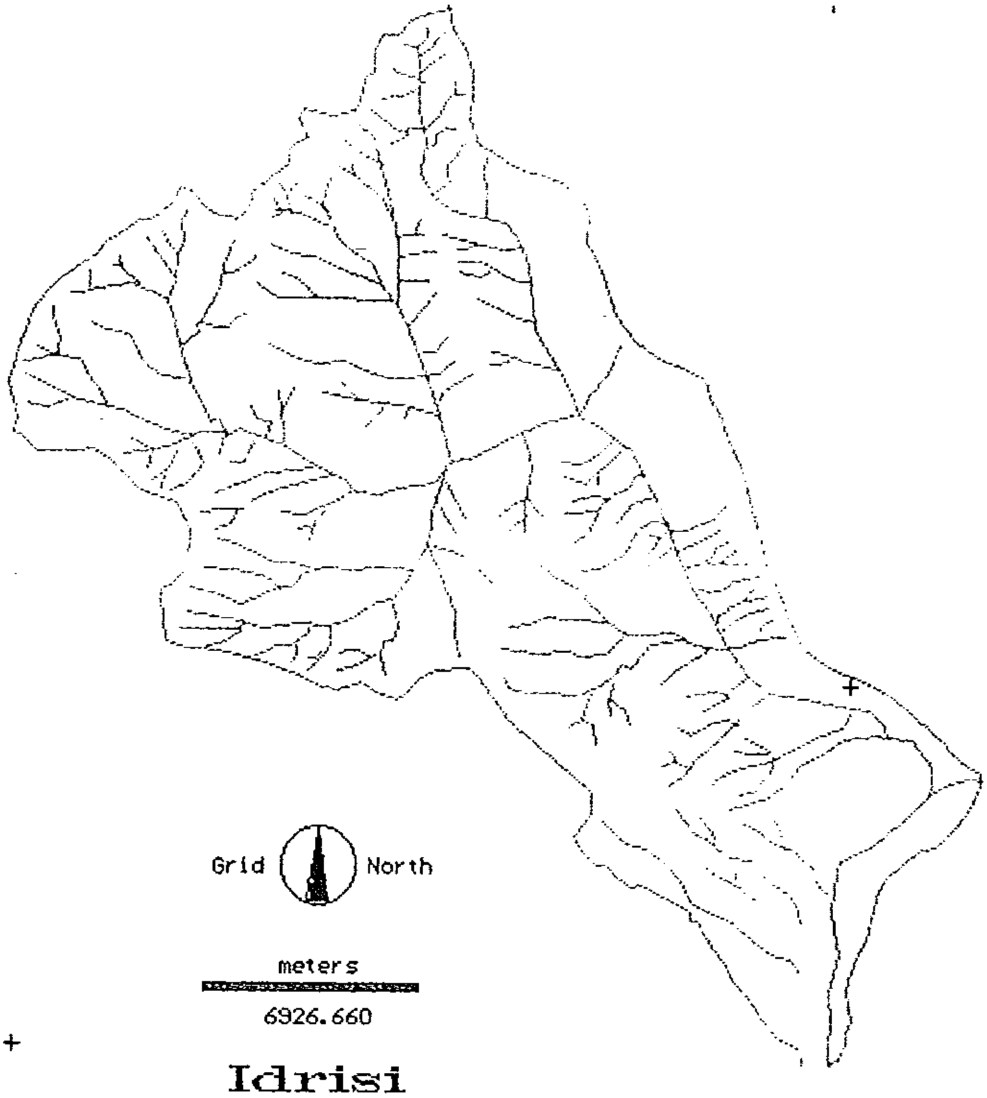


Figure 5: Drainage Pattern

collected from field work and laboratory studies. During this study a topographic map was used to delineate the basin boundary and as a base map for field investigations and for Geographical Information System (GIS) mapping.

Among the many types of GIS techniques, the IDRISI computer program was used to map the basin boundary, the contours, the drainage pattern, the meteorological stations and the other elements in the basin. A Digital Elevation Model (DEM) of the basin has been developed using this method. These techniques were also applied to generate the temperature and potential evapotranspiration maps of the area.

The data obtained from the Ministry of Water Resources were the starting information for the evaluation of the spring hydrogeology of the Arbaminch springs. The interpretation of spring water with respect to chemistry was also based on the analyses of data by Central Laboratories for Arbaminch water supply Project. Mapping of the different rock units and identification of water points were part of the field investigation. For bacteriological tests of springs, a *HACH* field kit was used.

1.7. Previous Work

Due to the nearness of the Kulfo river to the Arbaminch Water Technology Institute, students from the Institute, as well as visiting foreign students have conducted research on this river for the last five or so years. Some of the students working in the area include: Renate (1994) and Thonsten (1995). But none of them have described the hydrogeology of the basin especially the hydrogeology of the springs.

As far as the geology or hydrogeology is concerned, there are no papers published for that particular basin. Reports on the "Evolution of Chencha Escarpment and the Ganjuli Graben (Lake Abaya) in the Southern Ethiopian Rift" by Zanettin et al.(1978) and the "The Geology of Chencha and District" by James C. (unpublished report, 1972) are the only papers from areas nearby.

Papers like the "Arbaminch master plan project", (NUPI,1995) ; "Sanitation Problems in Arbaminch Towns" (WSSA,1994); and the "Arbaminch Water Supply Project", (GMPH, 1979) are focused on the Arbaminch towns. "Development Prospects in the Southern Ethiopian Rift Valley" by Makin M.J. et al.(1975) is another paper which gives general ideas on the natural resources of Southern Ethiopia.

CHAPTER TWO
GEOLOGY

2.1. REGIONAL GEOLOGY

The Ethiopian Rift Valley is a sunken block which cuts Ethiopia into two parts. To the west is the Ethiopian plateau proper, and to the east, the Southeastern plateau. This rift if shaped like a long corridor running NNE-SSW, about 80 Km across, opening out, in Afar, into a triangle onto the Red sea. It has the same volcano-tectonic origins as the other great African rifts which continue to the south (Kenya, Uganda, Tanzania, Rwanda, and Malawi) and into the Middle East (Red sea, Jordan, Israel, and Syria). It consists of a break and collapse of the earth's crust over a distance of nearly 6000Km, from Syria to Mozambique (Raunet, 1974).

Classically, the Ethiopian Rift is divided into: the Afar Rift, the Main Ethiopian Rift (MER) and the Southern Rift. The volcanically and seismically active MER system transects the uplifted Ethiopian plateau for a distance of approximately 1000 Km, extendiing from the Afar depression southwards to a broad zone of basins and ranges near the Ethiopian border with Kenya. The MER begins to broaden south of lake Abaya (Ganjuli basin) where the topographic expression of the rift valley broadens into two basins separated by the 20 Km wide Amaro horst, the 40 Km wide Chamo basin and the 30 Km wide Galana basin (Ebinger *et al.*, 1993).

According to Zanettin *et al.* (1978), the Southern part of the Main Ethiopian Rift, which includes the Ganjuli graben (Lake Abaya) and the western side of Lake Abaya including the plateau and the Escarpment of Chencha, has been affected by volcanism since the Oligocene (about 37 my ago). Initially, eruptions consisted of mildly alkaline basalt, which are correlated with the Aiba and Alagi(?) basalts of central Ethiopia, followed by rhyolite (Alaji ignimbrites). This volcanic activity gave rise to the eruption of Trap series lavas which are considered to be the immediate consequence of the updoming of the Arabo-Ethiopian swell (Mohr, 1964). This major uplift was associated with homogeneous fracturing of extensive continental areas, forming wide basin and concomitant fissural volcanism. The activity began in the southern regions, and then moved to the north, acquiring more and more tholeiitic affinities when approaching the Red Sea (central Ethiopian plateau) and the Gulf of Aden (Harari Plateau), (Zanettin *et al,* 1978).

About 25 my ago, the territory was lifted up, the Proto-Ethiopian rift formed, and on the plateau, the volcanism died out. Zanettin *et al.* (1978) hypothesized that the formation of the proto-Ethiopian Rift took place towards the end of the Oligocene or at the boundary between the Oligocene and the Miocene.

The Chencha plateau in the west and the Bale Plateau in the east where the two uplifted regions separated by the wide and quite shallow proto rift. The proposed age and the width of the rift seem to be confirmed by the fact that the Amaro flood basalts, which also flooded the present Amaro horst, were emitted into the rift during the Lower Miocene. The lifting up of the Amaro horst was beginning at the same time as the emission of basalts, and quickened after their emission (Levitte *et al.* 1974), causing the appearance of two parallel rifts, the Ganjuli and Galana graben inside the proto rift.

Other important eruptive episodes occurred in the upper Miocene (13 to 11 my ago) with the emplacement of rhyolites. The eruption of these rhyolites was followed by a lifting up, which narrowed the rift, and whose floor was later covered by Plio-Pleistocene rhyolite (Balachi Rhyolite, Zanettin *et al.*1978). The youngest formation, during the Quaternary, was the emission of alkali basalts and the accumulation of fluviatile and lacustrine deposits. Finally, the axis of the Ganjuli graben; which runs NNE-SSW, was fractured by the Wonji fault belt (Levitte *et al.* 1974), and alkali basalts, rhyolite, pumice, and obsidian were erupted.

The Oligocene volcanism and the subsequent volcanic episodes which occurred in the rift, were fed by fissures parallel to the axis of the Ganjuli graben. The main faults of the escarpment run in the same direction. It seems that the territory has been cyclically affected, from the upper-most Oligocene until the Quaternary, by a single crustal stress system (Zanettin *et al.* 1978).

Zanettin *et al.* (1978) report that the magma distribution changed from mildly alkaline basalts (Oligocene) over most of Ethiopia, to decidedly alkaline volcanic (hawaiites, mugeraites, benmoreites), which were erupted in the Ethiopian rift in the lower Miocene (Amaro flood basalt of Levitte *et al.* (1974) and in the Quaternary.

Schematic representation of the volcanic and tectonic evolution of the southern Ethiopia rift especially the Ganjuli graben and the Chencha escarpment by Zanettin *et al.* (1978), might give a general idea of the tectonism and volcanism of this part of Ethiopia (Fig 6).

2.2. GEOLOGIC SETTING OF THE STUDY AREA

The Kulfo river basin is comprised of volcanic rocks and alluvial sediments. The greater portion of the area is constituted by volcanic rocks whereas areas having elevation less than about 1200 m above sea level are restricted to alluvium.

Two quite different types of volcanic rocks are identified in the study area. Basalts which are found at the escarpments are grouped by Zanettin *et al.* (1978) as Trap basalts. Quaternary basalts (Aden Series) are the other type of basalt around the town and the "Bridge-of-God". (The hill between Lake Abaya and Lake Chamo is referred to as the "Bridge-of-God" by various authors). The large and old volcanoes are located on the plateaus, the relatively small and recent volcanoes are found on the rift floor along the Wonji fault belt.

2.2.1. Surface Geology

During the field reconnaissance, it was not easy to find fresh samples of rocks, since they are either covered by thick residual soils or are highly weathered on the exposed stream channels. The vegetation cover also contributes to obstruction of rock units in the study area. Most of the elevated parts of the basin are highly rugged and the geological descriptions of these areas are based on the works of M. Raunet's (1978)," Le Milieu Naturel Du Bassin Des Lacs Abaya Et Chamo".

1. Oligocene Basalt flows

The basalts of this area are part of the vast eruption of fissure basalts which took place in the Oligocene (Fig 18a & 18b). According to Levitte *et al* (1974), the total thickness of the lava is at least 850 m, but James (1972) reports that a minimum of 1600 m of stratoid basalt is exposed in this area.

This unit is the thickest and most extensive, which covers about 85% of the basin. It extends from a little west of Arbaminch, i.e. from 1400 m. a.s.l., to the highest point of the basin in the north-westerns part. So these basalts cover almost all the areas of the escarpment and plateau.

All exposures have undergone severe weathering, relatively fresh outcrops are exposed only in stream channels. No fresh outcrops of basalt along the cliffs were observed except for outcrops of columnar jointed alkali basalt in some parts of the area. Thus, the main exposures are a rubbly, finely crushed, fractured, sometimes onion (spheroidal) weathered basalt.

The outcrops around the junction between the main Kulfo river and the Wobale tributary are about 25 m thick, massive with columnar jointing structures, very often finely crushed along these joints which eventually detach large blocks into the valley bottoms. Samples taken from this rock unit usually are medium grained, gray to black in color. According to Crey J. (1972) the rock is rich (30%) in phenocrysts of anorthoclase and quartz within a fine glassy matrix. Zanettin *et al.* (1978) report the same rocks near Chencha as alkaline, which are typically transitional. The basalts near Chencha yielded radiometric ages ranging from 30-32 my (Zanettin *et al.* 1978). According to Meral *et al.* (1973), the Oligocene volcanic of this area are grouped into the Omo Basalts. Zanettin *et al* (1978) correlate this unit with the Aiba and Alaji(?) basalts of central Ethiopia.

2. Quaternary Basalt flows

These Quaternary basalts were identified around Arbaminch town and at the "Bridge-of-god". They are part of the Wonji Fault Belt basalt series. Although, if it is difficult to map Secha town (one of the two Arbaminch towns) since it is covered by colluvium, a very beautiful outcrop of basalt is found at the escarpment near Bekele Molla hotel. A series of NNE-SSW trending step faults have a displacement of approximately 200 m toward the east. The dip of the fault is 85-90^{0}W and strike N 20^{0}E. Various local normal faults splaying away from the step faults have general N-S trends. Step faulting is one of the major feature of the area. The basalt rock in this part of the basin is vesicular in nature and intercalated with soil horizons. The rock is largely affected by columnar jointing.

The main difference between this rock unit and the Trap basalt is that it is generally vesicular in nature, relatively fresh, and ranges in color from light grey to dark. Columnar jointing is one of the common feature of this rock. The most recent volcanic are scoraceous basalt flows and spatter cones (Zanettin et al. 1978) in the "Bridge-of-god". They were identified in the eastern edge of the basin. Zanettin et al (1978) correlate them with the Bishoftu basalts of central Ethiopia.

3. Alluvial Deposits

The rift floor near Lake Abaya and Lake Chamo is filled with alluvial sediments. They cover about 5% of the whole basin.

Well logs obtained from EWWCA boreholes at Arbaminch Water Technology

Institute reveal that the alluvium has an approximate thickness of about 90 m. The abrupt change in elevation between the escarpment and the basin floor allowed for the accumulation of thick alluvial deposit in the area.

The sediments range in size from gravel to clay mixed with varying proportions of soils. According to data from the AWTI wells, the sands within these sediments are volcanic in origin. The grain size of these loose sediments progressively decreases in proportion to the proximity of the lake.

2.2.2. STRUCTURE

One of the largest structural features of Ethiopia and of the study area is the Tertiary- Quaternary tectonic system known as the rift system. The rift runs generally N-S, but does not form one continuous unit.

The project area is located in the Main Ethiopian rift system, and is comprised of part of the rift floor and the western rift escarpment. Step faults, having a N-S trend, but various displacements, are the major structural features. A series of step faults rises to 3600 m high western rift escarpment. Around Zigiti mountain, a horst structure was identified. Most of the tributaries of the Kulfo river flow along faults. The other distinct structural feature of the area are columnar joints and fractures. These features dominates almost all exposures of the rocks around the basin (Fig. 18a&b).

The Wonji fault belt is the other tectonic system in the Quaternary. These young faults are also found on the rift floor near Bekele Molla Hotel and the Bridge-of-god". The trend of the faults is almost the same as that of the old faults.

CHAPTER THREE
SURFACE HYDROLOGY

3.1. Introduction

The study area is bounded on the basis of the surface divide of the Kulfo river and is surrounded by the following basins: the Hare basin to the north-east; the Omo-Ghibe basin to the north-west, and the Sile basin to the southwest. To the southeast are Lake Abaya and Lake Chamo. The area of this drainage basin is 438.125 km^2 and its circumference is 115 km.

The hydrographic basin is divided into two sub basins.

1. Upper sub-basin or main Kulfo basin (Fig 2): It covers about 378 km^2, which is 86% of the Kulfo watershed and a perimeter of 94.5 km. It extends from the higher elevated areas up to Sikela town, the lower town of Arbaminch. From the upper sub-basin will be referred to as Kulfo basin.

2. Genta Sub basin (Fig 2): This part of the basin covers about 60 km^2 and a perimeter of 46.5 km and is located at the lower end of the catchment area. Most of the area of the Genta mountains and some part of the "Bridge- of-god" drain directly into the bigger Kulfo river, which is a result of the joining of the Kulfo river from the escarpment and a surface water outpouring from Lake Abaya which flow in to Lake Chamo.

As there is no hydrological data available for the Genta sub-basin, a water-budget analysis will not be performed for this sub-basin. However, since the Arbaminch springs are located in this sub-basin, the hydrology and hydrogeology of the springs will be discussed in detail in the "Spring Hydrogeology" chapter.

3.2. Morphological Characteristics of the Kulfo Basin

3.2.1. Gravelius Coefficient or Compactness index K(c).

It is a dimensionless coefficient which is obtained by comparing the perimeter P of a given basin with the perimeter P' of a circle having the same areal extent.

$$K(c) = P/P'$$

P = 94.5 km and P' = 68.9 km

So for the study area $K(c) = \frac{94.5 \text{ km}}{68.9 \text{ km}}$

therefore K(c) = 1.37

3.2.2. Equivalent Rectangle

The runoff which characterizes a certain basin is nearly equal to that of a rectangle having the same area A and compactness index K(c) of the given basin together with the same distribution of the level contour lines. This rectangle can be drawn by evaluating the length of the largest and smallest side of the rectangle. The formula for finding the length of the two sides is the following:

$$L = \frac{K(c)[A]^{1/2}}{1.12}\left[1+\{1-[1.12/K(c)]^2]^{1/2}\right\}$$

and $$l = \frac{K(c)[A]^{1/2}}{1.12}\left[1-\{1-[1.12/K(c)]^2]^{1/2}\right\}$$

Taking the values of K(c) = 1.37 and A = 378 km^2, for the Kulfo river basin the largest side L is 37.47 km and the smallest side l is 11.63 km. The contour interval percentage distribution and the equivalent rectangle of the basin are shown figure 7 and 8.

3.2.3. The Hypsometric Behavior

The area distribution in a basin is usually displayed by plotting elevation against area, or percentage of area, above or below a given elevation. The use of the percentage of an area is convenient in comparing the elevation distribution in basins of different sizes. It is also useful to calculate the mean and median height of the basin.

The hypsometric behavior of the Kulfo basin is shown in Figure 8. From this, the mean and median height of the basin are 2400 m a.s.l., and 2350 m.a.s.l., respectively.

3.2.4. Drainage Density

The drainage density over a basin is the ratio of the sum of all stream lengths in the basin to the basin area. In case of the study area, the sum of stream lengths in the basin is 746 km and the area of the basin is 378 km^2, therefore the drainage density is 1.97 km/km^2.

3.2.5. Drainage Pattern

The drainage pattern may assume different shapes and behaviors depending on the soil types, rock formations, and structures. The study area is characterized by dendritic drainage pattern. This pattern is developed in regions which are made of rocks having the same resistance to erosion and a uniform structure. Generally, the drainage is tectonically controlled (Figure 5).

3.2.6. Order of the Hydrographic Net

Horton has classified stream order by assigning order 1 to small, unbranched, finger- tip tributaries; order 2 to those streams which have at least two branches of

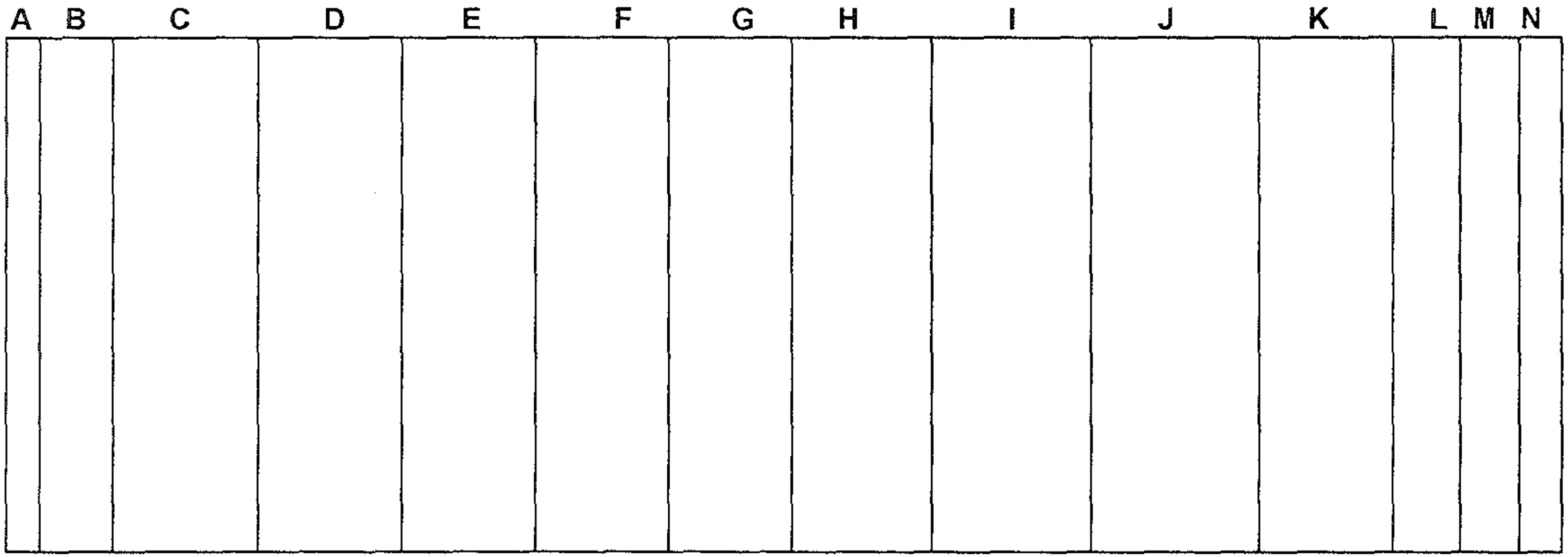


Figure 7: Equivalent Rectangle of the Kulfo Basin

Explanation:

A: 3600-3400 m;	B: 3400-3200 m;	C: 3200-3000 m;	D: 3000-2800 m;	E: 2800-2600 m;
F: 2600-2400 m;	G: 2400-2200 m;	H: 2200-2000 m;	I: 2000-1800 m;	J: 1800-1600 m;
K: 1600-1400 m;	L: 1400-1300 m;	M: 1300-1200 m;	N: < 1200 m	

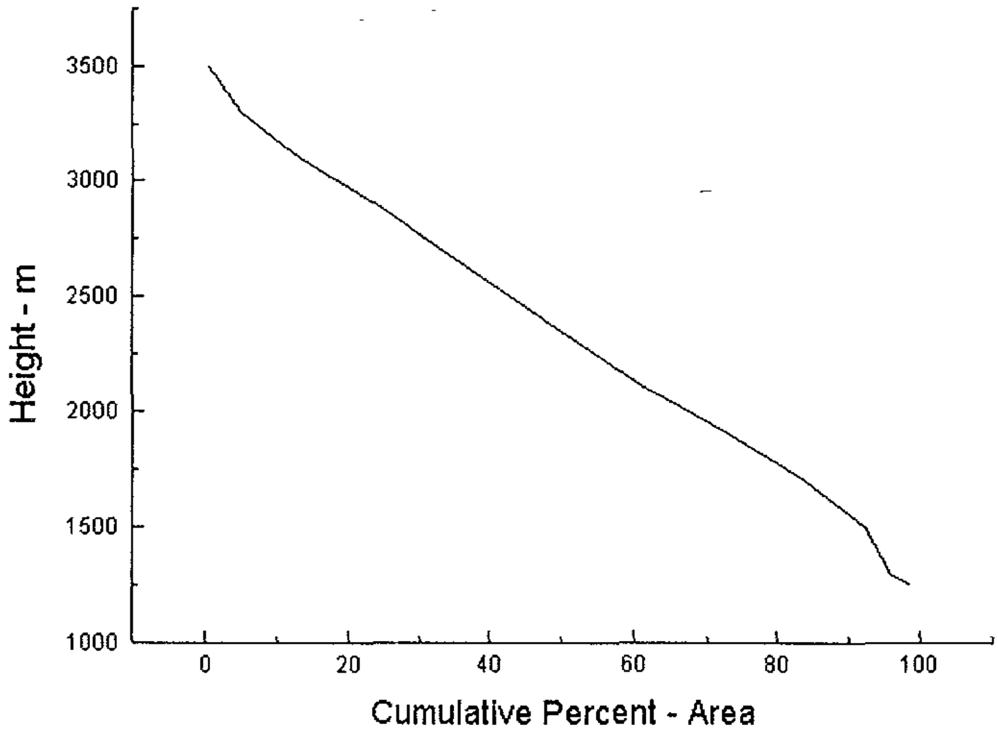


Figure 8: Hypsometric curve

the first order; etc. Thus; the order of the main stream indicates the extent of branching in the basin. According to this classification, the study area has 5th order of the hydrographic nets.

3.3. RAINFALL

Rainfall depth is one of the elements for calculating the water balance for a given drainage basin. The average depth of precipitation over a basin can be calculated by straightforward averaging of station observations, by weighting station observations according to the area commanded by each station, or by preparing a rainfall contour map and planimetering the areas between or enclosed by isohyets. The above methods are called arithmetic mean method, Thiessen mean method and isohyetal method, respectively.

Arithmetic averaging is unreliable when the topography is steep and the precipitation stations are widely spaced. The other two methods might give a relatively good estimate in a steep topography. However, to draw an isohyetal line we have to have relatively closely spaced stations. To get a comparatively good results in a basin like the project area, which has only 3 widely-spaced stations, it is better to use the Thiessen polygon method.

In the study area there are three climatic stations within and out of the basin. As shown in figure 2, only one station (Arbaminch station) is found in the basin, while the Chencha and Gerese stations are located outside the basin. All three stations have different years of record. They vary from 8 years for Gerese, 10 years for Arbaminch, and 20 years for Chencha.

In order to solve many hydrological problems it is necessary to calculate the mean yearly rainfall depth and the mean monthly rainfall depth over a basin. The following section will deal with mean annual rainfall depth over the Kulfo basin.

3.3.1. Mean Annual Rainfall Depth over Kulfo River Basin.

The stations described above are the only stations which may be used to calculate the mean annual rainfall depth over the basin. As shown in table 1, Arbaminch has a mean annual rainfall of 903 mm; Chencha has 1402 mm, and Gerese has 2108 mm.

Gerese station is located at an elevation of 2300 m a.s.l., and has a higher rainfall depth than Chencha station, which is located at an elevation of 2800 m a.s.l. This may be described by the orographic effect at Gerese station which is found at the foot of the mountain, SW of Arbaminch.

Station	Altitude m.a.s.l.	Area coverage %	Area coverage km^2	P_y in mm.
Arbaminch	1290	55	207.9	903
Chencha	2800	35	132.3	1402
Gerese	2300	10	37.8	2108

Table 1 : The relationship between elevation, area, and mean annual rainfall for the three stations. The total area of the basin is 378 km^2.

When weighted averaging is employed, Thiessen polygons are formed around each precipitation stations by drawing the perpendicular bisectors of the lines joining adjacent stations. The observed precipitation is weighted according to the area of the polygons or partial polygons associated with it. So for the Kulfo basin, Arbaminch station covers 55% of the whole basin i.e. 207.9 km^2, Chencha station covers 35 % of the whole basin i.e. 524.9 km^2 and Gerese station contributes 10 % of the whole basin i. e. 37.8 km^2.

Therefore, the mean annual rainfall depth **P** is

$$\mathbf{P} = \frac{A_a}{A} * Pa + \frac{A_c}{A} * Pc + \frac{A_g}{A} * Pg$$

where

A_a, A_c and A_g are representative for the basin of Arbaminch, Chencha and Gerese stations respectively.

P_a, P_c and P_g are mean annual rainfalls of Arbaminch, Chencha and Gerese stations, respectively. A is the total area of the basin.

Therefore, the mean yearly rainfall depth of the Kulfo river basin is 1232 mm.

3.3.2. Mean Monthly Rainfall Depth over the Kulfo River Basin.

The same Thiessen polygon method can also be applied for calculating the mean monthly rainfall depth of the basin.

$$P_j = \frac{A_a}{A} * P_{aj} + \frac{A_c}{A} * P_{cjj} + \frac{A_g}{A} * P_{gj}$$

Where:

P_j is mean rainfall depth of the jth month for Kulfo basin.

P_{aj}. P_{cj}, and P_{gj} are mean rainfall depth of the jth month for station Arbaminch, Chencha and Gerese, respectively.

Thus, the mean rainfall depths of all months for Kulfo river basin can be calculated using the above method. This is shown in table 2.

Month	Jan	Feb	Mar	Apr	May	June
P_m	34	62	118	186	171	122
Month	July	Aug.	Sep	Oct	Nov	Dec
P_m	89	86	142	124	64	33

Table 2: The mean monthly rainfall depths of the Kulfo basin.

3.3.3. Rainfall Coefficient

In order to distinguish whether a month is a 'rainy' month or a 'dry' month we can apply a term called Rainfall Coefficient. It is the ratio between the mean monthly rainfall depth and one twelfth of the mean yearly rainfall depth:

$$R_c = \frac{P_m}{P_y/12}$$

Where: R_c is rainfall coefficient

P_m is mean monthly rainfall depth

P_y is mean yearly rainfall depth

A month is designated as "rainy" when the corresponding monthly rainfall coefficient reaches 0.6 and distinctly rainy when it exceeds 0.8. Extremely rainy months may have a coefficient of more than one (Daniel, 1977).

The following four tables (table 3 to 6) show the rainfall coefficients for the three stations and for the weighted mean of the basin.

1. Station: Arbaminch

$$R_c = \frac{P_m}{P_y/12}$$

$$R_c = \frac{P_m}{75.22}$$

Month	Jan	Feb	Mar	Apr	May	June
P_m	36.25	50.05	99.35	145.15	141.65	58.7
R_c	0.48	0.67	1.32	1.93	1.88	0.76
Month	July	Aug	Sep	Oct	Nov	Dec
P_m	34.3	53.75	107.7	103.65	47.95	24.1
R_c	0.46	0.71	1.73	1.38	0.64	0.32

Table 3: Monthly rainfall coefficients for Arbaminch station.

2. Station : Chencha

$$R_c = \frac{P_m}{P_y/12}$$

$$R_c = \frac{P_m}{124.97}$$

Month	Jan	Feb	Mar	Apr	May	June
P_m	28.25	83.25	133.35	197.75	165.95	195.9
R_c	0.23	0.67	1.07	1.58	1.33	1.57
Month	July	Aug	Sep	Oct	Nov	Dec
P_m	134.3	119.85	178.9	138.8	77.6	45.75
R_c	1.07	0.96	1.43	1.11	0.62	0.37

Table 4: Monthly rainfall coefficients for Chencha station.

3. Station : Gerese

$$R_c = \frac{P_m}{P_y/12}$$

$$R_c = \frac{P_m}{175.68}$$

Month	Jan	Feb	Mar	Apr	May	June
P_m	42.3	54.0	170.3	371.2	349.4	211.1
R_c	0.24	0.31	0.97	2.11	1.99	1.2
Month	July	Aug	Sep	Oct	Nov	Dec
P_m	232.4	145.8	201.5	187.9	103.2	39.1
R_c	1.32	0.83	1.15	1.07	0.59	0.22

Table 5: Monthly rainfall coefficients for Gerese station.

4. The Total Kulfo Basin

$$R_c = \frac{P_m}{P_y/12}$$

$$R_c = \frac{P_m}{102.68}$$

Month	Jan	Feb	Mar	Apr	May	June
P_m	34.06	62.07	118.34	186.16	170.91	121.96
R_c	0.33	0.61	1.15	1.81	1.66	1.19
Month	July	Aug	Sep	Oct	Nov	Dec
P_m	89.11	86.09	142	124.38	63.87	33.18
R_c	0.87	0.84	1.38	1.21	0.62	0.32

Table 6: Monthly rainfall coefficients for the Kulfo basin.

According to the above values, the twelve months of all stations can be divided into dry and rainy periods. Based on Daniel (1977), the scheme of classification of monthly rainfall values are presented in table 7.

On the basis of the above classification, the study area can be classified as: i .Dry months: December and January

ii. Rainy months: February, March, April, May, June, July, August, September, October and November.

The dry months contribute about 5.46% of the total mean annual rainfall to the area where as the rest, i.e. 94.54% of the total annual rainfall, is contributed by the rainy months. Daniel (1977) grouped the study area into Regime IB. This is to signify that rainy months are contiguously distributed or in other word, regimes

Table 7. Classification Scheme of Monthly Rain fall Values.

STATION	DRY MONTHS Rc < 0.6	RAINY MONTHS			
		SMALL RAINS Rc = 0.6 TO 0.9	BIG RAINS		
			MODERATE CONCENTRATION Rc = 1 TO 1.9	HIGH CONCENTRATION Rc = 2 TO 2.9	HIGH CONCENTRATION Rc $\geq$ 3
CHENCHA	December, January	November, February	March, April, May, June, July, August, September, october	-	-
ARBAMINCH	December, January, July	November, February, June,	March, April, May, August, September, October	-	-
GERESE	December, November, January, February	August	March, June, July, September, October	May, April	-
KULFO BASIN, WEIGHTED MEAN	December, January	February, July, August, November	March, April, May, June, September, October	-	-

3.4. Evapotranspiration

Evaporation is the purely physical process whereby water is returned to the Earth's atmosphere through the medium of heat; transpiration is the biological process by which water is returned through the medium of plant growth.

Evaporation and Transpiration go on simultaneously and in practice can not be separated. It is not important, whether the water loss is due to evaporation or transpiration; it is the total loss that is vital in most cases. Consequently, the inability to separate them is of no importance, and the term evapotranspiration is used to describe water loss due to these two processes.

In studying the hydrologic balance for a catchment area, in particular, one is usually concerned only with the total evaporation (or evapotranspiration), the evaporation from all water, soil, ice, snow, vegetation, and other surfaces plus transpiration.

Distinction should be made between potential evapotranspiration (PET) and actual evapotranspiration (AET). The term PET was introduced by Thornthwaite as equal to "the water loss which will occur if at no time there is a deficiency of water in the soil for the use of vegetation." Because there is often not sufficient water available; the term AET is used to describe the amount of evapotranspiration that occurs under field conditions.

There are many methods of estimating evapotranspiration. Among these methods, the common one is calculating evapotranspiration by different empirical techniques (indirect method). They include the Thornthwaite method, the Blaney - Criddle (1958, 1959) method, and the Penman(1956) method. Most of these techniques use a series of climatic data to calculate evapotranspiration.

Blaney and Criddle also introduced a crop factor which varies as the growing season progress. Penman derived a theoretical equation which uses climatic data including vapor pressures, sunshine duration, net radiation, wind speed and mean temperature. Thornthwaite estimates the PET using only mean air temperature and a latitude factor.

Due to the shortage of data to estimate PET using the Blaney-Criddle, and the Penman methods, the Thornthwaite method was used to calculate the PET in the study area. Moreover, according to the work by Daniel (1977), the Thornthwaite method gives reasonably accurate results in Ethiopia. Thornthwaite's empirical formulae, tables and nomograms for estimating PET rates are employed in this study (Thornthwaite, 1948; Thornthwaite and Mather, 1957).

Thornthwaite method of estimating evapotranspiration is a function of latitude and air temperature, the relationship can be written algebraically :

$$e = k\,(t, l)$$

Where e represents PET, t air temperature and l latitude.

According to Thornthwaite, the PET for a standardized month of 360 hours of sunlight can be expressed with reasonable degree of accuracy by the empirical equation :

$$e = 16\,(10t/I)^{a}$$

Where e = PET in mm,

t = mean monthly air temperature in °C

I = an annual heat index obtained by summing the twelve monthly heat indices, each of which is defined by

$$i = (t/5)^{1.514} \text{ and}$$

$$a = 675I^{3}/10^{9} - 771I^{2}/10^{7} + 1792I/10^{5} + 0.49239$$

Recognizing the inelegance of these equations and the need to avoid lengthy numerical equations, Thornthwaite devised a method for evaluating PET involving three tables and a nomogram. These tables includes tables showing the monthly heat indices in terms of mean monthly air temperature, tables showing standardized

PET at temperature exceeding 26.5 °C and the tables showing the correction factor for the latitude of the locality and the month under considerations (see Appendix 1).

So in order to find the PET over the basin, the PET of all the three station have to be calculated first. Thus, tables 8, 9 and 10 summarizes the computation of the PET for each stations.

The assessed monthly PET is calculated by applying a correction to the standardized value which takes into account the varying lengths of the months and seasonal changes in the duration of sunlight.

To compute the water balance over the basin, the PET over the basin should be computed. This can be done using Thiessen Polygon method like that of the weighted rainfall over a basin, this is of course a PET over a basin.

Applying the same equation:

$$e_{basin} = (A_a/A * e_a) + (A_c/A * e_c) + (A_g/A * e_g)$$

Where e_{basin} = annual PET over the basin

e_a, e_c, e_g are annual PET for station Arbaminch, Chencha and Gerese, respectively.

$$e_{basin} = 0.55e_a + 0.35e_c + 0.1e_g$$

Therefore, the annual PET is 971 mm.

The monthly PET can be evaluated using the same method as of the annual PET. The computations are summarized in table 11.

The actual evapotranspiration has been evaluated through the calculation of the assessed PET using Thornthwaite's formula by taking into consideration the available water capacity of the soil, which in turn depends upon the texture of the soil and the rooting depth of the vegetation.

Table 8. Computation of PET for Chencha

MONTH	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	YEAR
Air T°C	15.3	15.5	15.4	14.7	14.3	14.1	13.2	12.7	14.0	14.8	15.1		
i	5.43	5.54	5.49	5.12	4.91	4.81	4.34	4.1	4.75	4.54	5.17	5.33	59.53
Stand. PET mm, e_s	62	63.5	62.7	57.5	56	55.5	51	47	55	53	58	51	
Correction factor, K	1.02	0.93	1.03	1.02	1.06	1.03	1.06	1.05	1.01	1.03	0.99	1.02	
Ass. PET mm, e_{cs}	63.24	59.06	64.58	58.65	59.36	57.17	54.06	49.35	55.55	54.59	57.42	52.02	665.05

Table 9. Computation of PET for Arbaminch

MONTH	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	YEAR
Air T°C	24.3	25.3	26	24.7	23.6	23.2	22.7	23.3	24.2	23.7	23.6	23.4	
i	10.95	11.64	12.13	11.23	10.48	10.21	9.88	10.28	10.89	10.55	10.48	10.35	129.07
Stand. PET mm, e_s	98	117	120	105	91	87	92	88	97	92	91	89	
Correction factor, K	1.02	0.93	1.03	1.02	1.06	1.03	1.06	1.05	1.01	1.03	0.99	1.02	
Ass. PET mm, e_{as}	99.96	108.81	123.6	111.3	96.46	89.61	97.52	92.4	97.97	94.76	90.09	90.78	1193.26

Table 10. Computation of PET for Gerese

MONTH	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	YEAR
Air T°C	17.8	18.3	17.2	16.7	15.7	15.1	15.5	15.8	15.6	16.0	17.0	17.2	
i	6.84	7.13	6.49	6.21	5.65	5.33	5.54	5.71	5.60	5.82	6.38	6.49	73.19
Stand. PET mm, e_s	68.5	73	65	62.5	57	53	55	57.5	56	59	64	65	
Correction factor, K	1.02	0.93	1.03	1.02	1.06	1.03	1.06	1.05	1.01	1.03	0.99	1.02	
Ass. PET mm, e_{gs}	69.87	67.89	66.95	63.75	60.42	54.59	58.5	60.375	56.56	60.77	63.36	66.3	749.135

Table 11 Computation of the Water Balance over Kulfo Basin

MONTH	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	YEAR
P(mm)	34.06	62.07	118.34	186.16	170.91	121.96	89.11	86.09	142.0	124.38	63.87	33.18	1232
PET (mm)	84.1	87.31	97.28	88.12	79.87	74.75	78.39	74.13	78.98	77.30	75.98	74.77.	971
P - PET (mm)	-50.04	-25.24	21.06	98.04	91.04	47.21	10.72	11.96	63.02	47.08	-12.11	-41.59	
APWL (mm)	-103.74	-128.98	-	-	-	-	-	-	-	-	-12.11	-53.70	
SM	146.5	131.28	152.34	230.00	230.00	230.00	230.00	230.00	230.00	230.00	218.2	182.11	
ΔSM	35.61	15.22	-	-	-	-	-	-	-	-	11.8	36.09	
AET (mm)	69.67	77.29	97.28	88.12	79.87	74.75	78.39	74.13	78.98	77.3	75.67	69.27	941
Surplus (mm)	0.00	0.00	0.00	20.38	91.04	47.21	10.72	11.96	63.02	47.08	0.00	0.00	291

APWL - Accumulated Potential Water Loss
SM - Soil Moisture
ΔSM - Change in Soil Moisture

According to the data from WBISPP(1995), the highland areas which represent about 80% of the basin , are predominately cultivated by enset plantation. The areas around the middle course of the Kulfo river are predominantly grassland. So in the computation of AET, the water holding capacities of these two vegetation types were used.

Both of these plant types are classified as deep rooted plants. The soil type for enset plant growth is clay loam and for grassland it is sandy loam. From the "Water-holding" table of C.W. Thornthwaite and J.R. Mather (1957), the available water for enset and grassland are 250 mm/m and 150 mm/m, respectively. Taking the root depth to be 1 m, the applicable soil moisture retention for enset is 250 mm and for grassland is 150 mm. Then by taking the percentage distribution of this plantation (80% for enset and 20% for grassland) the soil moisture capacity of the basin is 230 mm. The summary of the computations of the water balance is shown in table 11 and figure 9.

From table 11, of the total rainfall of 1232 mm, potential evapotranspiration accounts for 971 mm, while the actual evapotranspiration of the basin is 941 mm. The rest of the water, which is 291 mm, is left as surplus water.

3.5. Runoff

In a hydrological analysis, runoff is one of the most important components. It is the water flowing in a stream, which come from a combination of overland flow and from baseflow, which is groundwater that has seeped into the stream bed. Runoff may be expressed as:

Runoff = Baseflow + Overland flow.

The two main tributaries of the perennial Kulfo river are the Titika river and the Yermo river. The drainage area of the Yermo river is almost double that of the Titika river. The Yermo river drains most of the areas in the highlands of the southwestern part of the basin. It drains part of Haringe ridge, Laka ridge, Kuyle ridge, Kecha ridge, Wisha ridge, Gacho ridge and Merzo ridge. The Titika river drains part of the Merzo

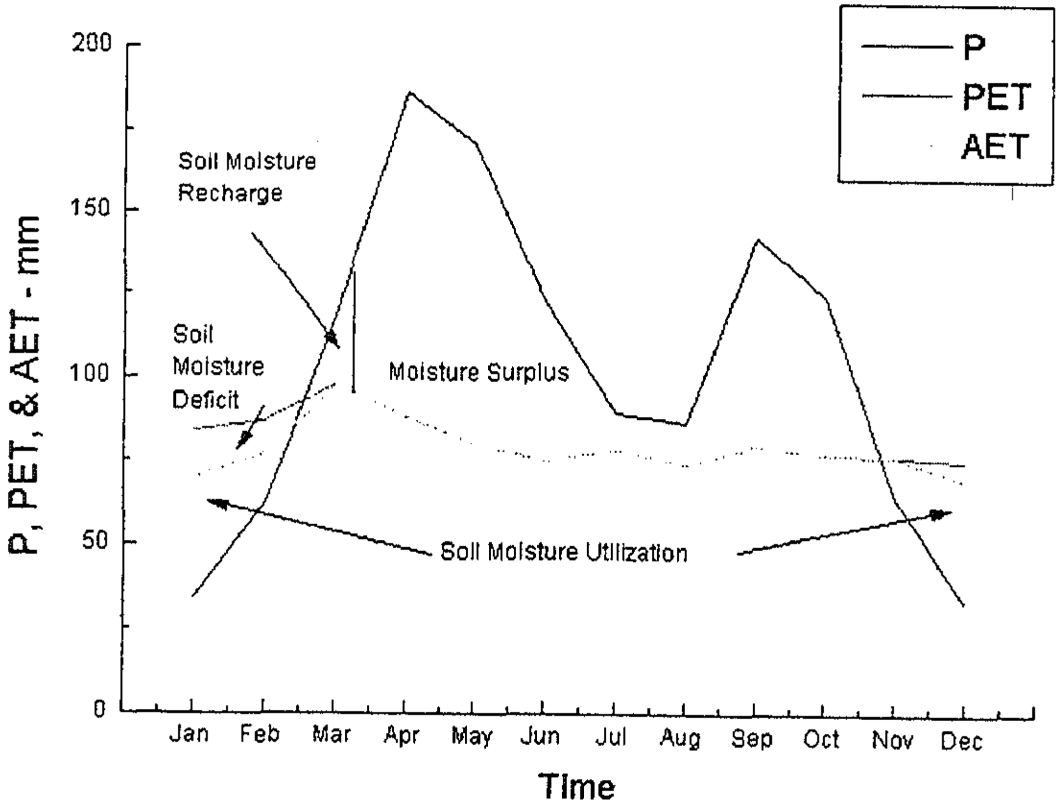


Figure 9: Monthly Water Balance for the Kulfo River Basin

ridge and the Guye mountains in the northwestern part of

the basin. The rivers unite and form the Kulfo river at the middle part of the basin, and travel long distance up to the lower part of the basin boundary.

The runoff gaging station in the study area is located near the bridge in Sikela town. It has seven years of record (see Appendix 2). The mean annual discharge of the Kulfo river is 1.37×10^8 m^3, which can be converted to runoff depth by dividing the discharge volume by the area of the basin, i.e. 1.37×10^8 m^3 divided by 378 km^2 which equals to 361.88 mm of runoff depth. Figure 10 shows the relationship between the mean monthly rainfall depth of the basin to the mean monthly runoff depth of the Kulfo river.

The baseflow component was separated graphically from total discharge by plotting baseflow on the discharge hydrograph of Kulfo river (fig 11). By subtracting baseflow from the total discharge, the overland flow component was obtained. Of the total runoff , i.e. 362 mm; 55.5% is accounted for by the groundwater component, and the rest, 44.5%, comes from overland flow. The monthly values of the two runoff components are shown in figure 12.

3.6. Altitude, Temperature and Potential Evapotranspiration Relationship over Kulfo River Basin

According to Daniel (1977), like for most parts of the world, the Potential Evapotranspiration rates in Ethiopia decrease with elevation. Since temperature normally decreases with increased altitude, and there is a direct relationship between temperature and potential evapotranspiration, this potential evapotranspiration - altitude relationship was anticipated. Regression analyses were preformed to determine the mathematical relationships among the three parameters.

The first step was to determine the relationship between terrain height and temperature. The data from the three stations (table 12) within the region was used

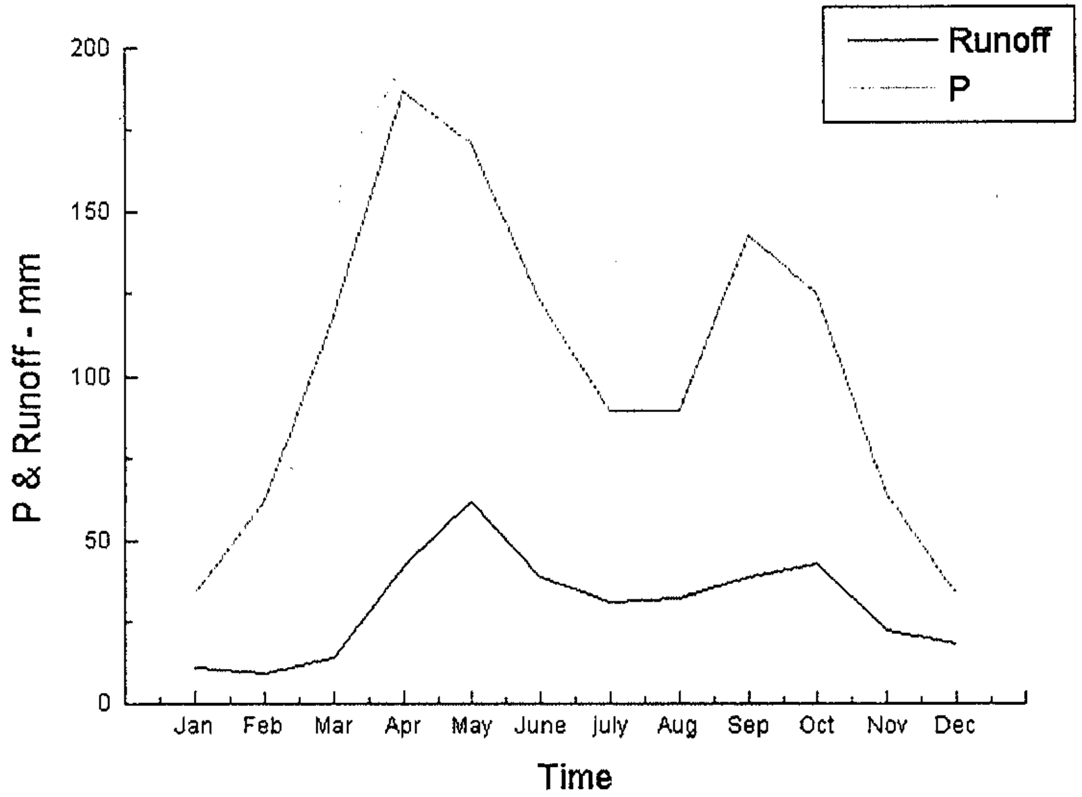


Figure 10: Monthly Rainfall and Runoff Depths

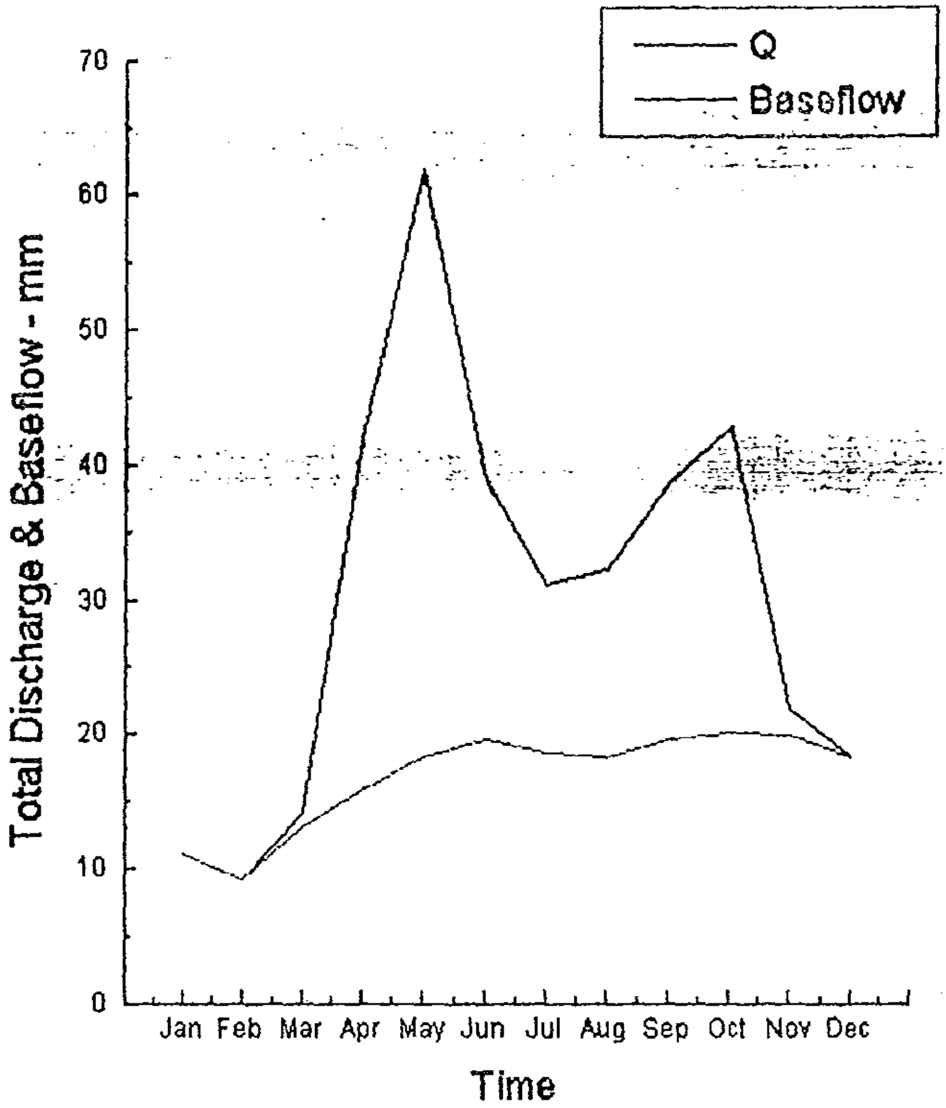


Figure 11: Baseflow Separation of Kulfo River Discharge

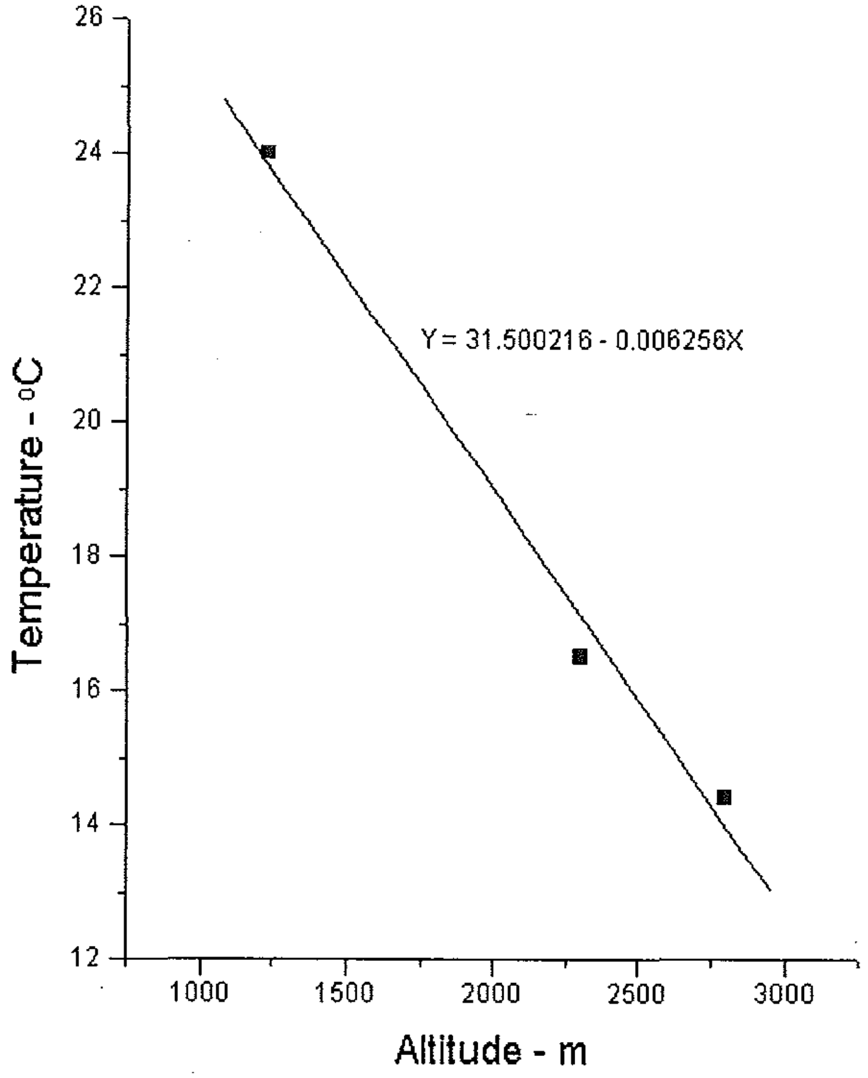


Figure 13: Linear Regression for Altitude - Temperature Relationship

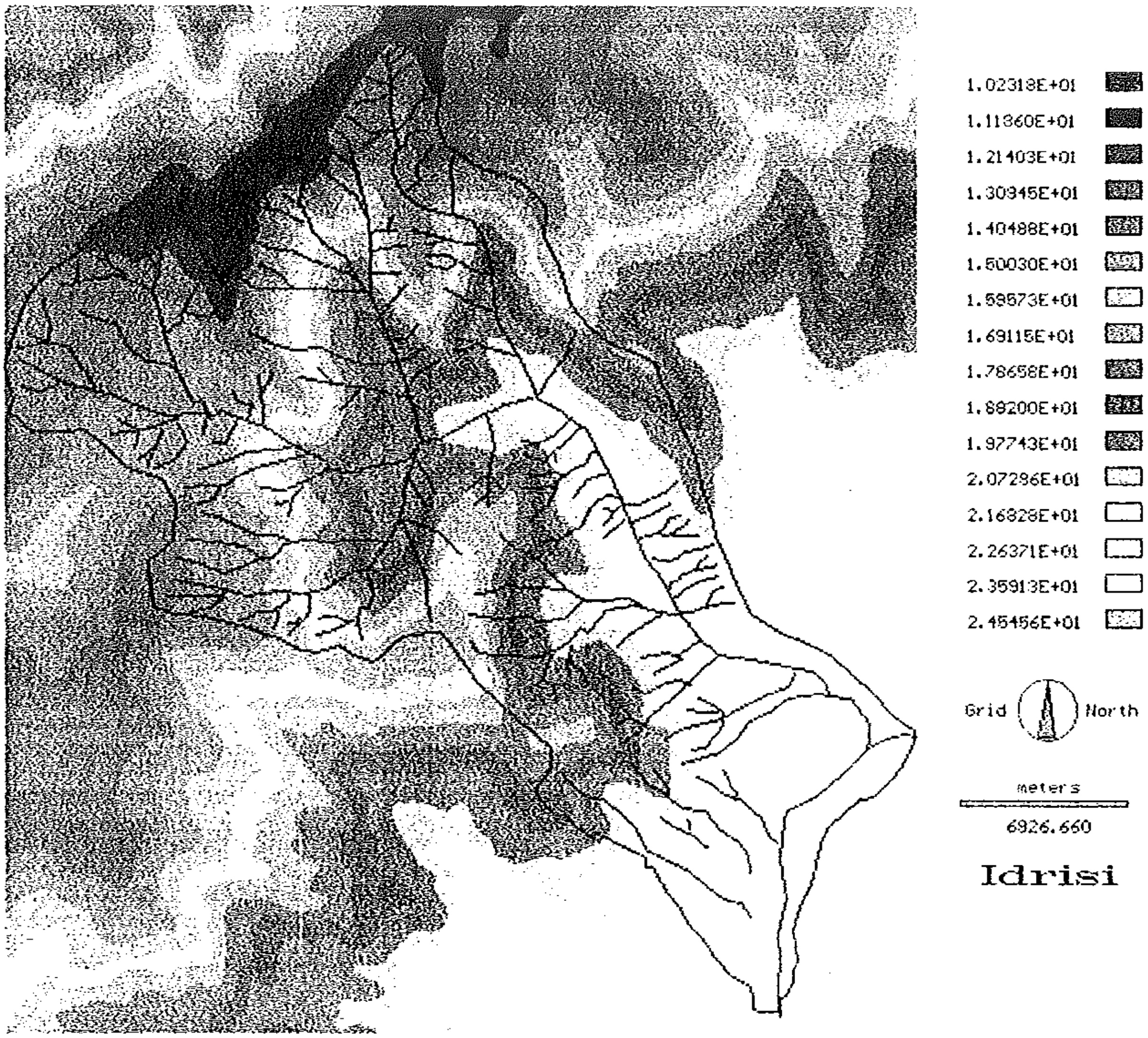


Figure 14: Temperature Map of the Kulfo Basin

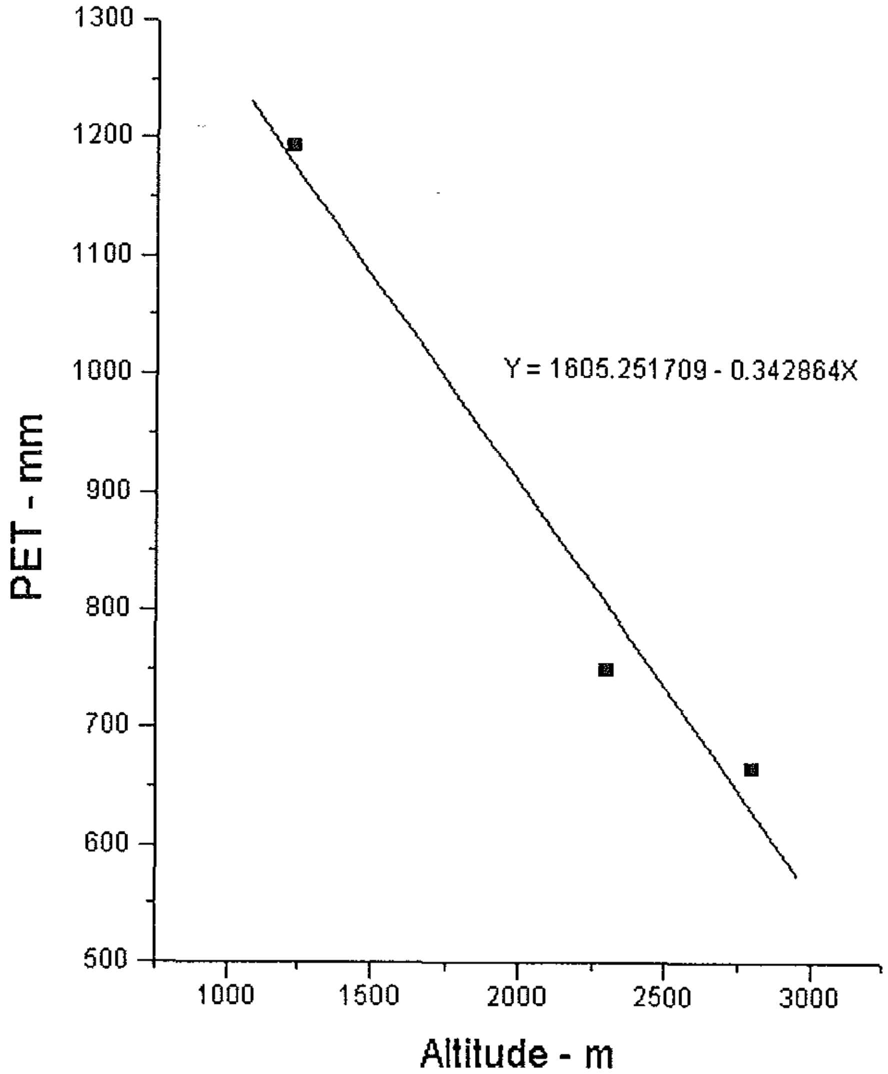


Figure 15: Linear Regression for Altitude - PET Relationship

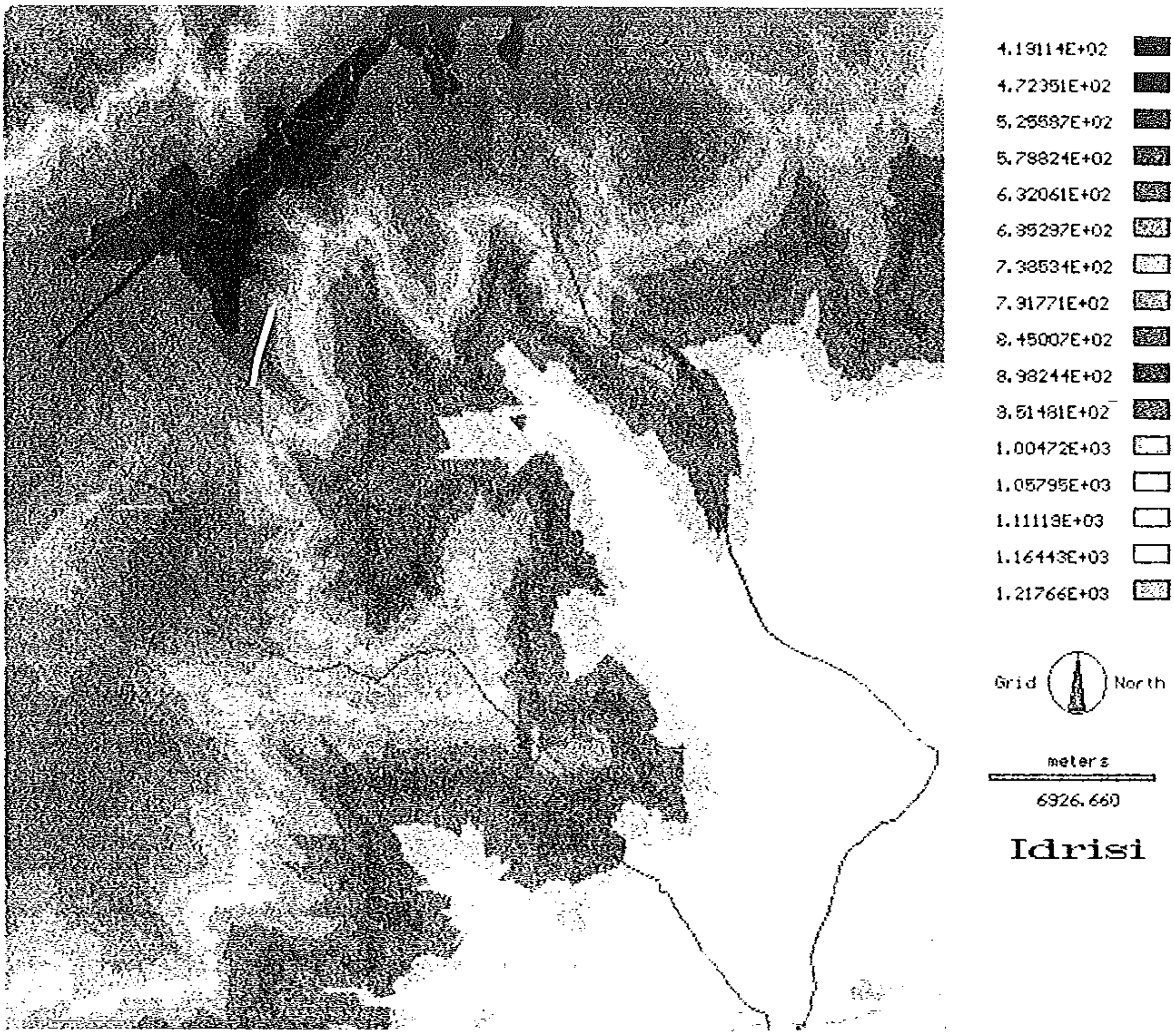


Figure 16: Potential Evapotranspiration (PET) Map

where Y is the PET and X is the temperature.

Figure 17 represents the regression plot for this relationship. The potential evapotranspiration map for the basin, based on temperature or on altitude are identical.

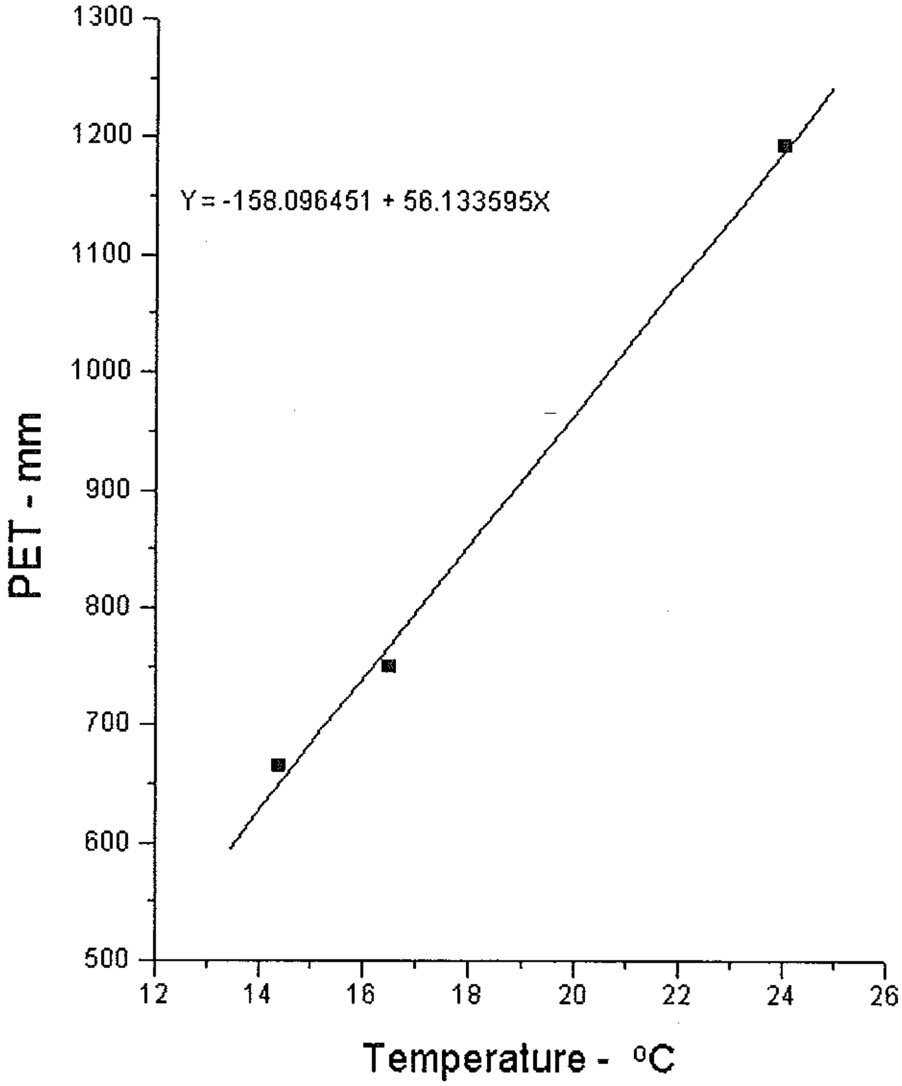


Figure 17: Linear Regression for Temperature - PET Relationship

CHAPTER FOUR

WATER BALANCE

The hydraulic equation states that all water entering a river basin or sub-basin during any period of time should either go into storage within its boundaries or leave the basin during the same period and a water balance is obtained. This fundamental equation is a simple statement of the law of mass conservation.

It may be mathematically expressed as:

INFLOW = OUTFLOW ± CHANGES IN STORAGE

Among the different components of inflow to and outflow from the basin, the following are the most important :

INFLOW

- Precipitation (P)
- Surface Inflow (Q_I)
- Subsurface Inflow (Q_{si})
- Imported Water (I_w)

OUTFLOW

- Evapotranspiration (ET)
- Surface Outflow (Q_o)
- Subsurface Outflow (Q_{so})
- Exported water (E_w)

Therefore the equation may be written as:

$$(P + Q_i + Q_{si} + I_w) - (ET + Q_o + Q_{so} + E_w) + \Delta S = 0$$

Where ΔS is the change in storage.

Most of the time, however, for the study of water balance over a certain river basin, the following simplified water balance equation is used:

$$P - (ET + Q + I) = 0$$

Where Q is the surface outflow and

I is infiltration to the ground water storage.

The reason this simplified formula is used is due to the fact that the different parameters in the original hydrologic equation are very difficult to measure. The simplified equation, however, makes a number of assumptions. These include :

- the net change of soil moisture and ground water storage are assumed to be zero.
- subsurface water exchange with neighboring basins is assumed to be zero.

Turning our attention to the study area, the annual rainfall of the basin is 1232 mm, which has a volume of $4.66 * 10^8$ m^3; the actual evapotranspiration is 941 mm, which is $3.56 * 10^8$ m^3. The difference of the two results in a water surplus of 291 mm, which is $1.01 * 10^8$ m^3. To fulfill the water balance equation, part of the surplus water goes to runoff and part of it goes to infiltration. However, the amount of surplus water is less than the runoff. This might be explained in two ways.

First, there may be an inflow of groundwater from an adjacent basin, or in other words the groundwater basin is wider than the surface water basin. So the assumption that subsurface water exchange with neighboring basins is zero is invalid. The second explanation may be that the runoff data obtained from the Ministry of Water Resources and/or the rainfall data from the National Meteorological Agency are incorrect.

Due to the results of the water balance, which indicate that runoff is greater that the calculated water surplus, a detailed study is needed to determine exactly how much water is imported as groundwater, or how the groundwater basin differs from the surface water basin. Therefore, it is not possible to determine the infiltration i.e. the total amount of water which is actually available to recharge the groundwater circulation within the hydrogeological basin.

CHAPTER FIVE
GROUNDWATER HYDROLOGY

5.1. Introduction

The nature and distribution of aquifers and aquitards in a geologic system are controlled by the lithology, stratigraphy, and structure of the geologic deposits and formations. The lithology is the physical makeup including the mineral composition, grain size and grain packing of the sediments or rocks of the geologic system. The stratigraphy describes the geometrical and age relations between various lenses, beds and formations in geologic systems of sedimentary origins. Structural features, such as cleavages, fractures, folds and faults are the geometrical properties of the geologic systems produced by deformation after deposition and crystallization. In unconsolidated deposits the lithology and stratigraphy constitute the most important controls. In most regions knowledge of the lithology, stratigraphy and structure leads directly to an understanding of the distribution of aquifers and aquitards (Freeze 1979).

Ground water inevitably occurs in geologic formations. Knowledge of how these geological materials formed and the changes they have undergone is vital to the hydrogeologists. The earth is basically heterogenous and geologic training is a prerequisite to understanding the distribution of geologic deposits of varying hydraulic conductivity and porosity.

Based on the above discussions, the different geologic formations in the investigated area have different characteristics with regard to ground water movement and storage. Thus, with respect to ground water occurrence, each rock type will be treated in the following sections.

5.2. Aquifer Characteristics

1. Oligocene Basalt

As discussed in previous sections, this unit consists exclusively of basalt from the Trap series. The main exposures are a rubbly, finely crushed, fractured, sometimes spheroidally weathered basalt. As far as ground water occurrence is concerned, the secondary structures in this unit are the most likely places where water may be found. The main outcrops of the unit in the west of Arbaminch town show rocks which are deeply fractured and weathered. This is one of the favorable conditions for the infiltration of a great amount of water (Figure 18a & 18b).

Areal photographs and topographic maps of the area show that most of the tributaries of the Kulfo river are structurally controlled, i.e. the rivers flow along the N-S trending faults. Thus, the high frequency of these faults over the area increases the permeability of rocks.

According to the above criteria, the basalt unit can be a good aquifer in the study area. However, due to the fact that the rocks are found in the topographically high areas, they act as a recharge area for the aquifers that occur in the topographically lower areas. This is especially true for the springs found at the bottom of the valley. Until now, no boreholes have been drilled into this unit. Therefore, there is no hard evidence regarding the aquifer characteristics these rocks.

2. Quaternary volcanics

These are the basalts and scoraceous basalts found near Arbaminch town and the Bridge-of-God. They are relatively fresh and show structures like gas vesicles and cooling joints as pore spaces.

No wells were drilled into this unit, but exposures revealed that an appreciable amount of water can be infiltrated through joints. Interconnected pore spaces can

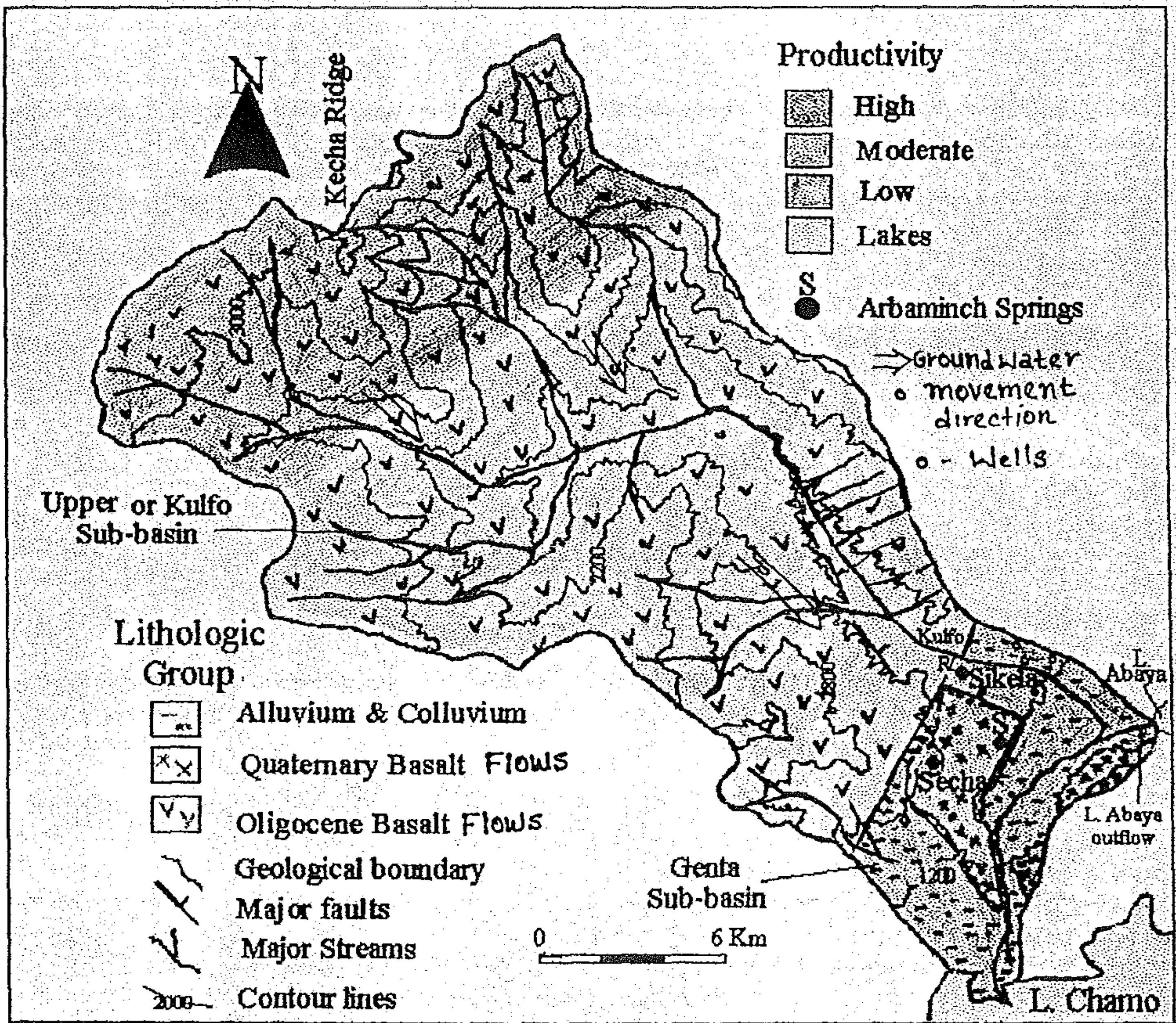


Fig.18a. General Hydrogeological map of the study area.

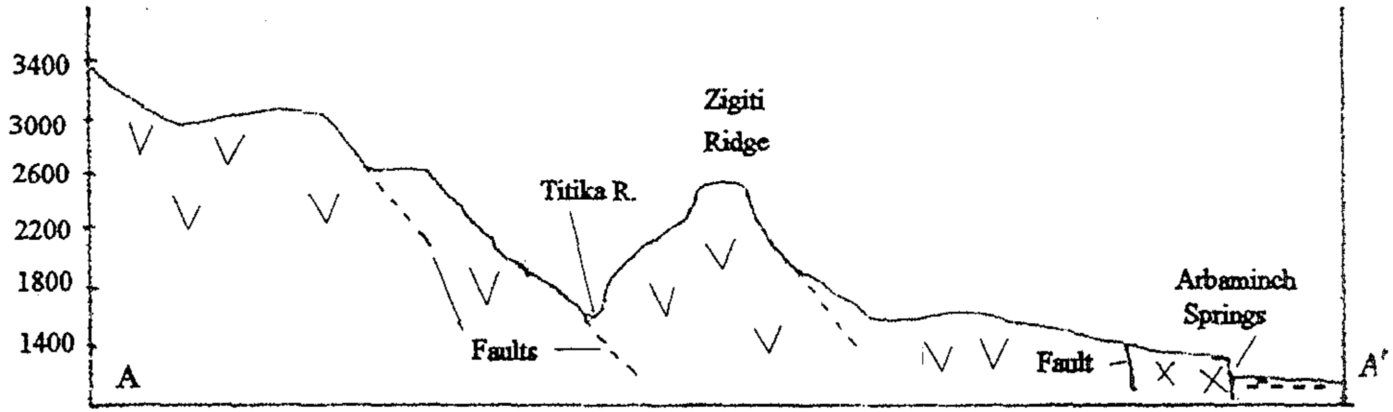


Figure 18b: Geological Cross-section A - A'

also increase the permeability of the rocks. Based on visual observations, this rock unit has lower permeability than the older basalts
(Figure 18a & 18b).

3. Alluvial Sediments

The most important unit for ground water occurrence are the alluvial sediments which occur at the rift floor of the study area. Because of the shifting position of river channels and the ever changing depositional velocities, river deposits have characteristic textural variability that causes much heterogeneity in the distribution of hydraulic properties. This anisotropy is shown on geologic logs taken from AWTI.

The lithology and stratigraphy constitute the major controls for ground water occurrence (Figure 18a & 18b). Generally, these deposits are composed of gravels, sands, silts and clays that are not bound or hardened by mineral cement or pressure. The gravels and sands can act as aquifers whereas the clay can be aquitards. So the water bearing formations in the study area are either gravel, sand or a combination of sand and gravel. The geological log of these formations is shown in figure19.

The thickness of this deposit varies from 60 m near the foot of the escarpment to 20 m near Lake Abaya. Generally the grain size of the sediments decreases when one goes from the foot of the escarpment to the lake and this is true for the deposit of fluvial origin.

5.2. WELL HYDRAULICS

The other steps for groundwater studies in a given area is to determine the hydraulic parameters of the aquifers. These types of information can be obtained by conducting aquifer or pumping tests. These tests allow us to calculate transmissivity, hydraulic conductivity and storativity and helps us to determine how much

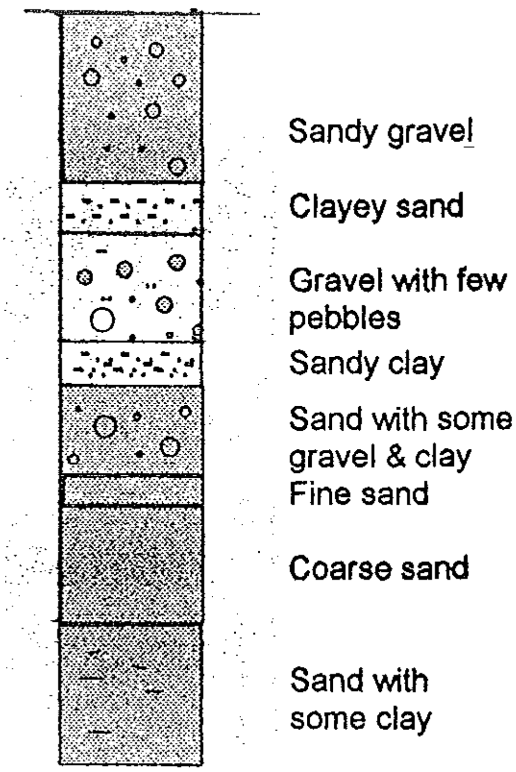


Figure 19: Geological Log of AWTI No.4 Borehole

groundwater can be safely withdrawn perennially from the aquifers in the area under study.

All the boreholes in the study area are found within alluvial sediments. About five wells are located within the catchment area, but it is not possible to find any type of information about these wells. However, the wells which are found in the Arbaminch Water Technology Institute(A.W.T.I.) represent the hydraulic properties of alluvial sediments since they are close to the study area and are within the same type of sediments. So all the hydraulic analyses are based on data from A.W.T.I. of E.W.W.C.A. boreholes.

Out of the seven wells in the institute, the pumping test data of only three wells still exist. In the following section, the analysis of well hydraulics will be presented.

There are two flow conditions in ground water:

a. A steady state condition: when the flow is steady and the water levels have ceased to decline. For steady flow of water in homogeneous and isotropic media:

$$\Delta^2 h = 0$$

where $\Delta = d/dx + d/dy + d/dz$ and

h = head causing flow

b. A non-steady state condition: when the rate of flow through the aquifer is changing and the water levels are declining; water is taken from storage within the aquifer and the water level or piezometric head (in confined aquifer) is gradually reduced.

The equation for such type of flow is:

$$\Delta^2 h = S/T \; dh/dT$$

Where S is the storativity of an aquifer

T is transmissivity of an aquifer

K is the hydraulic conductivity of an aquifer

Storativity (storage coefficient) may be defined as the ratio of the volume of water released from (or taken into) storage in a unit column of the full saturated thickness of the aquifer, under a unit change in head to the total volume of the unit column of the aquifer. Permeability (hydraulic conductivity) is a measure of rate at which water may be transmitted through cross-sectional area of an aquifer under an hydraulic gradient of unity. Transmissivity may be defined as a measure of the rate at which water is transmitted through a unit width of the full saturated thickness of an aquifer under a hydraulic gradient of unity.

$T = Kb$

Where b is the saturated thickness of an aquifer.

All the above parameters for the confined and unconfined aquifers will be treated in the following sections.

I-Steady Radial flow in to a well: (Dupuit 1863, Thies 1906): After prolonged pumping from the well the drawdown stabilizes, when the cone of depression spreads to natural discharge and recharge areas. i.e. the steady state and steady shape condition have developed.

1. Water table conditions (unconfined aquifers): They may be defined as aquifers close to the land surface with continuous layers of materials of high intrinsic permeability extending from the land surface to the base of the aquifer.

The yield from this well is $Q = \dfrac{1.36K(h_2^2 - h_1^2)}{\log r_2/r_1}$

Where K : hydraulic conductivity of the aquifer,

h_2 : depth of water in the observation well,

h_1 : depth of water in the pumping well,

r_2 : radius of the observation well from the pumping well,

r_1 : radius of the pumping well.

2. Confined aquifer: aquifers overlain by confining layers.

The yield from this well is

$$Q = \frac{2.72Kb(h_2-h_1)}{\log r_2/r_1}$$

or $$Q = \frac{2.72T(h_2-h_1)}{\log r_2/r_1}$$

The assumptions in Thiem's equations are:

i. stabilized drawdown

ii. constant thickness of the aquifer with constant permeability (isotropic),

iii. complete penetration of the well with 100% efficiency;

iv. radial flow into the well.

II. Unsteady radial flow into a well.

1. Confined aquifer: A well pumping at a constant rate from an extensive confined aquifer produces an area of influence which expands with time. It is possible to solve the hydraulic parameters of the aquifers in several ways, but all assume the following conditions:

i: flow is in the range of Darcy law,

ii. water is discharged instantaneously from storage,

iii. the aquifer is homogeneous and isotropic,

iv. the aquifer has a constant thickness and a negligible slope and is of infinite extent.

Among the different methods, the Theis method, the Copper-Jacob straight line method and the distance drawdown method are the most commonly used non-equilibrium methods.

2. Unconfined aquifer: In unconfined aquifer, water comes mainly by gravity drainage which is not instantaneous. The storage coefficient reduces with time and ultimately becomes equivalent to the specific yield. Two methods can be applied to solve the hydraulic parameters of the aquifer:

a. Non-equilibrium methods: It can be applied to unconfined aquifers with the following limitations;

i. if pumping drawdown does not exceed 10% of the aquifer thickness; then

$T = QW(u)/4pi(h_o\text{-}h)$ and

$S = 4Ttu/r_2$

Where W(u): well function of u, see table .

h_o: hydraulic head prior to the start of pumping,

h: hydraulic head after some time t,

t: time since pumping begun,

r: radial distance of an observation well from the pumping well.

ii. if the drawdown versus aquifer thickness is in the range of 10 to 25% correction factor must first be applied to drawdown data compiled in the filed.

The Jacob correction factor is:

$(h_o - h)_c = (h_o - h) - (ho - h)^2/2M$

Where $(h_o - h)_c$: corrected drawdown,

$(h_o - h)$: measured drawdown in an observation well,

M : saturated thickness of the aquifer prior to pumping.

iii. if the drawdown versus aquifer thickness is above 25%, non-equilibrium methods cannot be used reliably for unconfined aquifers.

b. Delayed-Yield Non- equilibrium methods: The most accurate techniques for analyzing pumping test data from unconfined aquifers involve a multiple curve-matching approach originally proposed by Boulton (1963). This combines a match of early data to a Theis curve, and later delayed-yield data to a second curve set. As implied, these methods provide the best model for the hydrologic phenomena that actually occur in the pumping drawdown of an unconfined aquifer.

The equation is $T = \frac{Q}{4pi(h_o\text{-}h)} W(U_{ay}r/M)$

$$S_{ed} = \frac{4Tt_1U_a}{r^2}$$

$$S_y = \frac{4Tt_2U_y}{r^2}$$

Where S_{ed} : early data storativity,

S_y : specific yield, or (true) storativity in unconfined aquifer,

r : radial distance of a monitoring well from the test well.

t_1 : time corresponding to the first (early data) match point,

t_2 : time corresponding to the second (delayed-yield) match point.

$W(U_{ay}r/M)$: well function

As has already been explained, the wells in the study area are found in alluvial sediments. As far as the productivity of these sediments is concerned, the have better aquifer properties than the volcanics. Among the five wells in the AWTI compound, well No. 4 was selected as most representative because it has very extensive pumping test data and a good geological log compared to the others. As shown in figure 19, the aquifer type is unconfined, i.e. it is a water table aquifer. The pumping test for 2700 minutes resulted in a drawdown of 0.8 m with a discharge of 193 liters/second. The "Non-equilibrium Radial Flow in an Unconfined Aquifer" equation was used to calculate the transmissivity and hydraulic conductivity of the aquifer. The drawdown and the type curves are shown in figures 20, 21a and 21b. The transmissivity (T) of the AWTI No.4 was calculated to be 242 m^2/day, while the hydraulic conductivity is 5 m/day. Storativity cannot be determined accurately when the observations are taken in the pumping well. (Fetter, 1994)

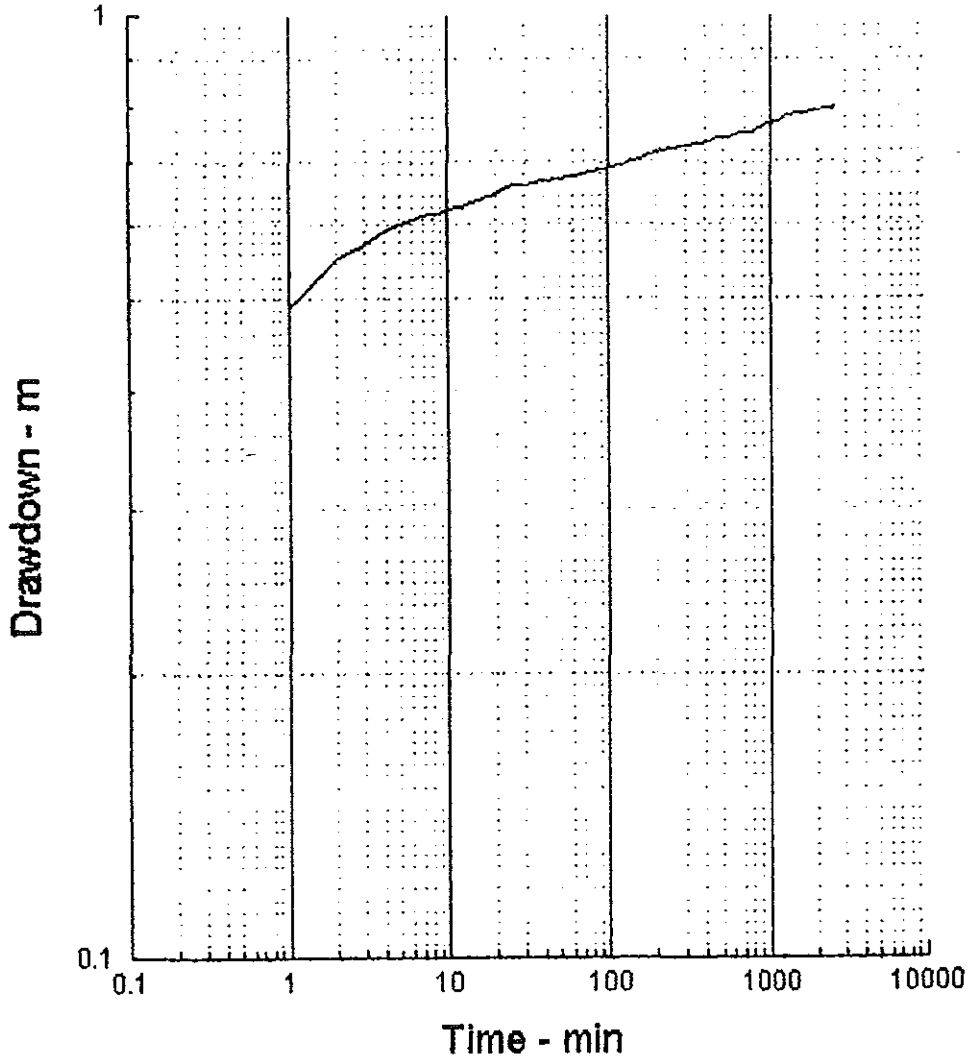


Figure 20: Drawdown Curve for AWTI No.4 Pump Test

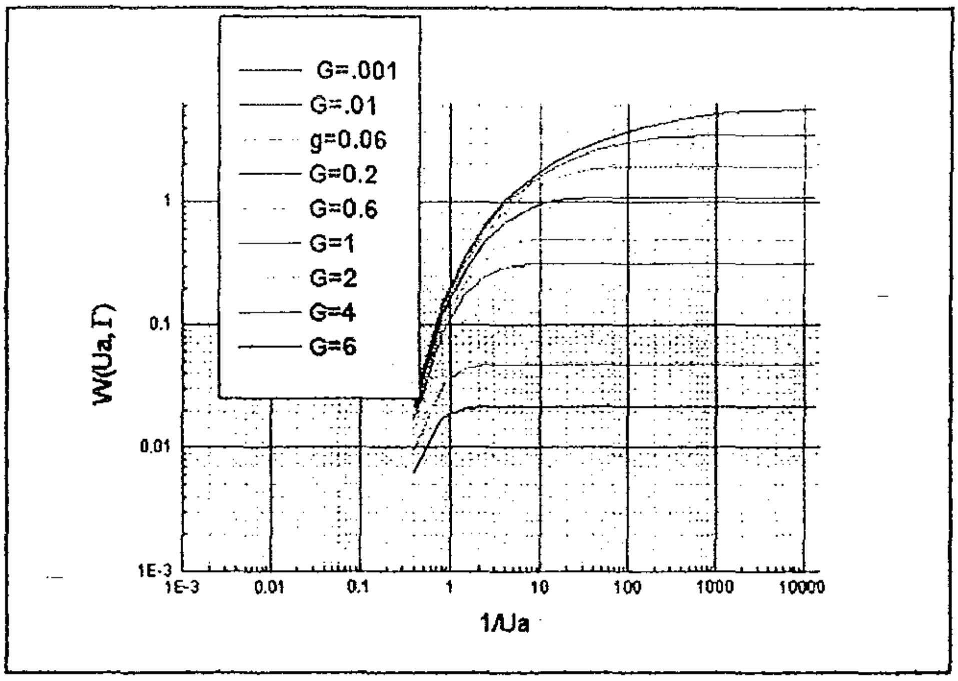


Figure 21a: Type Curve for Water Table Aquifers (early drawdown data)

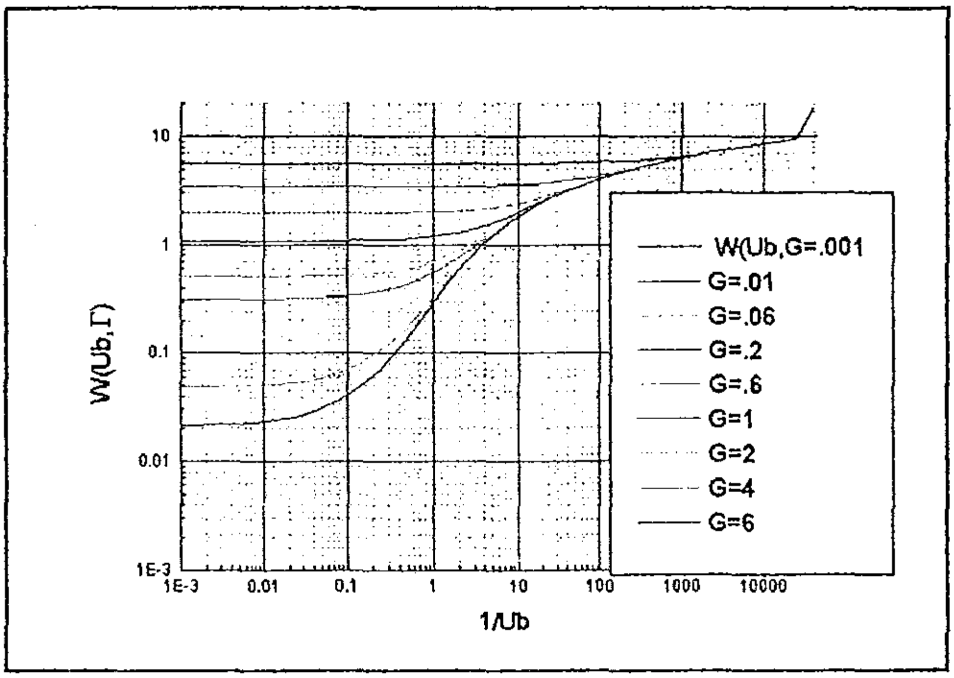


Figure 21b: Type Curve for Water Table Aquifers (later drawdown data)

CHAPTER SIX
THE SPRINGS

Springs are important sources of water supply and many towns depend on them. Among these towns, Arbaminch is one which uses spring water for drinking purposes. Since the town depends almost totally on springs, it is important to study the hydrogeological conditions of these springs.

6.1. General

Springs may be defined as points, lines, or limited areas of the earth's surface from which groundwater rises up according to the hydrogeological characteristics of the underground reservoirs. Generally they exist in different forms.

The Arbaminch (In Amharic, Arbaminch means 40 spring) springs are located at the foot of the NE-SW trending escarpment below the Bekele Molla hotel. It is difficult to determine exactly how many springs there are, but the springs align for about 100 to 150 meters along the foot of the escarpment. The existence of deep green vegetation for about one kilometer along this line reveals the presence of shallow groundwater. The presence of colluvium deposits along the line of springs makes it difficult to identify the exact place of the eye of the springs.

6.2. Type of the Springs

The main controls for the nature of the springs could be lithology, structure and topography. Based on these, the type of the Arbaminch springs could be fault springs. Fault springs are formed when groundwater overflow occurs through faults affecting different lithological formations. In the case of the Arbaminch springs a series of faults separate the recent basalt formations from the alluvial sediments (Fig 22). Generally, the regional ground water movement follows the law of gravity, i.e. from higher topography to lower one. As the groundwater reaches the fault system it tends to flow through the faults. The shallow water table at the alluvium side verifies

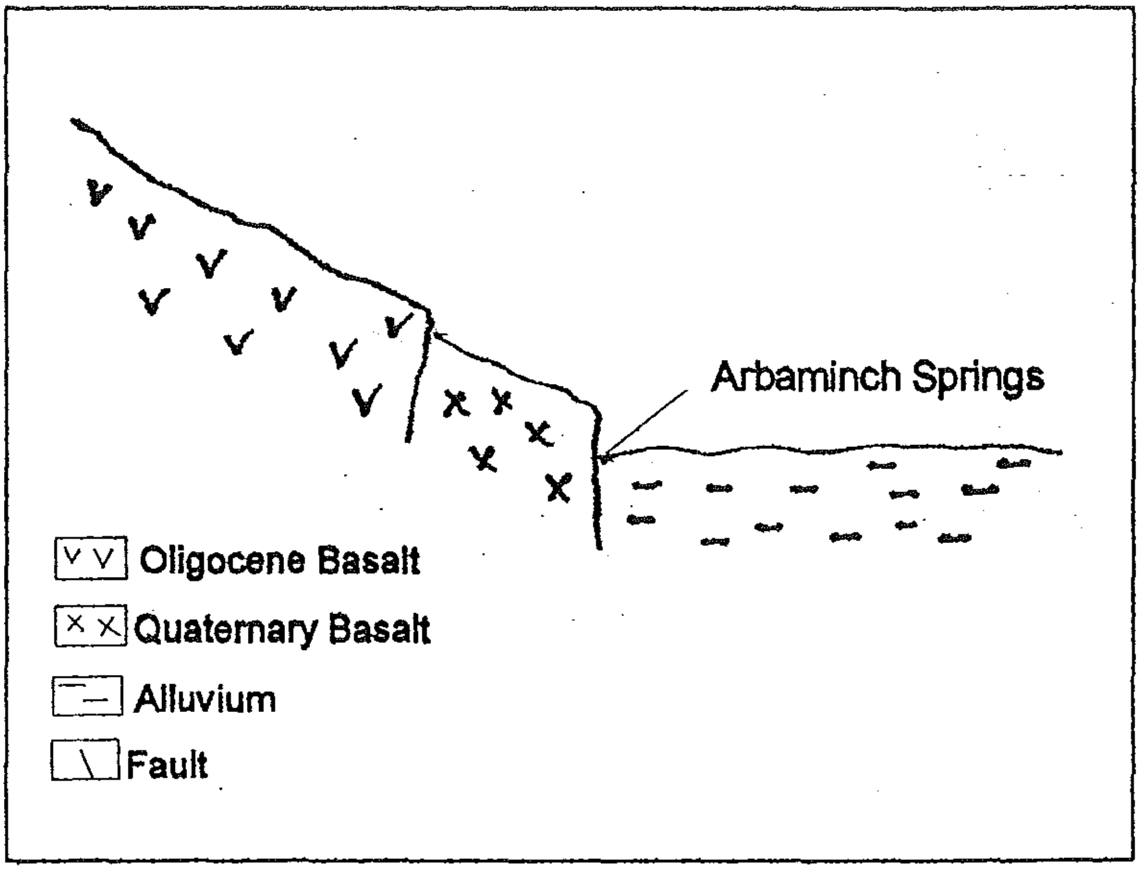


Figure 22: Fault Springs - Type Model for Arbaminch Springs

that water passes across the faults.

6.3. Spring Classification

Several authors have proposed different types of classifications for gravity springs. The springs in the study area may be classified in the following manner. These classifications are based on discharge data for the year 1978/79, which is the only available data for the springs. However, the classification based on these data give a reasonably accurate result since the recharge conditions of that years are similar to the other years. An interview with local residents implies that there is very little variability in the discharge rate of the springs from year to year.

A. Meinzer Index: Springs which refer to their discharge variability by using the Meinzer index R expressed in %.

$$R = 100 * \frac{(a-b)}{c}$$

Where a: The maximum discharge per unit time.

b: the minimum discharge per unit time.

c: The mean discharge per unit time.

By means of this method it is possible to classify the springs as follows;

-Constant Springs when R is less than 25%.

-Subvariable springs when R is greater than 25% and less than 100%.

-Variable springs when R is Greater than 100%.

As far as Arbaminch Springs are concerned, the maximum discharge is 250 l/s, the minimum discharge is 140 l/s and the mean discharge is 185 l/s.

$$R = 100 * \frac{(a-b)}{c}$$

$$R = 100 * \frac{(250\ l/s - 140\ l/s)}{185\ l/s}$$

R= 59.32%.

Therefore the springs are classified as subvariable springs.

B. Spring Classification based on mean discharge.

The following table (Table 13) shows Meinzer's classification of springs based on the mean discharge.

Magnitude(order)	Discharge
1st	>10 m^3/s
2nd	1-10 m^3/s
3rd	0 .1-1 m^3/s
4th	10-100 l/s
5th	1-10 l/s
6th	0.1-1 l/s
7th	10-100 ml/s
8th	<10 ml/s

Table 13: Meinzer's Spring Classification based on Discharge

Since the mean discharge of the springs is 185 l/s, the springs are classified as 3rd order springs.

6.4. Spring Hydrogeology

In order to characterize the importance of a spring, its regimen has to be known. Arbaminch springs' regimen is expressed by plotting discharge vs time in figure 23. From the rainfall-discharge graph it is possible to see the time lag between the rainfall and corresponding discharges. The time lag is dependent on the geological features and the hydraulic characteristics of the soils or rocks which constitute the hydrogeological basin.

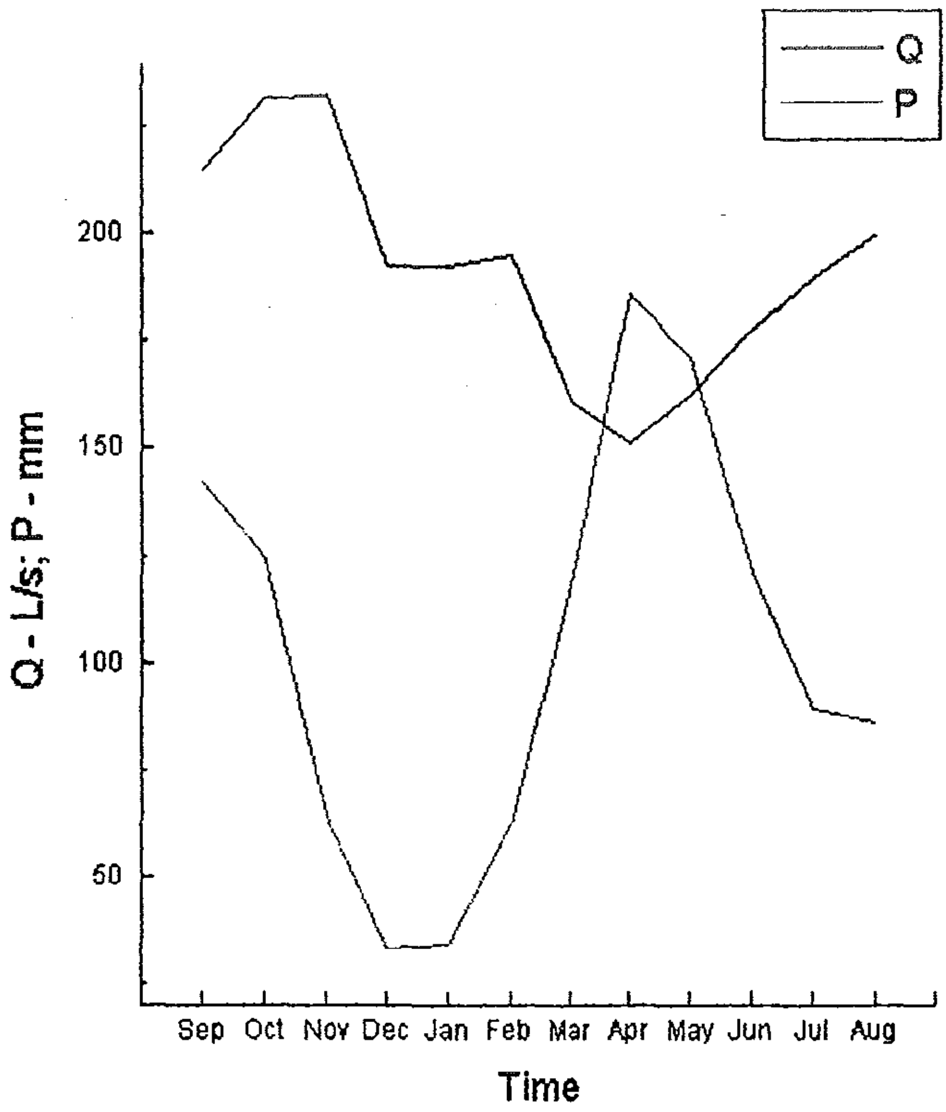


Figure 23: Arbaminch Springs: Discharge vs. Rainfall Relationship

Considering figure 24, the discharge - time graph, the sub-arch A-B corresponds to a period of high discharge, due to high rainfall rates, which reaches the maximum value after a certain time lag.

The sub-arch B-C characterizes the spring's discharge behavior during a period of rainfall recession. Two possibilities may then occur; the springs' discharge increases according to the curve C-D, or the springs' discharge decreases following the curve C-G.

The last sub-arch C-G (or generally B-G) corresponds to the "not influenced regimen of the springs". Such a curve is called the springs' recession curve. The recession curve of a spring may be analytically expressed by the following equation;

$$Q_t = Q_0 e^{-\alpha t} \text{ ------------------------(6.1)}$$

Where:

Q_t - any discharge value on the recession curve,

Q_o - initial discharge value at t= t,

e - basis of Neperien log,

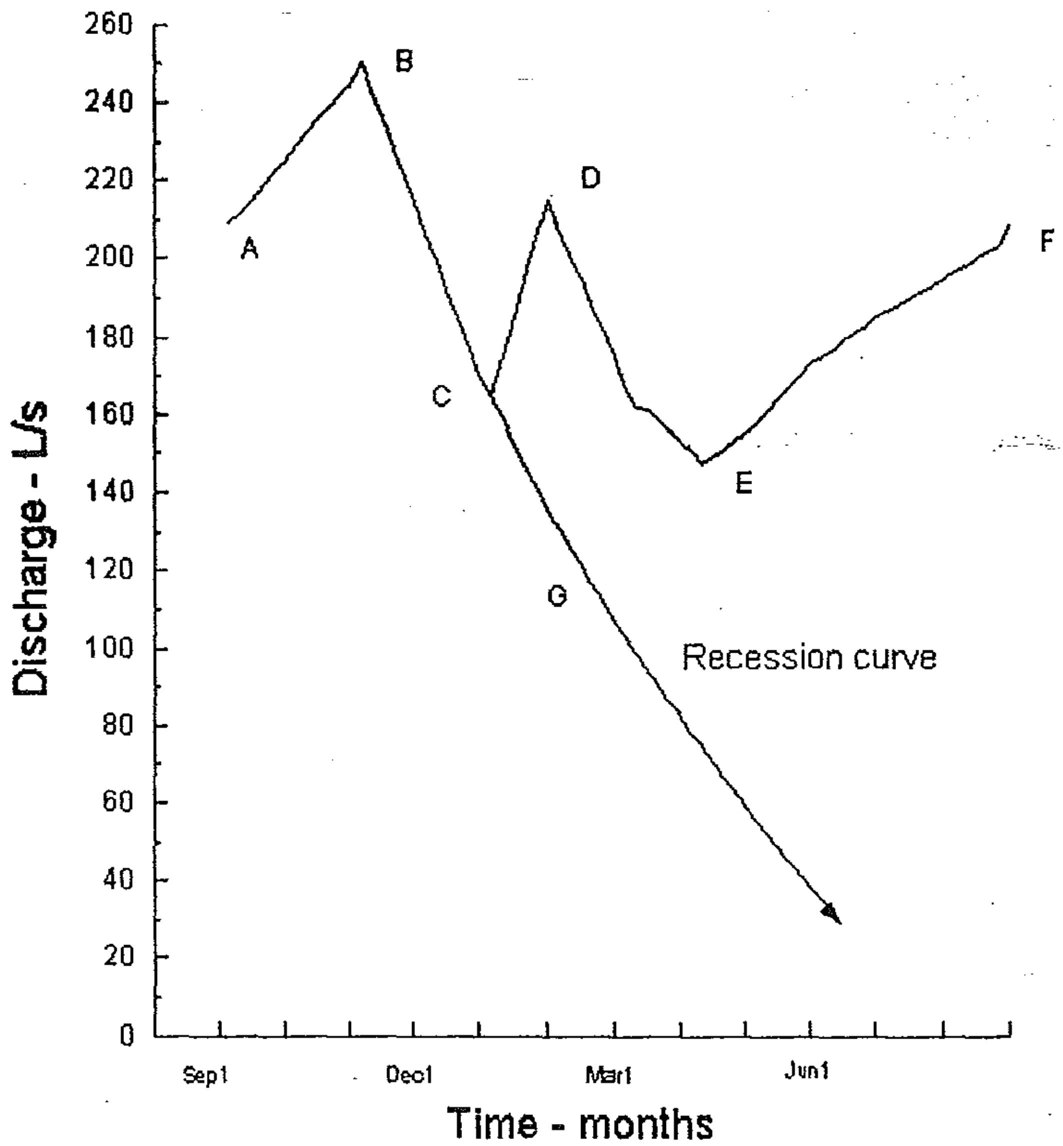
α - recession coefficient.

The coefficient α, which is given from the geometrical point of view by the subtangent to the curve at any point, is constant for each representative curve. It gives at the same time the shape of the curve on which the more or less stable regimen of the springs depends.

Let us consider equation 6.1 and figure 24. It is possible to calculate the recession coefficient α by taking two points from the springs' recession curve.
At time t=0, discharge Q = 243 l/s and at time t = 50 days , the discharge Q = 170 l/s.

Then ; $Q_1 = Q_o \, e^{-\alpha t1}$ ------------------------(6.2) and

Figure 24: Hydrograph of Arbaminch Springs



$$Q_2 = Q_o \ e^{-\alpha t2} \text{ ------------------------(6.3).}$$

Therefore;

$$\frac{Q_2}{Q_1} = \frac{Q_o \ e^{-\alpha t2}}{Q_o \ e^{-\alpha t1}} \qquad (6.4)$$

Using the Arbaminch springs' data and the above equation the following α value is obtained: 0.00714/day or 8.26×10^{-8} 1/s.

Therefore the equation of the curve for "the not-influenced regimen" is

$$Q_t = 243e^{-8.26^{*} 10\text{-}8t} \qquad (6.5)$$

where t = seconds

Qt = l/s

The discharge- time relationship for the "not influenced" regimen is also shown in figure 24. From this curve it is possible to see the discharge at any time t. For the not-influenced regimen, it is possible to forcast the discharge of the springs at any time t. So, for instance, with the help of this curve, one can predict the time at which the discharge will be less than the minimum needed for the population in case of lack of rainfall.

As time t approaches infinity the discharge Q approaches zero. But for small amounts of discharge it is possible to see the relationship. For Q= 10 l/s, t = 446.85 days; for Q = 1 l/s, t = 769.34 days and for Q = 0.1 l/s, t = 1091.8 days.

In order to determine the discharge behavior of a spring, the hydraulic volume of the hydrogeological basin which instant by instant feeds the same spring has to be evaluated. The following continuity equation is valid for ground water reservoirs as the hydrogeological basin:

$$Q_a dt - Q_e dt = dV \text{ -------------------(6.6)}$$

Where

Q_a- the inflow rate (rainfall) during the time interval dt.

Q_e- The outflow rate (discharge) during the same time interval dt.

dV- the infinitesimal volume variation during dt in to the ground water reservoir.

During the not influenced regimen the inflow rate Qa is zero; then the above equation becomes:

$-Q_e dt = dV$ ---------------------------(6.7)

then $Q_e = Q_t = Q_0 e_{-t}$

Solving the above equation results the following relationship:

$$\alpha = \frac{Q_t}{V_t} \implies vt = Q_t/\alpha \qquad (6.8)$$

$vt = 0.12 \times 10^8$ Qt

where Qt = l/s, and vt = l

For instance, at a discharge of 200 l/s , the volume of the hydrogeological basin which feeds the springs is equal to $2.42 * 10^9$ l or $2.42 * 10^6$ m^3.

From the above result, Q_t being equal, the recession coefficient α is inversely proportional to the volume V_t. For such a very small α, we have a great volume of water with a high yield capacity of the spring.

6.5 Water Quality

6.5.1. Introduction

The quality of water that we ingest as well as the quality of the water in our lakes, streams, rivers, and oceans is a critical parameter in determining the overall quality of our lives. Water quality is determined by the solutes and the gases dissolved in the water , as well as the matter suspended in and floating on the water.

Water quality is a consequence of the natural physical and chemical state of the water as well as any alteration that may have occurred as a consequence of human activity. The suitability of water for a particular purpose is determined by the water quality.

Water naturally contains a number of different dissolved inorganic constituents. The major cations are calcium, magnesium, sodium and potassium; the major anions are chloride, sulfate, carbonate, and silica. Because water is such a powerful solvent, it contains some measure of dissolved constituent even in a pristine environments. The type and amount of these constituents determine the suitability of water for drinking, for industrial, or agricultural use. Ground water, by virtue of long residence time in contact with geologic material, generally contains higher concentration of dissolved solids than surface water. Some important factors contributing to the quality/chemistry of ground water are:

1- the mineral composition of aquifer rocks

2- the general hydrogeologic parameters of the area

3. the potential for ground water mixing and for the occurrence of interactive geochemical reactions.

4. the activities of men relative to recycling capacity of the aquifers.

6.5.2. Water chemistry of the Arbaminch Springs.

Generally, springs develop when ground water reaches the earth surface. So the chemical composition of springs is related to the soluble products of the host rock, weathering and decomposition, and changes with respect to time and space.

The following chemical analysis data is a result of the data from twelve towns water supply project, Arbaminch, May 1983. 15 samples were analyzed from the springs from 1976 to 1977 but the chemistry of the springs was done only on 9 samples. Of the nine samples, 8 samples were analyzed by the central laboratories and one was done by the Ministry of Mines.

All the analyses show that the natural temperature of the spring water is 22°C. The analyses showed that the spring water is colorless, odorless, tasteless and clear. The pH of the springs ranges from 7.0 to 7.75. Generally the pH range of most natural waters is between 6 and 8, and hence the pH of the springs is within expected limits.

Another basic measure of water quality is the total dissolved solids (TDS), which is the total amount of solids that remain when a water sample is evaporated to dryness. Table 14 gives a classification of water based on Total Dissolved Solids.

Table 14: Classification of water based on Total Dissolved Solids (Fetter, 1988)

Class	TDS (mg/L)
Fresh	0 - 1000
Brackish	1000 - 10000
Saline	10000 - 100000
Brine	> 100000

The TDS of the springs range from 200 - 289 mg/ L. So according to the classification, the water from the springs is categorized as fresh water. This value of TDS is a result of the interaction between rocks and water.

The hardness of the spring water as $CaC0_3$ ranges from 110- 125 mg/l. According to the classification of water based on hardness (Seyer and McCerty, 1967) (table 15) it is moderately hard water.

Table 15: Hardness Classification of water

Water class	Hardness, mg/L as $CaC0_3$
Soft	0 - 75
Moderately Hard	75 - 150
Hard	150 - 300
Very Hard	over 300

Based on the chemistry of the major cations and anions , the piper diagram for the springs has been plotted (Figure 25). Hydrochemical classification using the piper diagram shows that the spring water is of bicarbonate type. Of the 9 samples, 2 samples are alkaline (sodium) Bicarbonate type , 3 samples are Calcium bicarbonate type and the rest are alkaline- Calcium bicarbonate type. The bicarbonate concentration in igneous rocks could be accounted for the dissociation of the water under the presence of CO_2, but Cl^-, and SO_4^{2-} are not significant constituent in igneous rocks and there is no interaction as ground water moves along flow paths in these rocks.

Generally, iron and manganese are not present in the sample. But the SiO_2 content ranges from 40 - 45 mg/L. This value is higher compared to the medium value of silica, for ground water. Crystalline SiO_2 is the major constituent of many igneous rocks. This amount of dissolved silica observed in this spring water may be from the chemical break down of the silicate minerals in the process of weathering.

Bacteriological analyses in the year 1977 reveled that total coliform bacteria were present in the springs. Another bacteriological test was also performed by the author in 1996 and all total coliform bacteria tests were positive. This might be explained by poor sanitation in the Secha town, where human wastes may easily percolate into the springs. This is also witnessed by the relatively high content of nitrates.

The total coliform bacteria (common species and Escherichia coliform) occur in great amounts in the intestinal tracts of warm blooded animals, and the presence of these in water is generally considered as evidence of fecal pollution. The coliform bacteria are not themselves directly harmful, but their presence is considered suggestive of the presence of other species that are pathogenic.

6.5.3. Relation of Water Quality to Use.

An immediate purpose of the study of the quality of water is to determine if the

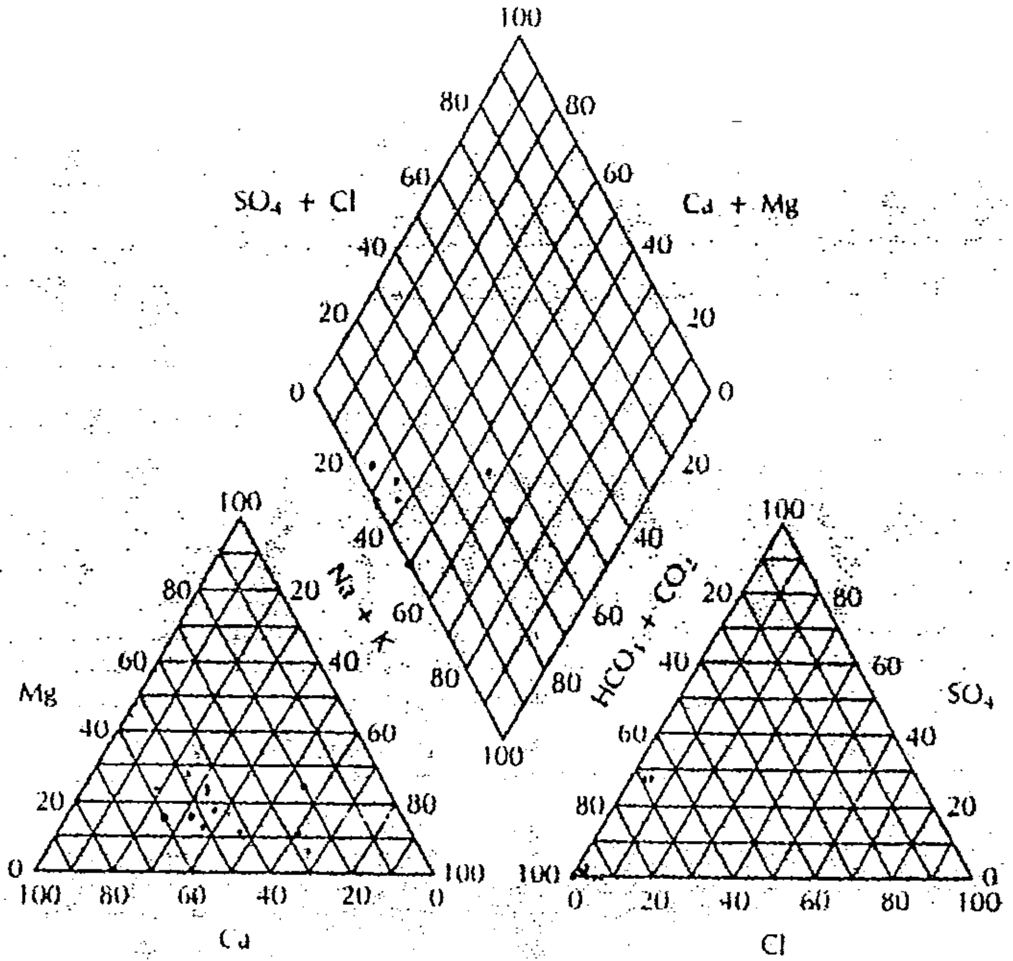


Figure 25: Piper Diagram for Arbaminch Springs

water is adequate for various use purposes. Accordingly, the subject of water analysis interpretation must often include some consideration of standards and tolerances that have been established for water that is to be used for various purposes. Standards for water to be used for drinking and other domestic purposes have been established in many countries. Published literature contains tolerance levels and related data for the constituents of water to be used in agriculture, industry, for propagation of fish and for a number of other specific purposes.

Requirements for water that is to be used as a public supply generally are more restrictive than those that would be applied to water for farm supply or industrial use.

1. Domestic Uses

Besides being chemically safe for human consumption, water to be used in the home should be free of undesirable properties such as color or turbidity and should have no unpleasant taste or odor. Harmful microorganisms should be absent.

According to the standards for drinking water by the World Health Organization (WHO, Table 16) the spring water is safe to drink. However, the presence of total coliform Bacteria requires chlorination of the water before being used as drinking water..

Table 16: World Health Organization International Drinking Water Standards.

Characteristics	Limit of general acceptability (mg/l)	Allowable Limit (mg/l)
Total solids	500	1500
Color (pH)	5	50
Turbidity	5	25
Chloride	200	600
Iron	0.3	1
Manganese	0.1	0.5
Copper	1	1.5
Zinc	5	15
Calcium	75	200
Magnesium	50	150
Mg and Na sulfate	500	1000
Nitrate (as NO_3)	45	-
Phenols	0.001	0.002
Synthetic detergents (ABS)	0.5	1
Carbon-chloroform extract	0.2	0.5
pH	7-8	

2. Agricultural Use

The chemical quality of the water is an important factor to be considered in evaluating its usefulness for irrigation. Factors of chemical composition that need to be considered include the total concentration of dissolved matter in the water, the concentration of certain potential toxic constituents, and the relative proportions of some of the constituent present. According to the water quality standards for agriculture there is no restriction to use.

While a high salt concentration in water leads to the formation of saline soil, a high sodium leads to development of alkaline soil. USDA has defined an alkaline soil having a pH of 8.5 or more with a Na-saturation of 15% or more. An alkaline soil has an unfavorable structure, puddles easily and restricts the aeration. Further, the high Sodium saturation directly causes Calcium deficiency. Irrigation water with a low sodium absorption (SAR) is desirable. SAR is defined as :

$$SAR = \frac{Na^{+}}{\sqrt{Ca^{++}+Mg^{++}/2}}$$

where the concentrations are expressed in meq/L

The sodium percentage is calculated as:

$$Na\% = \frac{Na + K}{Ca + Mg + Na + K}$$

Where all ionic concentrations are expressed in meq/L.

The electrical conductivity results have been calculated from the Total Dissolved Solids by conversion, where 1 meq/l of cations equals 100 EC x 10^6 µS/cm and 1 mg/L is equal to 1.56 EC x 10^6 µS/L. According to Todd, 1959, for most water the EC ranges from 100 - 5000 µS/cm at 25° C.

As shown in table 17, the SAR value of the springs ranges from 0.495 to 2.93; which is "excellent" water according to the quality classification of irrigation water (Table 18) and ranges from "excellent" to "good" with regard to the salinity hazard classification (Table 18).

The classification based on electrical conductance and soluble sodium percentage by Wilcox (1955) was also performed. Based on the Wilcox diagram (Figure 26), the class of water ranges from good to permissible.

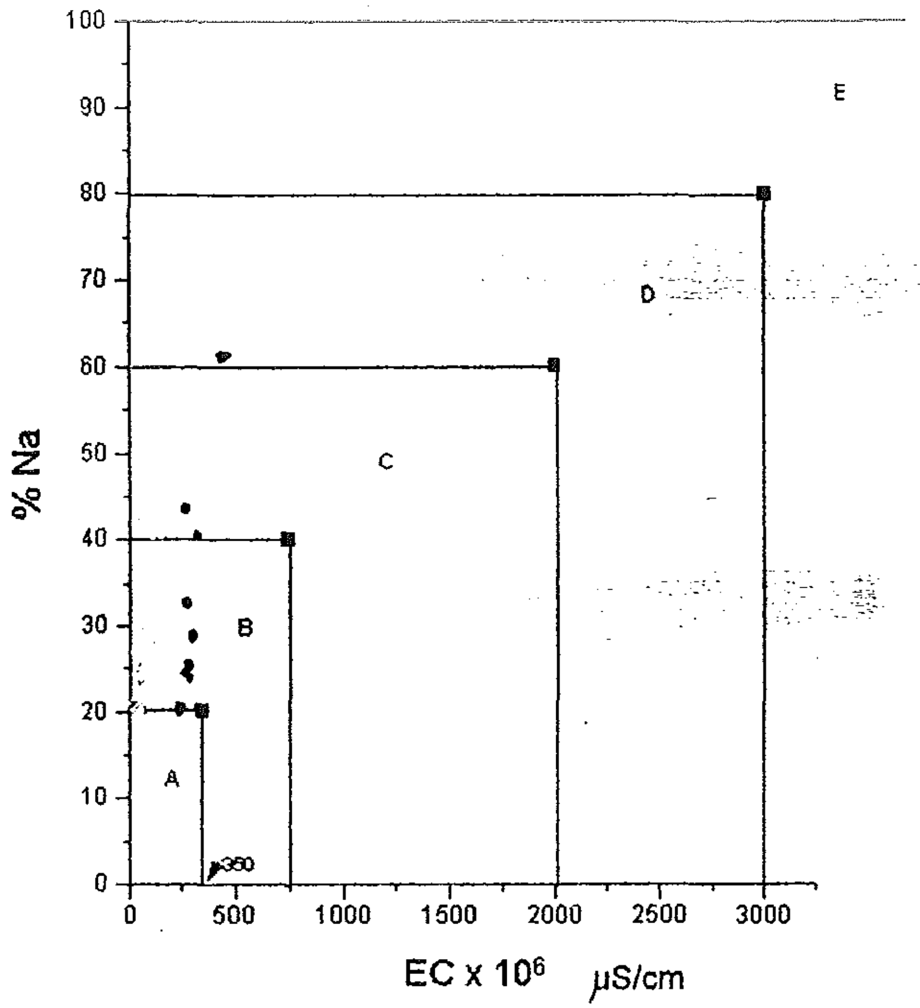


Fig 26: Arbaminch Springs: Water Quality for Irrigation
(After Wilcox, 1955)

A = Excellent
B = Good
C = Permissible
D = Doubtful
E = Unsuitable

Table 17: The value of SAR, % Na and Electrical conductivity for nine samples in the Arbaminch spring water.

Sample No	SAR	% Na	EC * 10^6
1	0.495	20.36	276
2	0.71	25.71	320
3	0.74	23.69	336
4	0.68	24.23	293
5	1.06	42.97	211
6	0.81	28.75	335
7	1.41	40.76	370
8	2.93	61.32	470
9	0.87	32.54	317

Table 18: Quality classification of irrigation water (USDA)

water class	Salinity hazard EC ohms/cm	Alkali hazard SAR
Excellent	<250	up to 10
Good	250-750	10-18
Medium	750-2250	18-26
Bad	2250-4000	>26
Very bad	>4000	

Concentration of certain specific elements such as Boron and Lithium are toxic to plants. But the concentration of these elements are insignificant in the spring water and hence toxicity is not a problem to the quality of water in the area. Generally, the spring water chemistry confirms with the International standards of water for agriculture.

3. Industrial Use

The quality requirements for industrial water supplies range widely, and almost every industrial application has its own standards. For some uses such single-pass condensing of steam or for cooling or for concentrating ores, chemical quality is not particularly critical and almost any water may be used. At the opposite extreme, water approaching or equaling the quality of distilled water is required for processes such as the manufacture of high-grade paper or pharmaceutical, where impurities in the water would seriously affect the quality of the product.

CHAPTER SEVEN
CONCLUSION AND RECOMMENDATION

The Kulfo River Basin having an area of 439 km^2., constitute a part of the rift floor and the western escarpment. More than 85% of the basin is covered by Oligocene basalt and the rest is by Quaternary volcanics and Alluvium.

Considering three meteorological stations at Arbaminch, Chencha, and Gerese towns, Thiessen polygon methods were employed to calculate the weighted mean rainfall depth and the Potential Evapotranspiration over the basin (upper or Kulfo Sub-basin). The calculated mean annual rainfall is 1232 mm and the actual evapotranspiration is 941 mm. In principle the difference between rainfall and actual evapotranspiration is the surplus water which is divided into runoff and infiltration. But the measured amount of runoff depth (362 mm) is greater than the calculated surplus water, which is 291 mm and hence it is not possible to determine how much water is infiltrated in to the ground. This might be due to the fact that ground water may be imported from other basin or in other word the ground water basin is wider than the surface water basin. The other reason may be the information from meteorological and hydrological stations (for runoff) are incorrect. Therefore further study is recommended to know exactly the ground water basin boundary. This study may also give a clue as to the size of the recharge area of the springs.

The aquifer classification in the basin are based on topography, rock type and structure. The different rock units in the area have their own typical characteristics to groundwater occurrence. the sediments being the main aquifers in the study area.

Taking into consideration the discharge value of the Arbaminch springs in 1979, the springs hydrogeology (including spring classification) was computed. The Arbaminch springs, which are fault springs, have third order magnitude. From the spring hydrograph it is possible to find the spring recession curve and the recession constant for the not-influenced regimen. Therefore the equation for the "not-influenced" regimen for the Arbaminch springs is $Q_t = 243^{e-8.26*10-8t}$.

where Q_t is discharge at any time t in l/s and
t is time in s.

Generally this equation is the general hydrological equation for Arbaminch springs. Thus, using this equation it is possible to obtain the discharge of the springs at any time in case there is no rainfall after the end of the rainy season.

The hydraulic volume V_t of the hydrogeological basin which instant by instant feeds the springs has been also evaluated.

$$V_t = 0.12 * 10^3 Q_t$$

Where Vt is in l and Qt is in l/s. This is used to determine the discharge behavior of the springs. Thus, for such a small amount of recession constant, there is a great volume of water with a high yield capacity of the springs.

The chemistry of the spring water is good for drinking purposes, except the presence of total coliform bacteria. This is caused by the seepage of human wastes in to the spring from the upper town of Arbaminch (Secha). In general, poor sewage system are practiced in the town. An interview made with local people revealed that there is almost no lined concrete waste disposal (especially for human wastes) sites in the town. So it is recommended to build a lined waste site not to pollute the spring water.

Considering the quality of water to agricultural use, it is classified as good to permissible class. But the quantity of the water may restrict the use of it to a large-scale agriculture. As far as industry is concerned , almost every type of industries have their own standards. And the quantity is also questionable.

Electric power is necessary to pipe water from the springs to town. During interruptions of power, no water is available from the springs. So people suffer periodic water shortages during power outages. Therefore, further study is recommended to re-designing the water supply system using local aquifer conditions.

APPENDIX 1. MONTHLY RAINFALL AT ARBAMINCH STATION

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	No.Mths
1987	13.2	10.1	65.3	139.4	163.2	-99	18.4	6.8	52.6	92.4	44.9	17.4	11
1988	38.7	29.5	32.7	217.5	134.1	68.1	97.7	98.7	116.8	167.4	38.4	24.3	12
1989	39.8	82.8	49.9	163	114.5	48.5	64.3	71	50.1	161.5	85.5	94.7	12
1990	24.6	107.4	64.5	106.6	104	25.5	30.6	52.5	28.6	27.6	25	25.4	12
1991	72.4	45.3	79.3	52	130.3	85.1	30.7	80.8	81.6	49.1	35.7	14.6	12
1992	12.8	18.1	27.1	164.8	140.2	131.9	32	42.8	132.2	172.7	59.6	29.3	12
1993	178	120.8	34.4	94.8	198.2	52.6	3.1	24.6	31.4	117.1	18.2	1.2	12
1994	0.3	4.1	36.4	183.9	164.6	59.9	72.1	82.9	29.7	70.3	59.6	18.8	12

APPENDIX 2. MONTHLY RAIN FALL AT CHENCHA STATION

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	No.Mths
1953	-99	-99	-99	-99	-99	127.9	129.1	135.4	82.6	168.5	-99	96.1	6
1954	0	8	-99	201.2	129	8	31	38.9	60.2	174.9	-99	-99	9
1955	-99	-99	-99	-99	-99	47.1	63.4	191.2	196.3	206	55.7	44.9	7
1956	65.9	-99	-99	296	126.4	48.6	99.9	171.2	130.5	267.8	1.3	16.5	10
1957	84	93.1	193.9	203.8	195.9	141	129.1	91.2	117.9	221.1	41.8	39.1	12
1958	96.9	122.9	-99	-99	61.7	313.6	190.2	150.9	180.7	221.9	-99	34.8	9
1959	23	102.4	-99	312.9	371.9	-99	-99	-99	-99	-99	2.7	53.5	6
1960	11.4	-99	123.2	385.2	180.4	52.7	-99	-99	-99	114.4	70.1	115.7	8
1961	-99	4.3	185.2	-99	-99	-99	-99	-99	-99	-99	-99	-99	2
1972	-99	21.1	69.1	220.7	155.7	70.7	103.5	117.3	124.2	133.8	96.8	24.3	11
1973	57.3	37.6	5.5	135.6	286.4	140.5	204	135.7	204.6	237.2	49.2	2	12
1974	4.8	33.3	293.7	29	220.8	66.3	141.2	104.6	108.4	146.3	35.9	20.2	12
1975	5.1	3.1	70.3	311.8	139.5	107.8	119.2	157.4	98.9	150.9	82	11.6	12
1976	10.2	14.7	76.4	187	175.6	99.7	187.1	117.5	59	126.1	46.5	8.3	12
1977	110.6	31.6	70.5	116.5	177.4	87.9	104.2	81.2	72.4	233.4	37.2	14.5	12
1978	0	170.1	49.3	56.8	66.6	61.2	216.4	144.8	93.6	134.3	60.1	30.8	12
1979	188.2	144	132.7	102.5	172.1	129.7	153.9	61	154.2	187.4	22.1	28.8	12
1980	20.5	30.7	51.6	259	274.1	81	64.8	84.1	110.6	75.6	75.5	2	12
1981	0.5	54.3	215.6	188.4	131.4	39.1	182.9	56.9	135.9	136.2	73.9	1.5	12
1982	7.2	-99	-99	-99	-99	-99	-99	-99	-99	-99	-99	-99	1
1987	42.8	58.1	118.2	200.4	179.1	95.5	132.5	115	120.6	172.7	50.1	32	12
1988	-99	-99	-99	-99	-99	-99	-99	-99	-99	-99	-99	30.6	1
1989	54.5	76.3	205.2	163.3	163.3	129.6	191.5	94.4	214.3	167.5	144.5	222.8	12
1990	0.2	262.1	157	202.8	269.3	56.1	100	133.3	61.8	73.4	136.2	30.9	12
1991	0	131.5	138.3	60	75.6	201.9	128.2	67.8	546.1	28.7	36.5	0	12
1992	-99	4.3	37.8	263	76.2	31.8	-99	-99	-99	-99	-99	-99	5
1994	-99	-99	-99	-99	61	111.6	124.6	203.2	126.7	150	103.3	13.2	8

1995	0	67.8	204.3	286.6	270.6	71.6	-99	-99	-99	-99	-99	-99	6

APPENDIX 3. MONTHLY RAINFALL AT GERESE STATION

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	No.Mths
1985	-99	-99	-99	-99	426.1	60.7	201.2	125.5	171.6	-99	95	6	7
1986	0	25.7	128.8	292.5	403.7	340.7	0	73.7	261.2	224	41	85.8	12
1987	22.1	24.7	-99	249.8	-99	-99	-99	-99	174.7	-99	216	15.9	6
1988	7.5	21.3	-99	377.8	477.6	255.3	473.4	268.2	360.1	59.9	58.1	15.9	11
1989	81	-99	233	114.3	292.9	63.6	228.7	70.9	260	456.6	39.1	182.6	11
1990	22	-99	329.9	276.3	166.9	145.5	137.2	52	120.7	114.1	180	8.5	11
1991	45.7	56.9	54.1	142.6	337.9	213.3	259.3	190.7	177.6	191	54.2	11.8	12
1992	0	-99	97.1	250	160.4	348.8	188.6	143.8	264.5	-99	-99	-99	8
1993	244.4	140.6	34.3	238	380.8	168.5	218.4	231.9	64.1	145.7	127.4	16	12
1994	0	10.5	356.4	638	459.1	303.9	384.7	155.1	160.9	124.1	117.4	9.8	12
1995	0	98	129.1	1131	388.4	-99	-99	-99	-99	-99	-99	-99	5

APPENDIX 4. MEAN MONTHLY TEMPERATURE AT ARBA MINCH STATION

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	No.Mths
1987	24.3	25.3	26	24.4	23.5	-99	24.1	24.3	25.1	24.1	24	24.6	11
1988	25.9	26.7	27.4	25.2	23.5	23.1	22	22.3	23.1	23.2	22.6	22.6	12
1989	23.1	24.1	25.5	23.7	23.1	23.1	22.1	23.4	23.6	23.1	23.2	23.7	12
1990	23.2	25.1	24.8	23.9	23.7	23.5	23.2	23.6	24.7	24.6	24.7	24.1	12
1991	25	25.8	26.1	25.1	24.5	23.7	22	23.7	23.8	24.3	24.4	23.9	12
1992	25.1	26.7	27.9	25.6	23.8	23.3	22.9	23	23.7	22.6	22.6	23.7	12
1993	23.4	22.9	23.9	25.2	23.4	22.5	23.2	23.4	-99	-99	-99	22.1	9
1994	24.3	25.9	26.8	24.8	23.1	22.8	22.3	22.8	25.1	24	23.6	22.9	12
1995	-99	25.2	-99	-99	-99	-99	-99	-99	-99	-99	-99	-99	1

APPENDIX 5. MEAN DAILY TEMPERATURE OF CHENCHA STATION

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	No.Mths
1953	-99	-99	-99	-99	-99	15.2	12	12.8	14.7	15.5	15.3	14.4	7
1954	15.4	15.3	-99	11.7	11.3	-99	-99	8	-99	1.2	-99	-99	6
1955	-99	-99	-99	-99	-99	17	12.3	12.2	-99	-99	-99	-99	3
1956	-99	-99	-99	-99	-99	-99	-99	-99	-99	-99	16.7	18	2
1957	18.6	19.1	17.2	-99	-99	17.6	15.7	13.6	15.6	16.4	18.7	18.7	10
1958	17.6	16	-99	-99	16.9	13.8	12.1	12.2	-99	-99	-99	17	7
1959	17.6	15	-99	-99	-99	-99	-99	-99	-99	-99	-99	-99	2
1960	-99	-99	-99	17.3	16	15.2	-99	-99	-99	16.5	16	16.4	6
1961	-99	17.2	17.4	-99	-99	-99	-99	-99	-99	-99	-99	-99	2
1972	-99	14.1	14.7	13.5	13.9	12.9	12.5	12.8	13.8	14.2	13.8	14.5	11
1973	14.5	16.2	17.4	16.5	14.6	13.2	13.9	12.9	13.6	13.6	14	13.6	12
1974	14.4	15	13.5	14.3	13.5	13.3	13	12.7	13	13.6	13.6	14.1	12
1975	14.3	15.7	15.9	14.6	14.3	12.8	12.4	12.9	13.9	13.9	13.2	14	12
1976	13.9	15	14.8	14.3	13.8	13.1	13.4	13.1	13.3	13.9	14	14.1	12
1977	13.9	14.2	15.1	15.1	14.6	14.2	14.8	14.3	14.3	14.8	14	14.1	12
1978	13.9	14.4	14.6	14.8	14.7	13.4	13.5	14.6	14	14	13.8	13.7	12
1979	13.7	14	13.6	14	14.1	14	14	12.4	13.7	14.1	14.2	14.2	12
1980	14.8	15.4	16	15.4	14	13	12.6	12.9	14.1	14.2	14.5	15	12
1981	15.7	16.2	15	15.3	14.7	13.3	12.3	12.7	13.4	14.6	14.9	15	12
1982	15.8	-99	-99	-99	-99	-99	-99	-99	-99	-99	-99	-99	1

APPENDIX 6. MEANMONTHLY TEMPERATURE AT GERESE STATION

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	No.Mths
1985	-99	-99	-99	-99	15.4	13.3	13.9	15.1	15.4	-99	16.3	16.8	7
1986	17.7	17.6	17.1	16.1	16.2	14.2	17	17.3	15.4	15.9	17.4	17.8	12
1987	17.9	18.2	-99	16.7	-99	-99	-99	-99	17.2	-99	17.2	17.8	6
1988	18.5	20.8	-99	17.5	16	15.5	15	15.3	15.3	16	19	17.8	11
1989	18.3	-99	15.8	15.9	15.5	15.1	15.1	15.6	15	15.4	16.5	16.1	11
1990	17	-99	16.2	17	15.6	16	15.9	15.6	15.5	15.9	16.4	16.8	11
1991	17.9	18.1	18.3	18.2	15.6	15.3	14.6	15.1	14.9	16.1	16.9	17.9	12
1992	18.8	-99	18.3	17.3	16.1	15.1	15.8	15.9	15	-99	-99	-99	8
1993	16.1	16.5	17.9	17.6	15.6	16.3	16.5	15.9	16.4	16.5	17.4	17.7	12
1994	18.7	18.9	17.7	15.4	14.8	15.1	15.2	15.9	15.9	16.4	15.8	16.5	12
1995	17.3	18.2	16.4	15.3	15.4	-99	-99	-99	-99	-99	-99	-99	5

-99 - not measured

APPENDIX 7. KULFO RIVER MONTHLY RUNOFF IN MILLION CUBIC METER

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL
1980	4.4	3.64	3.31	15.1	28.43	11.98	10.09	8.97	11.44	11.25	6.55	4.43	119.49
1981	2.91	2.65	5.31	15.38	14.43	7.45	14.4	15.6	22.5	14.5	5.86	4.86	124.69
1982	3.67	3.73	4.8	13.22	20.84	17.76	12.93	13.63	14.86	22.1	12.02	8.61	148.17
1983	5.98	5.22	5.5	18.95	13.87	14.27	14.61	14.44	15.07	19.38	12.56	4.36	144.21
1984	3	2.6	3.09	5.12	15.38	15.76	7.65	8.81	15.38	13.85	7	6	103.64
1985	3.5	2	1.5	17.27	31.4	15.87	14.54	13.92	14.49	16.62	7.29	5.19	143.59
1986	2.48	2.92	4.44	13.84	20.52	24.11	14.59	12.83	20.81	18.16	10.06	12.69	157.45
1987	7.5	5.13	14.29	28.29	41	10.5	5.18	9.81	2.89	13.5	5	9	152.09

APPENDIX 8. Drawdown Data for AWTI well No. 4

Time after pumping (min)	Water level(m)	Drawdown (m)
1	24.33	0.49
2	24.39	0.55
3	24.41	0.57
4	24.43	0.59
5	24.44	0.6
6	24.445	0.605
7	24.45	0.61
8	24.455	0.615
9	24.455	0.615
10	24.46	0.62
12	24.465	0.625
14	24.47	0.63
16	24.475	0.635
18	24.48	0.64
20	24.485	0.645
25	24.5	0.66
30	24.5	0.66
40	24.505	0.665
50	24.51	0.67
60	24.515	0.675
90	24.525	0.685
120	24.53	0.69
180	24.55	0.71
240	24.56	0.72
300	24.565	0.725

360	24.57	0.73
420	24.575	0.735
480	24.58	0.74
540	24.58	0.74
600	24.585	0.745
660	24.59	0.75
720	24.59	0.75
780	24.59	0.75
900	24.6	0.76
1020	24.605	0.765
1140	24.61	0.77
1260	24.62	0.78
1380	24.62	0.78
1500	24.625	0.785
1680	24.625	0.785
1860	24.63	0.79
2040	24.63	0.79
2220	24.635	0.795
2460	24.635	0.795
2700	24.64	0.8

APPENDIX 9. Arbaminch spring Resalt of water analysis (SOURCE Arbaminch Water supply Project 1983)
Cataions and and anaions

Analysed by	EIGS			CENTRAL LABORATORY					
Year	1976	1976	1976	1976	1977	1977	1977	1977	1977
Ammonia		0.8	1.24	nil	0.33	nil	Nil	1.6	Nil
Sodium	12	18	19	16.36	18.8	19.9	33.8	63.9	2.1
Potassium	1.1	1.4	1.7	Trace	1.6	1.81	0.7	1.7	1.7
Calcium	31	27	27	28.1	7.9	27.3	30.5	26.5	31.3
Magnesium	8	13	13.6	9.7	9.4	11.9	7.8	5.8	7.8
Iron	Nd	Nil	Nil	0.5	Nil	Nil	0.05	Nil	Nil
Manganese	Nd	Nil	Nil	Nil	Nil	Nil		Nil	Nil
Aluminium				0.03					Nil
Chlorides	3	Nil	Nil	17.7	11	10.6	Nil	7	7.1
Nitrites		Nil	Nil	0.13	0.06	0.02	0.02	0.02	Nil
Nitrates		6.7	3.2	Trace	Nil	1.6	1	Nil	1.9
Fluorides	0.4	Nil	2.1	0.3	2.2	0.5	0.73	Trace	Nil
Bicarbonates	171	195.2	195.2	183	170.8	177	219.6	183	183
Carbonates	Nd	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
Silcon	49	40.8	57	60	39.8	28.5	45	40	60
Sulfates	4	Nil		Nil	72	Nil	Nil	72.8	Nil
Phosphate			Nil	Nil		0.2	Nil		Nil

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