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# HYDROGEOLOGY AND HYDROCHEMISTRY OF LAKE ZIWAY AREA AND THE SURROUNDING


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# ABSTRACT

The studied area is located in the northern part of the central sector of the Main Ethiopian Rift. It is bounded by $7^{0}$ 35' N & $8^{0}$12' N latitudes and $38^{0}$25' E & $39^{0}$15' E longitudes. It is covered by Pliocene to Recent volcanic rocks and lacustrine sediments. Volcanic rocks are dominantly acid ignimbrites, pumices and lavas with a few basaltic lava flows and strombolian scoriae. The maximum altitude in the area is 4080 meters above sea level at the tip of Chillalo mountain and the lowest point is 1636 meters above sea level at the western shore of Ziway lake.

The effective annual depth of precipitation in the area is 936.62 mm, the actual and potential evapotranspirations are 735.87 mm and 893.64 mm respectively in the lowlands and 639.06 mm and 695.83 mm respectively in the highlands. From the total mean annual volume of water entering the lake about 123.3 x $10^{6}$ $m^{3}$ of water leaves the lake as surface runoff, about 88.4 x $10^{6}$ $m^{3}$ of water leaves the lake as groundwater outflow and about 643.91 x $10^{6}$ $m^{3}$ of water leaves the lake in the form of evaporation.

The main aquifers in the area are coarse grained lacustrine sediments, scoria cones, hyaloclastites and highly weathered and fractured basalts and ignimbrites. Depth of ground water level ranges from less than two metres up to 130 meters and the general groundwater flow direction is towards the lake from east, west and north of the area and out of the area from the southern part of the lake .

The water in the area is mainly of sodium bicarbonate type and a few are of calcium-sodium bicarbonate type. The chemical analyses of ground waters of the lowlands show high total dissolved solids and high fluoride concentrations. High fluoride concentrations may result from input from fumarolic activity, water-rock interaction and low Ca concentrations. Generally ground waters from the lowlands have poor quality while surface waters and ground waters in the highlands have good chemical quality for different purposes.

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# CHAPTER ONE

# INTRODUCTION

## 1.1 Objective

Hydrogeology can be applied in various ways in planning water uses and treatments. Therefore hydrogeological studies of surface and ground waters in a given area is necessary in order to satisfy both quantitative and qualitative needs of water for drinking, agricultural and industrial uses.

The studied area incorporates such towns as Ziway, Meki, Adamitulu and Assela and many small and big villages. According to the Central Statistical Office (1976) population density per square km. in the studied area is 250 for towns and 60 for rural areas. By assuming 400 sq.km of the area covered by towns and 5 % growth rate per year and 2536 sq.km of the area covered by rural area (excluding the area covered by the lake) and 3 % growth rate per year, by the year 2000 the total population of the area is estimated to be about 658,336. This rapid growth of population will raise the water demand of the area which is insufficient at present.

Most of the water supply for domestic use in the area is from groundwater sources. However, there is a quality and quantity problem, mainly in the western part of the area.

Even though there is shortage of water supply in the area, the main problem is quality problem due to high TDS and high fluoride concentrations. Therefore it is necessary to study the source of this problem and suggest the control and preventive methods for the problem.

A larger part of the area has semi - arid climate as a result of low rainfall and high potential evapotranspiration which decrease the amount of water recharging the aquifers. Therefore the future increase in demand of water for irrigation and industrial uses from Ziway lake will increase which makes the water balance study of the lake indispensable.

Therefore, the objectives of this study are:
1. to calculate the water balance of Ziway lake from different hydrological and meteorological information in the area.
2. to verify the sources of quality problem of water in the area and to suggest the control and preventive methods.
3. to check the quality of water in the area based on international standards for different uses.
4. to classify the geologic units in the area according to their relative permeability.
5. to relate the chemistry of ground waters with the reservoir rocks and regional ground water flow.
6. to delineate groundwater flow direction from the ground water levels and altitudes of the wells in the area.
7. to suggest the water management of the area.

## 1.2 Location

The studied area is located at about 155 km south of Addis Ababa on the road to Awassa. It lies within the central sector of the Main Ethiopian Rift. It is bounded by $7^0$ 35' N & $8^0$12' N latitudes and $38^0$25' E & $39^0$15' E longitudes.

The studied area has a total surface area of about 3370 sq.km, while Ziway lake for which water balance study is conducted represents the central part of the area and covers a surface area of about 434 sq.km.

The studied area is bounded to the west by Koshe - Dugda ridge, to the south by Aluto mountain, to the east by Chillalo mountain, and to the north-east by Bora mountain (fig 1.1).

## 1.3 Accessibility

Ziway lake which is found at the centre of the studied area is located along the main road to Awassa from Addis Ababa which divides the studied area into two.

There are many gravel roads and motorable tracks within the studied area. The main once are Ziway - Butajera, Meki - Abura - Assela, Adamitulu - Abura - Assela, Assela - Kersa and Assela - Sagure. Hence large part of the studied area, except ridges and gorges, is accessible by a field vehicle.

## 1.4 Climate and Vegetation

According to Chernet T. (1982), the studied area is classified into three climatic zones: the area east of Assela has humid to dry sub - humid climate, the area west of Gademota ridge and the area between Ziway lake and Assela town have dry sub - humid to semi - arid climate. The rest of the area which is around Ziway lake has arid to semi - arid climate.

Average annual rainfall ranges from about 751 mm at Ziway to 1180 mm at Assela. Mean annual temperature range from 14.85 $^0$C at Assela to 19.94 $^0$C at Ziway. The potential annual evapotranspiration exceeds the total annual precipitation in the lowlands of the area, while in the highlands the reverse is true.

The main vegetation types in the area are tropical woodland and thornbush. Some grassland are found in the eastern escarpments of the area. The eastern highlands have dense vegetation at cliffs and mountains, since normally in steep slopes and cliffs deforestation is lower. In the area around Ziway lake there are extensive coverage of acacia trees and some pheratophytic trees are also found.

### 1.5 Soils

According to Chernet T. (1982), three main types of soils are found in the area: sandy soils, lateritic clay soils and dark clay soils. Sandy soils occur around Ziway lake which are derived from ignimbrites, unwelded pumiceous pyroclastics and coarse beds of lacustrine sediments. Lateritic clay soils cover the area above 2000 meters elevation at the highlands of the eastern side of the studied area and they are highly susceptible for erosion, since they are found at the highlands with maximum precipitation. Dark clay soils occur in the area east of the lake where there are basalt flows on fine grained Quaternary sediments. The top soils in the Meki river valley are dark brown or black clay loam to clay and they are underlain by greyish and yellowish brown soil.

### 1.6 Land Use

The area investigated is an agricultural area where different crops are cultivated during the July - September rains. Irrigation is not a common practice; a few semi - mechanised farms are present along the western shore of Ziway lake.

According to the Central Statistical Office (1995), the total land use in Arsi zone, in which the studied area lies is about 786.35 thousand hectares, from these 66.9 % is covered by temporary crops, 1 % by permanent crops, 19.6 % is grazing land, 7.8 % is fallow land, 0.004 % is woodland and 4.3 % is covered by other land uses. From the temporary crops cereals like wheat, barely, maize, teff and sorghum are the major growing crops. Wheat, barely and maize cover more than 70 percent of the area during the growing seasons.

Arsi zone has the largest cattle population from the Oromia region(Central Statistical Office, 1995). Cattle, sheep, goats, horses, asses and mules are found in large numbers. From these cattle, sheep and goats contain more than 90 percent of the total livestock population in the area particularly in the lowlands.

### 1.7 Physiography And Drainage

The studied area is found within the Main Ethiopian Rift (MER) which is characterised by generally North North-East - South South-West oriented faults forming grabens and horsts. The physiography of the studied area is, therefore, mainly the result of volcano - tectonic activities that occurred in the past and also deposition of sediments which are largely of lacustrine origin. As a result, the main landscape features in the area include the volcanotectonically formed Ziway lake, fault scarps, fault controlled depressions, volcanic domes, calderas and craters.

Elevation of the studied area varies from around 1630 metres a.s.l. at Ziway lake to more than 4080 metres a.s.l. on Chillalo mountain (east of Assela town).

The area at the western part of Ziway lake is characterised by relatively low - lying topography. The main topographic highs are Gademota caldera slopes and Koshe - Dugda ridge in the west. Aluto mountain is the highest point at the southern part of the area which is more than about 2320 metres a.s.l. The area north of Ziway lake is also characterised by flat topography except mount Bora NE of Ziway lake and its height is about 2000 metres a.s.l.

A larger part of the studied area lies at the eastern side of Ziway lake in which the Wonji Fault Belt (the axis of the Main Ethiopian Rift) faults are very intense, which result in the formation of minor grabens and horsts and many volcanic domes. In this part of the area, the main topographic features from west to east are Weshe - Danta ridge, Kobata ridge, Galana ridge, Bosha ridge and Denbaba ridge. At about 10 km east of Assela Chillalo mountain is found which is the eastern border of the MER.

There are a number of different scale perennial and intermittent streams and gullies which usually originate from the sides of the sloppy scarps, ridges and domes of the area and flow into the lake. Only one river(Bulbula) flow out of the lake to Abijata lake (south of the study area). The two main perennial rivers which flow towards the lake are Meki (join the lake at the northern part) and Ketar(join the lake at the north eastern part).

From the western side of the studied area the only surface water inflow into the lake is Meki river which is one of the big rivers in the central sector of the Main Ethiopian Rift. In the studied area Meki forms a U - shaped valley and divides into two main parts towards the lake as most rivers cutting the sediments do. Ketar river is another big river in the central sector of the MER and in the studied area. From east to west, its main tributaries are Aleltu, Yeloma, Murkicha, Kechema, Chiro, Koto and Chufa. Most of them start from the mountains and ridges.

The southern and eastern parts of the studied area are characterised by relatively well developed parallel drainage pattern. In the southern and south-eastern part the intermittent streams and gullies start from Aluto mountain and the surrounding ridges, flow directly towards the lake, however, most streams in the eastern and north-eastern part of the studied area drain towards the lake via Ketar river, most of which are seasonal and start from Chillalo mountain slopes.

Drainage in the northern, western and south-western part of the studied area is not well developed. Many streams and gullies draining from Koshe - Dugda ridge and rim of Gademota caldera usually sink into the lacustrine deposits in the lowlands before reaching the lake, probably flowing into the lake as ground water during rainy seasons.

The only natural surface outlet from the lake is Bulbula river which start from the south-western part of the lake and flows towards south and joins Abijata lake.

There seems to be a relationship between the main stream courses and the faults and fractures in the area. This is evidenced by parallel patterns of the streams in the eastern part of the area which is affected by faults of the Wonji Fault Belt.

## 1.8 Previous Work

A large number of publications on the geology and volcano - tectonic development of the Main Ethiopian Rift in general, and on the central sector in particular have been produced in the past. This helps to understand regional geology of the studied area.

Di Paola G.M. (1970) provided geologic descriptions of different rock types and geothermal conditions in the area and gave a brief description of hydrothermal areas in the Lakes District.

Di Paola G.M. (1972) presented an overall account of the geology, stratigraphy and structural patterns of the Main Ethiopian Rift within $7^{0}00'$ to $8^{0}40'$ N latitudes including a geologic map of the area with an approximate scale of 1: 60,000 in which he reconstructed the stratigraphy and volcano-tectonic history of the Central Sector of the MER.

Weldegabriel G. (1987 ) in his Ph.D. thesis presented stratigraphic sections and correlation's for the rift escarpment and rift floor geothermal drill hole cores, and age histogram of volcanic rocks of the area including a geologic map of the Main Ethiopian Rift with a scale of 1: 700,000.

Weldegabriel et. al. (1990) described the stratigraphic relations of the central sector of the MER by using K/Ar datings of volcanic rocks from plateau escarpments and from the rift floor. From this stratigraphic framework and structural pattern of the area they discussed the history of rifting and volcanism in the central sector.

In addition to the above, Mohr(1962;1966; 1967a) and Di Paola (1971) gave some general idea about the geology of the area and the vicinity.

There are also few hydrogeological and hydrochemical reports in the area, of which UNDP(1973), Chernet T. (1982), Gizaw B.(1985; 1996) are specifically interesting to the present investigation.

UNDP(1973), located and classified springs in the Main Ethiopian Rift and Afar according to their chemical composition and also estimated underground temperatures of hot springs.

Chernet T. (1982), presented a regional hydrogeological description and a hydrogeological map of the Lakes Region (which include Ziway-Shalla and Awassa lake basins) at a scale of 1: 250,000 based on geological, meteorological, hydrological, chemical and geothermal investigations. The report includes chemical analyses of surface and ground waters from different parts of the area, regional classifications of different types of rocks of the area into different permeability groups and water balance of the region.

Gizaw B. (1985), presented data on the chemical composition of water and gas as well as isotopic data from five geothermal areas in Lakes District and estimated the temperature of geothermal areas.

Gizaw B. (1996), presented chemical data on different waters from the lakes region and discussed the source of high fluoride concentrations and total dissolved solids in the area.

Within the present area of investigation, no detailed hydrogeological and hydrochemical work have been done. The only related work that have been done are drilling and chemical data on wells in Meki - Ziway area by a Non Governmental Organisation called L.V.I.A.(Lay Volunteers International Association).

## 1.9 Methodological Approach

After identification of hydrogeological and hydrochemical problems in the area, extensive review of available literature on different aspects of the studied area relevant to the research, including reviewing of topographic, geologic and hydrogeologic maps in the area and the surrounding have been done.

Hydrometeorological data (rainfall, temperature, runoff ...etc.) have been collected from different sources in Addis Ababa and other towns with in the project area.

Field hydrogeological and hydrochemical investigations were aimed :

- to identify the various lithological units and geologic structures in the area
- to collect representative surface and ground water samples in the area and to take in situ measurements of temperature, conductivity and pH of water samples, and
- to locate and take different hydrodynamic measurements of hand dug wells and bore wells in the studied area.

After data collection was completed, hydrologic parameters, i.e. precipitation, evapotranspiration, runoff and infiltration in the studied area were investigated.

Mean annual rainfall in the area was computed by using Theisson polygon method and seasonality of rainfall was examined by using rainfall coefficient.

Monthly and annual potential evapotranspiration of the two stations, Ziway and Assela, which are representatives of the lowlands and highlands in the area respectively, were determined by using Thornthwait empirical method and the monthly and annual actual evapotranspiration were computed by using the procedure of Dunne and Leoplod (1978).

Water balance study was conducted only for Ziway lake by using the water balance equation of free water bodies:

$$\Delta s = P + \Delta g + Qsi - E - Qso$$
$$\Delta g = (Qgi - Qgo)$$

where $\Delta S$ = change in storage, P = precipitation, Qsi = surface inflow into the lake, E = evaporation, Qso = surface outflow from the lake, Qgi = groundwater inflow into the lake and Qgo = groundwater outflow from the lake.

Various sets of geological information and well log data in the area were used to classify lithologic units according to their relative groundwater potential.

Physical properties measured in the field and chemical analyses results of major cations and anions of waters were used to identify the source of major constituents of surface and ground waters and to examine the suitability of the waters for different purposes i.e. domestic, industrial and agricultural.

# CHAPTER TWO

# GEOLOGY

## 2.1 Regional Geology

The Ethiopian rift system, which is part of the East African rift system, is sub-divided into three sectors. These are the South - Western Rift Zone, the Main Ethiopian Rift and Afar.

The Main Ethiopian Rift, which sub- divides Ethiopia into north - western plateau and south - eastern plateau extends for about 650 km from south western rift zone to the Afar depression in the north. Its average width is about 80 km. The Main Ethiopian Rift is a NNE trending rift characterised by extensional faults which are associated with various volcanic centres. The MER is geographically divided into three sectors Northern, Central, and Southern (Woldegabriel et .al. 1990). The present area of investigation is situated within the floor of the central sector of the Main Ethiopian Rift. The central sector of the MER itself is more than 175 km long and 75 km wide, widening towards the northeast and narrowing southward (Mohr, 1967).

Overall, the all Tetiary and Quarternary geological history of Ethiopia is dominated by a distension tectonic regime and widespread volcanism (Woldegabrial et al., 1990). The Tertiary volcanism started in the Late Oligocene, and was dominated by fissural eruptions of tholeiitic and transitional basaltic lavas with minor ignimbrites. This formed the thick sequence of lava flows and interbedded ignimbritic sheets that is known as the Ethiopian plateau. In the middle Miocene large central volcanoes were formed. These have variable composition, from transitional to aNa-alkaline. A third phase of activity is late Miocene to Recent and is more directly associated with the full development of the MER. Rocks are dominated by rhyolitic pyroclastics, with minor basalts. These are aligned in a NE-SW direction, along the Wonji Fault Belt which is the active axis of the Main Ethiopian Rift.

Wonji Fault Belt is the most active part of the MER. It forms a graben within a larger graben or a rift within a rift structure and the faults in this zone are short normal type and are oriented NNE - SSW. The MER extends from south of lake Chamo in southern Ethiopia to the lake Abhe area in central Afar.

Generally in the MER volcanism migrated from the plateau areas to the rift. Starting from five million years before present volcanism was mostly concentrated within the rift and since about 1 million years ago volcanism was mostly restricted along the axis of extension (i.e. Wonji Fault Belt).

Woldegabriel et. al (1990), based on K/Ar ages and lithologic correlation, grouped and described the Cainozoic rocks of the central sector into six chronostratigraphic units from Oligocene to Quaternary as follows:

Table 2.1 Stratigraphic sequence in the Central Sector of the Main Ethiopian Rift

| UNIT | EPOCH | AGE |
|---|---|---|
| Wonji Group | Quaternary | < 1.6 Ma |
| Chillalo Trachyte | Middle to Upper Pliocene | 1.6 - 3.5 Ma |
| Butajira Ignimbrite | Upper Miocene to Middle Pliocene | 3 - 4.2 Ma |
| Guraghe Basalts | Middle to Upper Miocene | 8.3 - 10.6 Ma |
| Sheble Trachytes | Upper Oligocene to Middle Miocene | 12 - 17 Ma |
| Kella Basalts | Lower Oligocene to Upper Oligocene | 26 - 32 Ma |

1. Kella Basalt -This is the oldest volcanic unit in the central sector of the MER and is found at Agreselam, Ambo and Kella. These rocks are dominated by basalt with localised rhyolite and sedimentary strata. Except at Ambo, the bases of the Kella basalts are not exposed, and older volcanic units may exist below them.

2. Sheble Trachyte - The rocks of this unit are exposed along some deep canyons of the Omo river and of the Wabi Sheble. This group is dominated by intermediate and acidic volcanic rocks ssuch as trachyte, phonolite, rhyolite and intercalated volcanoclastic strata, and some basalts. Mount Chike is the only one of the numerous rift shoulder volcanoes that belongs to this group.

3. Guraghe Basalt - Basalts and subordinate silicic flows of this unit are found at Awassa, Guraghe and the Omo river canyon. In Omo river canyon these 10.6 Ma old basalts are underlain by several undated basalt flows and Middle Miocene Shebele trachytes. At Awassa and Guraghe, the base of correlative units are not exposed.

4. Butajira Ignimbrite - voluminous silicic pyroclastic material and subordinate basalt flows of this unit were erupted from the Awassa Caldera, the Wagebeta Caldera complex, and a major caldera probably buried beneath the Ziway - Langanno - Abijata basin. Petrologically this group of rhyolitic rocks are distinguished from those of the Quaternary Wonji group as being transitional or mildly peralkaline while the Wonji group are peralkaline.

5. Chillalo Trachyte - This group includes the products of the Pliocene centres of the eastern & western shoulder of the rift and compositionally correlative units from the Awassa caldera. This unit includes trachyte, silicic rocks and basalt that overlie units of either the Shebele trachyte or the Butajira Ignimbrite.

6. Wonji Group - This group is generally confined to the Wonji Fault Belt along the entire MER and include the young basalts from the Silti - Debrezeit fault zone and the 0.68 m.y old flood basalt in the Ambo area of the central sector. This group consists of diverse Quaternary lava, pyroclastic rocks and volcanoclastic strata younger than 1.6 Ma.

Earlier, Di Paola (1972) identified four main successive events of volcanic activity in the MER between $7^{0}00'$ and $8^{0}40'$ latitudes North as follows:

1. Fissure eruptions with emplacement of explosive dominantly ignimbritic products followed by volcano - tectonic collapses.
2. Building of silicic central volcanoes on the ignimbrites.
3. Basaltic fissure eruptions.
4. Edification of recent mostly pantelleritic centres with associated "sub historical" basaltic fissure eruptions.

He also identified nine volcanic centres in the Ethiopian Rift Valley between $7^{0}00'$ and $8^{0}40'$ latitudes north, from north to south, they are:

1. Ziquala Volcano - located about 20 km SW of Mojo town and made up of several thick and viscous alkali trachitic lava flows .

2. Boseti - Gudda and Boseti - Bericcia Volcanic Complex - located about 15 km east of Nazaret town, close to the eastern escarpment and consisting mostly of very recent pantelleritic obsidian lava flows associated with pumice and ashes.

3. Gademsa Caldera Volcano - located adjacent to the Wonji sugar estate farm and formed mostly by rhyolitic lavas with pumice and ignimbrites.

4. Bora - Bericcio Volcanic Complex - located between Koka lake and Ziway lake close to the eastern escarpment and most of the products are silicic pyroclastics.

5. Chillalo Volcano - located about 30 km east of lake Ziway, on the eastern escarpment and mostly constituted by thick alkali trachytic lava flows.

6. Badda Volcano - located just east of Chilallo and majority of its products are alkali trachytes.

7. Aluto Volcano - located between lake Ziway and lake Langano, close to the eastern escarpment of the Wonji Fault Belt and constituted by silicic pyroclastics such as pumice flows, pumice falls and ashes, with subordinate rhyolitic lava flows, mostly obsidians.

8. Lake Shalla Caldera - located along the Wonji Fault Belt and cutting ignimbrites and pumice deposits of "sillar" type and also some rhyolitic lavas.

9. Corbetti Caldera - located between lake Shalla and lake Awassa, along the axis of the rift (Wonji Fault Belt) and mostly consisting of pumice flows and pumice falls with subordinate obsidian lava flows.

Woldegabriel et al (1990) identified two stages of rifting from the stratigraphy, geochronology & tectonic patterns of the central sector. First late Oligocene - early Miocene stage - formation of a series of alternating half - grabens along the rift with major border faults on one side, second Miocene - early Pliocene stage - formation of the more symmetrical rift valley of today. In the northern part of the central sector the rift axis has bifurcated into two marginal zones one at each edge of the rift floor, Silti - Debrezeit fault zone at the west & Wonji fault zone at the east both marked by swarms of closely spaced normal faults and associated with volcanic flows of the Quaternary Wonji group. However, in the other parts of the MER the Wonji Fault Belt is the single thoroughgoing medial volcnotectonic axis.

In the central sector, the Wonji Fault Belt is right laterally offset into four "en echlon" rift - axis segments Gadamsa - East Ziway, Ziway - Shalla, Shalla - Awassa and the Duguna - Abaya Zones.

## 2.2 Geology of The Studied Area

A composite stratigraphy of the area has been reconstructed based on previous works, field investigations and well log data.

The oldest volcanic rocks exposed in the area are trachytes of the Chillalo volcano with an age of Middle to Upper Pliocene and the youngest rocks are lacustrine sediments with an age range from Pleistocene to present.

The general stratigraphic sequence of rock units in the area is summarised in table 2.2.

Table 2.2 Stratigraphic outline of the studied area

| Stratigraphic Unit | Age | Correlative Unit |
|---|---|---|
| Alluvial and Lacustrine sediments | Recent to Pleistocene | Alluvium and Lacustrine sediments of Di Paola (1972) |
| Rhyolitic pumice, Ashes and Obsidian lava flows | Holocene | Central Volcanic Complex of Chernet T. (1982) |
| Basaltic lava flows, cones and hyaloclastites | Recent to Pleistocene | Recent Basalts of Kazmin et al (1978) Basalts of The Rift Floor of Chernet T. (1982) |
| Ignimbrites, Tuffs and Pumice falls | upper Pliocene | Dino Formation of Chernet T. (1982) Rift Pyroclastic Formation of Di Paola(1972) |
| Trachytic lava flows | middle to upper Pliocene | Chillalo Trachytes of Woldegabriel et al (1990) |

### 2.2.1 Trachytic Lava Flows

This unit mainly consists of trachytic lava flows. In the studied area these rocks are found around Assela and along the slopes of Chillalo volcano, the biggest individual volcano in the area, just along the eastern escarpment of the Main Ethiopian Rift. On the north-eastern rim of Chillalo caldera, basalts overlie trachytic lava flows which are most probably related to post caldera activity.

### 2.2.2 Ignimbrites and Tuffs

This group include ignimbrites, tuffs and subordinate lacustrine sediments. In the western part of the studied area these rock units are found west of Gademota Caldera and Gubiba mountain around Koshe and in the eastern part along the eastern fault escarpment of the Wonji Fault Belt. In the studied area ignimbrites are mostly highly welded with well developed " fiamme", and contain abundant lithic material. In the eastern part of the area, coarse and less welded ignimbrites intercalated with big pumice fragments are exposed.

The ignimbrites are constituted by several layers with variable thickness from 0.5 up to 20 meters. East of Ziway lake mostly lacustrine deposits are intercalated with ignimbritic sequences, but west of Ziway lake ignimbritic sequences are separated by paleosoils. Another common pyroclastic product associated with the well welded ignimbrites are unwelded thinly layered pumice, while the poorly welded ignimbrites are mostly rich in big pumice fragments. These rock units are intensely faulted and exposed extensively in the area even when it is covered by more recent volcanic or lacustrine products.

### 2.2.3 Recent Basalts

This unit includes Pleistocene to Recent basaltic lava flows, basaltic scoria and hyaloclastites. In the studied area, they are mainly found in the eastern part of lake Ziway, north and east of Abura and they are elongated parallel to the main trend of the Wonji Fault Belt ( NNE- SSW) which indicate that these rocks are affected by the faults of the Wonji Fault Belt. These rocks are also found in Tulu Gudo and Tedecha islands of Ziway lake.

The overall thickness of these basic products reach up to about 100 metres in some scoria cones. Phreatic explosion craters rarely occur in the recent basalt formation at Kune and Baua mountains north and north-east of Abura, respectively.

Basaltic hyaloclastites are found in the southern shore of lake Ziway mostly associated with basaltic lava flows. The occurrence of these rocks can be ascribed to explosive activity of a basaltic magma under shallow water. The hyaloclastites in the area consist of a fine glassy material which contains small boulders of basaltic lava.

The rocks of this unit overlie ignimbrites as it is observed on fault scarps affecting this unit.

### 2.2.4 Upper Acidic Volcanics

This unit includes rhyolitic lavas, tuffs , pumice and obsidian and they are the latest volcanic products in the area. In the studied area these rocks are found on the slopes of some volcanoes such as Bora (North east border of the studied area), Tulu Moje, Sarara and Aluto. All of these volcanoes lie within the Wonji Fault Belt .

Most of these acidic volcanic rocks around Bora, Tulu Moje and Sarara are pyroclastics such as unwelded pumice flows, pumice falls and ashes. Obsidians are mainly found on the slopes of Aluto volcano, located south of Ziway lake which is one of the recent volcanoes in fumarolic stage of the Main Ethiopian Rift. These very recent volcanic products are affected by faulting.

### 2.2.5 Alluvial and Lacustrine Sediments

The rocks of this unit cover a large part of the studied area as compared to other lithologic units. The sediments include silts, clays, volcanoclastic sediments and tuffs.

The alluvial sediments occur along the channels of Meki and Ketar rivers.

Lacustrine sediments cover almost the entire low - lying flat land in the area mainly western, south-western, northern and north-eastern flanks of Ziway lake. The age of these lacustrine deposits is considered to be Pleistocene to Recent and the sediments are believed to have been deposited in a large lake which occupied the rift floor in the past (Di Paola 1972).

From well log data, in the western part of Ziway lake a vertical variation in grain size has been noted. The top few metres are mostly clay sand soils then the intercalated volcanic ash and tuff and the lower parts of this lacustrine sediments are clayey sand and intercalated sand and pumice.

The thickness of this sedimentary unit ranges from a few metres up to 50 metres, the maximum being in Bora mountain.

### 2.2.6. Tectonic Structure and Volcanotectonic History

The main geologic structures that have been observed in the studied area include: faults, joints, fractures, calderas and craters.

The area is intensively dissected by a number of minor and major normal faults running almost parallel to each other in a NNE - SSW direction and are usually arranged in "en-echelon" fashion, which belong to the Wonji Fault Belt and form graben - horst structures. The faults dissect almost all units outcropping in the area and recent volcanism like Bora and Aluto has been observed to be associated with these faults. Faults are dominant in the eastern part of Ziway lake.

Jointing and fracturing are abundant in welded ignimbrites, rhyolites and recent basalts of the area. The only caldera present in the area is the Gademota caldera, which is located south-west of Ziway town. While explosion craters are widespread in the area like: Bora, Tulu - Moje, Kune , Balla and Chillalo.

The volcanotectonic history of the studied area is part of the volcanotectonic history of the MER and can be summarised as follows based mainly on the available literature ( Di Paola, 1972, Woldegabriel et. al., 1990 ...)

The area has been affected by volcanism since Pliocene with fissure eruptions and growth of individual volcanoes, and volcanotectonic activity was episodic.

The eruption of trachytes around Chillalo and Assela occurred in the beginning followed by major border faulting, of the Wonji Fault Belt; following or accompanying the above faulting ignimbrites were erupted associated with pumice, which are highly affected by major faulting. Next the rising of basaltic lava flows occurred, which were also affected by major faulting. This was followed by the emplacement of acidic volcanic lavas. The pumice and rhyolites of Bora and Obsidians of Aluto are the result of this event. Finally minor faulting event occurred, which resulted small cliffs and step faults.

Lacustrine sediments represent the youngest unit in the area which were deposited starting from the time of emplacement of ignimbrites up to the present day.

# CHAPTER THREE

# SURFACE WATER HYDROLOGY

Ziway sub - basin is part of the Ziway - Shalla basin having an aerial extent of 3370 sq. km, more or less heart shaped, wider at the north and narrower at the Southeast and mainly constitute parallel pattern of seasonal and intermittent streams. The main water courses in the studied area are Meki, Ketar and Bulbula rivers which are characterised by perennial flow. The first two flow towards the lake while Bulbula river flows out of the lake.

In the following discussion, the general hydrological considerations of the basin will be presented.

## 3.1 Precipitation

From hydrological point of view there are two main forms of precipitation, snow and rain. In the study area rainfall is the most important source of precipitation and thus the main contributor to runoff, stream flow and aquifer recharge.

The prevailing types of rainfall that occur in the area are orographic and convective. Frontal precipitation is restricted only to the wettest months as a result of seasonal wind blowing in the Indian Ocean from south-west from April to October. The effect of orographic precipitation is higher in the eastern highlands of the area.

There are four, currently operating, rain gauge stations in the studied area located at Adamitulu, Assela, Meki and Ziway towns .The only class -1 station in the area is Ziway station which records rainfall, temperature, evaporation, relative humidity, wind speed and radiation and it is located at an altitude of 1640 metres a.s.l. The station at Assela is class -3 which records only rainfall and temperature and located at 2350 meters a.s.l. Meki and Adamitulu stations are class - 4, record only rainfall and their altitude is 1660 and 1650 metres a.s.l. respectively.

The three stations used to classify the area according to their rainfall depth are Meki, Ziway and Assela , which have 30, 27 and 31 years period of record respectively.

The effective annual depth of precipitation in the studied area has been calculated by using Theissen polygon method for 27 year mean annual precipitation (1970 -1996) of the three stations, which gives 936.62 mm: (see fig 3.1 and appendix 5).

Fig 3.1 Theissen Polygon

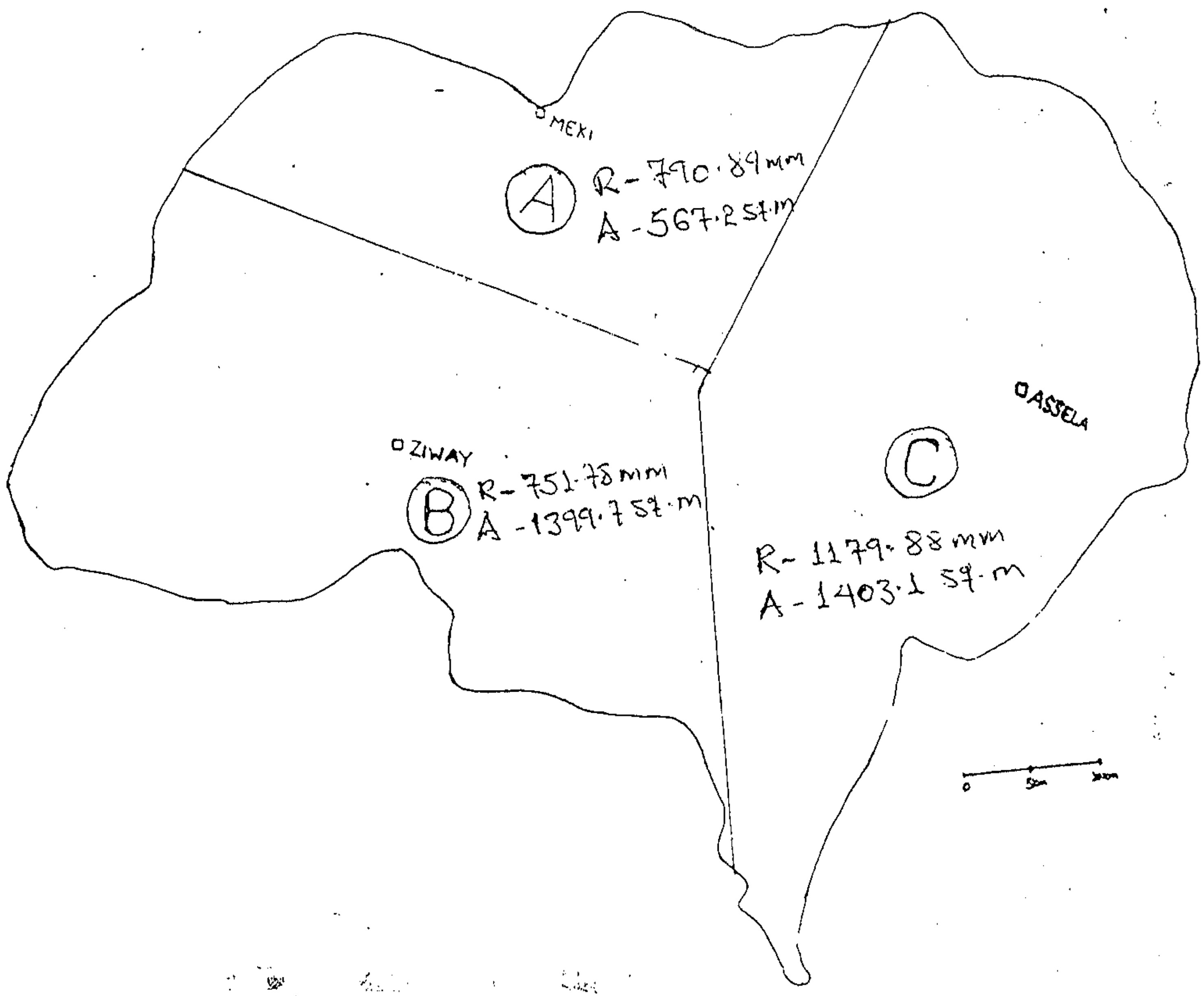
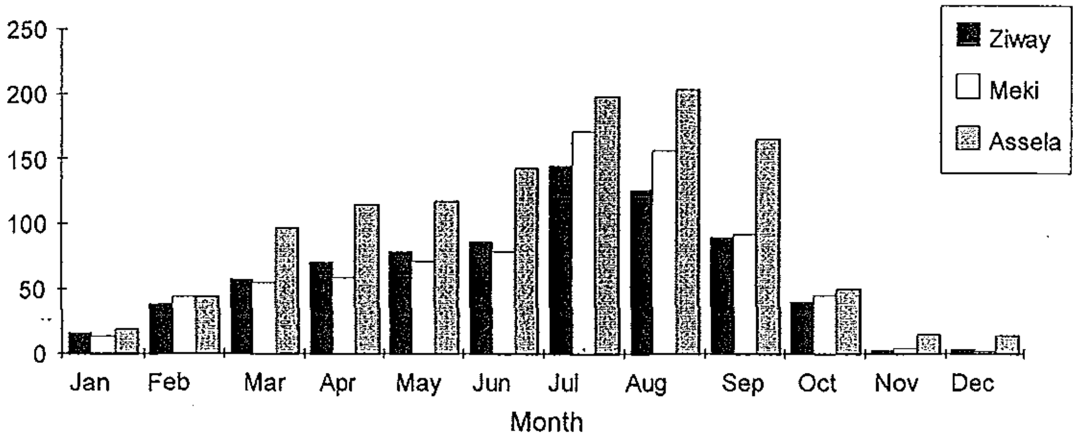


Fig 3.2 27 Years Mean Monthly Rainfall of Ziway, Meki and Assela




As it can be depicted from fig 3.2 there is a significant seasonal variation in the amount of rainfall for all the three stations. Therefore seasonal rainfall variation of area A, B, and C of fig 3.1 has been examined by using the rainfall coefficient (RC), which is the ratio between the mean monthly rainfall and one twelfth of the annual mean.

Table 3.1 Rainfall Coefficient at Meki, Ziway and Assela Stations

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Meki | 0.21 | 0.67 | 0.82 | 0.90 | 1.07 | 1.14 | 2.61 | 2.38 | 1.39 | 0.68 | 0.06 | 0.02 |
| Ziway | 0.26 | 0.60 | 0.91 | 1.13 | 1.26 | 1.37 | 2.31 | 2.00 | 1.43 | 0.63 | 0.05 | 0.05 |
| Assela | 0.20 | 0.45 | 0.98 | 1.17 | 1.19 | 1.46 | 2.02 | 2.07 | 1.68 | 0.50 | 0.15 | 0.14 |

RC< 0.6 Dry months
0.6≤ RC < 1 - Small rainy months
1≤ RC < 2 - Big rainy months with moderate concentration
2≤ RC < 3 - Big rainy months with high concentration
RC≥ 3 - Big rainy months with very high concentration

**AREA A**

It covers about 567.2 sq. km. Mean annual precipitation is 790.89 mm and seasonal rainfall variation of this area is divided as follows:

1 - Big Rainy Period ( RC≥1): include months from May to September and constitute 71.85 percent of the total annual rainfall in the area with maximum depths in July and August.

2 - Small Rainy Period ( 0.6 ≤RC<1) :include February, March ,April and October and constitute 25.75 percent of the total annual rainfall.

3 - Dry Period ( RC< 0.6 ) : include January, November and December and constitute only 2.4 percent of the total annual rainfall.

**AREA B**

It covers about 1399.7 sq. km. Mean annual precipitation is 751.78 mm which is considered as the minimum amount of precipitation depth for the whole area since the amount of rainfall increases with elevation and Ziway station is located at the lowest altitude in the area (1640m). By using the rainfall coefficient approach the year can be divided into three main periods.

1 - Big Rainy Period ( RC≥ 1) : include Months from April to September and constitute 79.2 percent of the total annual rainfall with high concentrations in July and August.

2 - Small Rainy Period ( 0.6≤ RC < 1) : include February, March and October and constitute 17.8 percent of the total annual rainfall.

3 - Dry Period ( RC < 0.6 ) : include January, November and December, which constitute only three percent of the total annual rainfall.

**AREA C**

It covers about 1403.1 sq. km. Mean annual rainfall is 1179.88 mm and the Year can be divided as follows based on rainfall coefficient :

1 - Big Rainy Period ( RC ≥ 1) : include Months from April to September and constitute 79.8 percent of the total annual rainfall with July and August high concentrations.

2 - Small Rainy Period ( 0.6≤ RC<1 ) : consist of only the Month of March and constitute 8.2 percent of the total annual rainfall.

3 - Dry Period ( RC< 0.6) :include January, February, October, November and December and constitute 12 percent from the total.

From these we can conclude that seasonal rainfall variation in the area is almost similar with big rainy periods from April to September, however the dry period in Assela is longer which indicate that highlands are characterised by longer dry period and higher total annual rainfall and the lowlands are characterised by short dry period and lower total annual rainfall.

### 3.2 Evapotranspiration

Evapotranspiration is the total amount of water which returns back to the atmosphere within a given time by evaporation from land or free water bodies and by transpiration from the vegetation cover. Therefore it is the combination of evaporation and transpiration. It is considered as a loss from the water budget of a given area due to the fact that it reduces the amount of surface and ground water in the area.

Potential evapotranspiration is 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. Therefore, it is dependant on the evaporative capacity of the atmosphere and possible to calculate it from meteorological data in the area .

Actual evapotranspiration is the amount of evapotranspiration that occurs under a given climatic and soil moisture conditions. Therefore it is always less than or equal to potential evapotranspiration.

Direct measurement of potential evapotranspiration is possible by using a lysimeter ( a large container holding soil and plants), initially by determining the soil moisture content and by measuring the precipitation and irrigation water added in the lysimeter we can calculate the amount of water lost by evapotranspiration by the following equation.

$$ET = Si + P + I - Sf - D \quad (3.1)$$

ET - the evapotranspiration for a given period
Si - the volume of initial soil moisture
Sf - the volume of final soil moisture
P - the precipitation into the lysimeter
I - the irrigation water added to the lysimeter
D - the excess moisture drained from the soil.

However, this method is time consuming and expensive since it is necessary to designate the lysimeter according to the type and profile of the soil, moisture content and type and size of vegetation of the surrounding area. This is the reason why direct measurement of evapotranspiration is not a common practice.

Empirical methods of evapotranspiration are commonly used for estimating the potential evapotranspiration for a given area in the given period of time. Among these the most common are: Thornthwaite(1948), which is based only upon meteorological conditions and ignor the effect of vegetative density and maturity; Blaney and Criddle (1950), which include a crop factor but the effect of wind and relative humidity are not included in the formula; and Turc (1955), which is based on only precipitation and temperature neglecting the other factors.

In the studied area the only direct measurement of evaporation is pan evaporation measurement at Ziway station, which has a record of eleven years from 1981 to 1991. By multiplying a correction factor of 0.75 the mean annual evaporation rate of Ziway lake was computed as 1438 .67 mm. This value compared with the mean annual rainfall for the same period ( 749.36 mm) it is very high and indicates a heavy loss of the lake water and implies that all the precipitation falling into the lake during wet months has been returned back to the atmosphere during dry months.

In the studied area the empirical method used for estimating evapotranspiration is Thornthwaite method due to its minimal data requirement and reasonably accurate determination of annual values.

Thornthwaite correlates temperature and evapotranspiration from experiments carried out in the United States which enables us to estimate the gross potential evapotranspiration from short, close vegetation set with an adequate water supply. According to him, the gross potential evapotranspiration for a standardised month of 360 hours of sunlight can be calculated by the following equation:

$$GPET = 16(10\ T/I)^a \text{ - - - } (3.2)$$

GPET = Monthly gross potential evapotranspiration in millimetres
T = Mean monthly air temperature in $^oC$
I = An annual heat index obtained by summing the twelve monthly heat indices(i) as follows:

$$I = \sum_{n=1}^{12} i \text{ ------------------- } (3.3)$$

$$i = (T/5)^{1.514} \text{ -------------- } (3.4)$$

$$a = 0.000000675\ I^3 - 0.0000771\ I^2 + 0.01792\ I + 0.49 \text{ ------------- } (3.5)$$

The gross potential evapotranspiration computed by equation 3.2 is a theoretical standard value for a month of 30 days and 12 hours of day sunshine, therefore, this value must be corrected by multiplying the appropriate latitude factor (it accounts the number of days per month and the length of the day), which can be calculated by the equation;

$$K = \frac{N}{12} \times \frac{D}{30} \text{ - - - } (3.6)$$

where K = latitude factor ( for monthly value )
N = maximum number of hours of solar energy per day
D = number of days in the month

Thus, the corrected monthly potential evapotranspiration ( PET) is given as:

$$PET = K \times GPET \text{ - - - - - } (3.7)$$

In the studied area calculation of actual evapotranspiration and monthly water balance were conducted for the two stations Ziway and Assela which are expected to represent the lowlands and highlands of the area respectively.

To calculate different hydrologic parameters used for the average monthly water balance of the two stations table 3.2 and table 3.3 ) the procedure was taken from Dunne T. and Leoplod B. ( 1978) as follows:

Gross potential evapotranspiration, annual heat index, mean monthly heat index and potential evapotranspiration are calculated by using equations 3.2, 3.3, 3.4 and 3.7 respectively.

The latitude correction factor(K) is taken from appendix 6 by considering $10^0$N latitude for the studied area.

From raw ( P -PET) of table 3.2 and table 3.3 we can define two seasons: wet seasons {( P - PET) >o} , indicates all the water demand by the potential evapotranspiration is satisfied by precipitation and dry seasons { ( P - PET)<0}, the water demand by the potential evapotranspiration is not satisfied by precipitation falling in the corresponding months which needs additional water from soil moisture to meet the demand by potential evapotranspiration. As a result, in Ziway station wet season is from June to September and dry season is from October to May and in Assela station wet season is from March to September and dry season is from October to February.

Accumulated potential water loss (APWL) expresses the severity of the dry season and it increases during the sequence of months with excessive potential evapotranspiration. In table 3.2 and 3.3 it is calculated by cumulating the negative values of ( P - PET) for the dry seasons starting from the end of the wet season which is September for both Ziway and Assela Stations.

In the lowlands of the area (mainly west of Ziway lake) the dominant type of soils are silty sand. The available water holding capacity of such soils is equal to 15% (150 mm of water per meter depth of soil) by approximately taken as that of fine sand loam (Appendix 7). In this part of the area deep rooted crops are dominant which gives rooting depth as 1.00 meter (Appendix 7), then the field water holding capacity is equal to 150 mm ( 1.00 x 150 mm).

In the eastern highlands of the area the dominant type of soils are clay soils with considerable amount of silt and the dominant types of vegetation are moderately deep rooted. From appendix 7 the available water holding capacity is equal to 25% ( by approximating as clay loam) and the rooting depth is equal to 0.8 metres which gives the field water capacity equal to 200 mm( 0.8 x 250 mm).

The soil moisture (SM) of the dry seasons can be found by reading the water retained in the soil from the graph in appendix 8 for the accumulated potential water loss (APWL) of the corresponding month with an available water capacity of 150 mm for Ziway station and 200 mm for Assela station. Soil moisture for the wet seasons are obtained by adding the excess precipitation(P - PET) to the soil moisture level at the end of the dry season. The soil moisture can not exceed 150 mm for Ziway and 200 mm for Assela stations, since the soil can not hold above its field capacity. Therefore if the calculated value is greater than the field capacity, soil moisture of that month is equal to field capacity. In Ziway the wet months August and September and in Assela the wet months April, May, June, August and September have soil moistures equal to their field capacities.

The change in soil moisture ($\Delta$SM) can be found by subtracting the soil moisture value of a month under consideration from that of the preceding month. Negative values of $\Delta$ SM for the months of October through May of Ziway and October through February of Assela stations (table 3.2 & table 3.3) indicate the amount of contribution of the soil moisture storage to evapotranspiration.

Actual evapotranspiration (AET) for wet seasons is equal to potential evapotranspiration( PET), because the rain water is considered to be easily available to the plant, even if the soil moisture of the whole root zone is not raised to the available water capacity. This is true for the months June through September for Ziway station and March through September for Assela Station. For dry seasons, actual evapotranspiration is the sum of precipitation and the amount of soil moisture withdrawn from storage (AET= P + I ΔSM I).

Soil moisture deficit (D) is the amount of water needed to satisfy the demand of potential evapotranspiration of a given month and it can be computed by subtracting the actual evapotranspiration from the potential evapotranspiration of the corresponding month .

Soil moisture surplus (S) is the amount of water Contributing to runoff and groundwater recharge. For dry seasons it is taken as zero while for wet seasons it can be calculated by subtracting the change in soil moisture content (ΔSM) from the difference of precipitation and potential evapotranspiration (P - PET).

In the studied area Thornthwaite's methods of calculation for the two stations Ziway (located at 1640m) and Assela (located at 2350m) presented in table 3.2 and table 3.3 respectively, gives the annual potential and actual evapotranspiration values of 893.64 mm and 735.87 mm for Ziway and 695.83 mm and 639.06 mm for Assela respectively. From the altitudes of the two stations we can say that the calculation of Ziway station represents the lowlands of the area, mainly the western and northern parts of Ziway lake and Assela station mainly represent the eastern highlands of the area.

From these we can observe that about 97% of precipitated water in the lowlands and about 54% of the precipitated water in the highlands return to the atmosphere by evapotranspiration.

The total annual precipitation is equal to 752 mm for Ziway and 1180 mm for Assela. From these the surplus water available for runoff and ground water recharge is equal to 18.2 mm for Ziway and 541.39 mm for Assela, which indicates that the contribution to surface runoff and groundwater recharge of lowlands is very low about 4% and that of the highlands is very high about 96% of the total annual surplus water in the studied area.

From tables 3.2 and table 3.3, fig 3.3 and fig 3.4 are produced respectively, to indicate the seasonal pattern of precipitation, actual evapotranspiration, potential evapotranspiration, soil moisture deficit, soil moisture utilisation, and surplus soil moisture.

T - mean monthly temperature
i - monthly heat index
GPET - gross potential evapotranspiration
K - latitude factor
PET - potential evapotranspiration
P - mean monthly precipitation

APWL - accumulated potential water loss
SM - soil moisture
ΔSM - change in soil moisture
AET - actual evapotranspiration
D - soil moisture deficit
S - soil moisture surplus

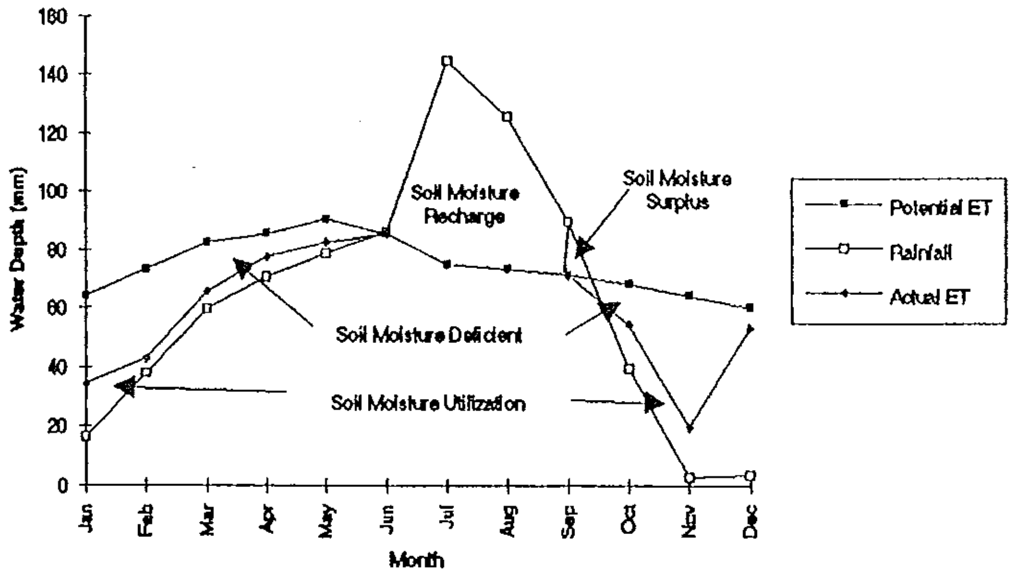
Table 3.3 Monthly Water Balance of Assela Station

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Annual |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| T °c | 13.92 | 14.81 | 15.83 | 16.12 | 16.34 | 15.61 | 14.69 | 14.48 | 14.03 | 14.75 | 13.80 | 13.46 | |
| i | 4.71 | 5.18 | 5.73 | 5.89 | 6.01 | 5.61 | 5.11 | 5.00 | 4.77 | 5.14 | 4.65 | 4.48 | 62.28 |
| GPET(mm) | 52.19 | 57.17 | 63.05 | 64.75 | 66.06 | 61.76 | 56.49 | 55.30 | 52.80 | 56.83 | 51.53 | 49.67 | |
| K ($10^0$ N) | 0.97 | 0.98 | 1.00 | 1.03 | 1.05 | 1.06 | 1.05 | 1.04 | 1.02 | 0.99 | 0.97 | 0.96 | |
| PET(mm) | 50.62 | 56.03 | 63.05 | 66.69 | 69.36 | 65.47 | 59.32 | 57.51 | 53.86 | 56.26 | 49.98 | 47.68 | 695.83 |
| P (mm) | 19.3 | 44.1 | 96.6 | 115.0 | 117.1 | 143.1 | 198.0 | 203.2 | 165.2 | 49.5 | 15.0 | 13.9 | 1180 |
| P- PET(mm) | -31.32 | -11.93 | 33.55 | 48.31 | 47.74 | 77.63 | 138.68 | 145.69 | 111.34 | -6.76 | -34.98 | -33.78 | 484.17 |
| APWL(mm) | -106.8 | -118.8 | - | - | - | - | - | - | - | -6.76 | -41.74 | -75.52 | |
| SM(mm) | 146 | 138 | 172 | 200 | 200 | 200 | 200 | 200 | 200 | 194 | 175 | 160 | |
| ΔSM(mm) | -14 | -8 | 34 | 28 | 0 | 0 | 0 | 0 | 0 | -6 | -19 | -15 | |
| AET(mm) | 33.3 | 52.1 | 63.05 | 66.69 | 69.36 | 65.47 | 59.32 | 57.51 | 53.86 | 55.5 | 34.0 | 28.9 | 639.06 |
| D(mm) | 17.32 | 3.93 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.76 | 15.98 | 18.78 | 56.77 |
| S(mm) | 0 | 0 | 0 | 20.31 | 47.74 | 77.63 | 138.68 | 145.69 | 111.34 | 0 | 0 | 0 | 541.39 |
| | | | | | | | | | | | | | |

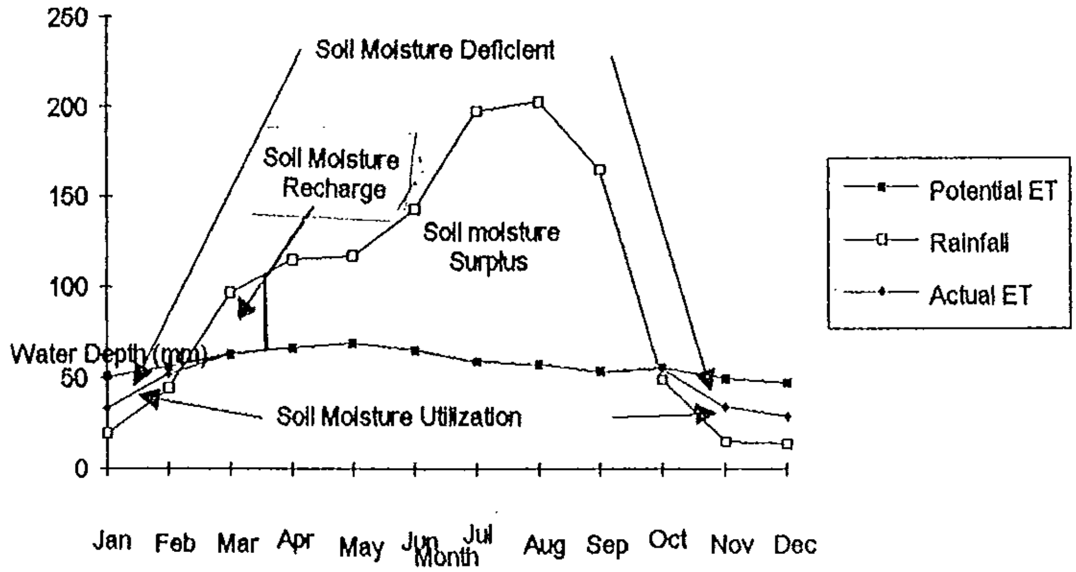
T - mean monthly temperature
i - monthly heat index
GPET - gross potential evapotranspiration
K - latitude factor
PET - potential evapotranspiration
P - mean monthly precipitation

APWL - accumulated potential water loss
SM - soil moisture
ΔSM - change in soil moisture
AET - actual evapotranspiration
D - soil moisture deficit
S - soil moisture surplus

## Fig 3.3 Thornthwaite Monthly Water Balance of Ziway Station




## Fig 3.4 Thornthwaite Monthly Water Balance of Assela Station



### 3.3 Runoff

The studied area is located in the northern part of Ziway - Shalla basin and it is drained by three perennial streams Meki, Ketar and Bulbula. The first two flow towards Ziway lake while Bulbula river flows out of the lake.

In the western and northern part of the area the only perennial surface runoff into the lake is Meki river, which receives the majority of its discharge from the intermittent streams in the western highlands out side the studied area. In this part of the area only very few intermittent gullies flow towards the lake during the time of large storm rain events. It is generally low during small and short rains even in the rainy season. This is due to large infiltration capacity of lacustrine sediments and relatively flat topography of this part of the area. In the southern part of the studied area there are few intermittent streams that flow towards the lake from the slopes of Aluto volcano during rainy seasons. This is mainly due to high altitude variation in this part of the area. In this part the only perennial river is Bulbula which flows towards south from Ziway lake.

In the eastern part of the studied area there are many intermittent streams that flow from the eastern highlands, mainly from the slopes of Chillalo mountain into the lake through Ketar river. Most of them flow during big rainy period and some flow during small rainy period. This is due to low infiltration capacities of welded ignimbrites and trachytes and due to steep slopes in the area. When the topography is flat and surrounded by mountains, the runoff from adjacent mountains is sluggish and result in small swampy areas during wet season. In the eastern shore of Ziway lake there is no surface runoff into the lake due to highly drained nature of hill slopes, through the fractures, which creates a chance for the runoff to percolate into the soil.

In the studied area there are three operating river gauging stations at Meki village for Meki river, at Abura village for Ketar and near Kerkersity village for Bulbula. Meki and Ketar rivers gauging stations have 26 years record from 1970 to 1995 while Bulbula river station has been recorded for 17 years from 1979 to 1995. From the available data mean annual runoff was calculated and gives 285.794 million $m^3$ for Meki, 420.467 million $m^3$ for Ketar and 154.267 million $m^3$ for Bulbula. The average annual runoff leaves the studied area is 154.267 million $m^3$, since the only surface outlet from the basin is Bulbula river and the basin is closed just at this gauging station.

Fig 3.5 Discharge Hydrograph of Meki River

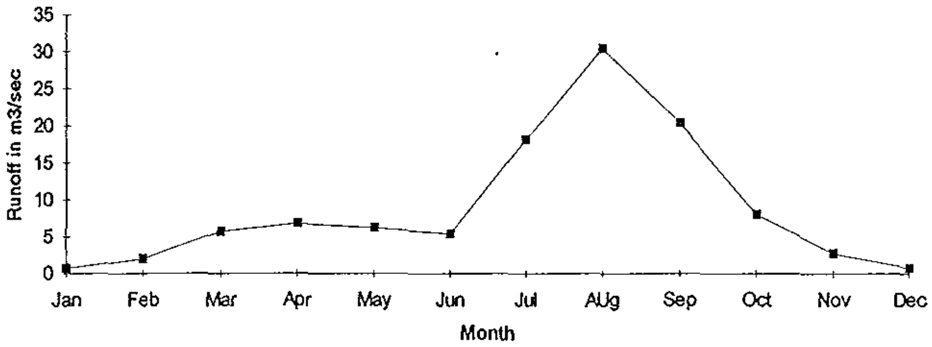



Fig 3.6 Discharge Hydrograph of Ketar River

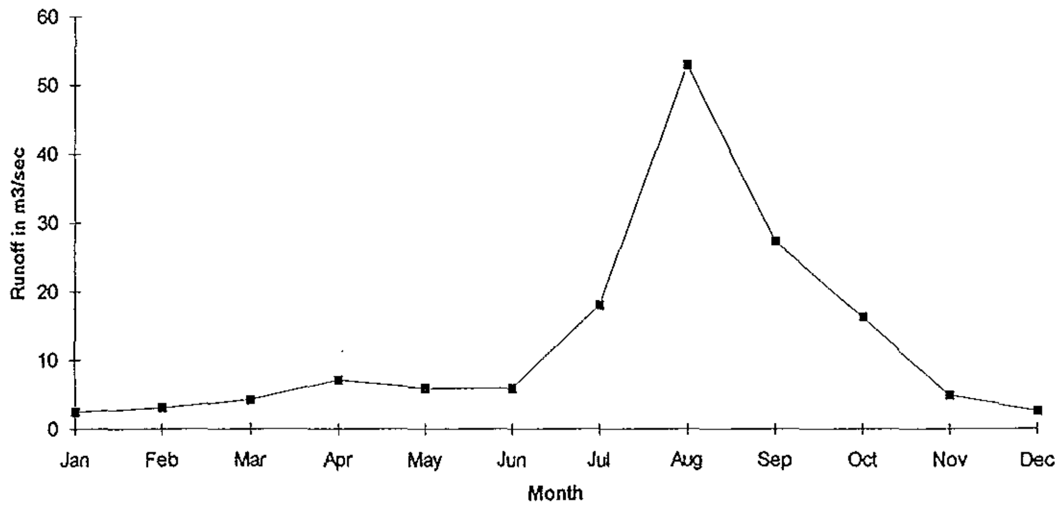


Fig 3.7 Discharge Hydrograph of Bulbula River

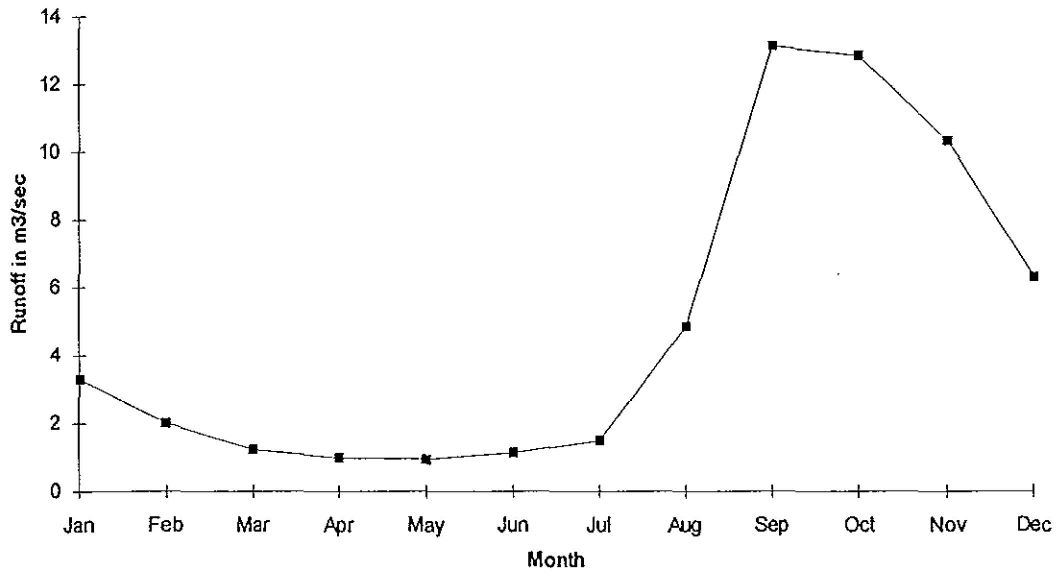
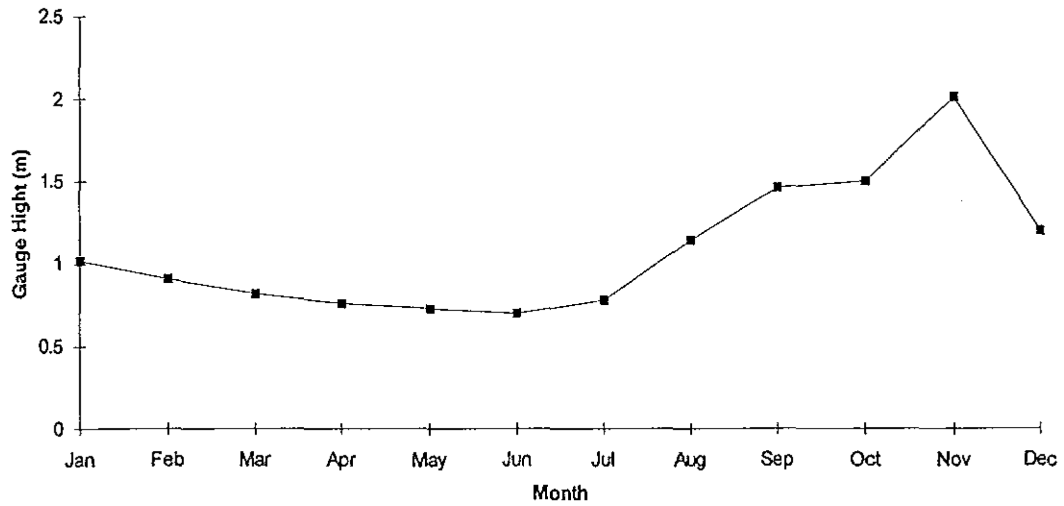



Fig 3.8 Lake Level Fluctuation of Ziway Lake



### 3.4 Infiltration

Among the several components allowing to estimate the hydrological balance of a certain basin, Infiltration is not directly evaluated. In fact infiltration is mostly estimated by means of indirect calculations which take into account precipitation, evapotranspiration and runoff, as I = P - ET - R. The main factors affecting infiltration are rainfall intensity; size, shape and arrangement of soils; porosity and permeability of rocks; vegetation cover; soil moisture content and the amount of available water.

In the studied area the main types of infiltration are:
- Direct infiltration of water during rain events
- Infiltration through faults, fractures and joints
- Infiltration from runoff through perennial and intermittent stream channels and
- Infiltration through Ziway lake bed and intermittent swampy areas.

Depending on the dominant type of infiltration and the main factor affecting it the studied area can be classified in to three broad groups.

1. The area west and north of Ziway lake - The dominant type of infiltration is direct infiltration of water during rain events and the main factors affecting it are rainfall intensity and shape, size and arrangement of soils. Generally in this part high infiltration capacity of soils, as we have observed from the intermittent streams disappearing into the lacustrine sediments and there is no surface runoff into the lake from this part even in the rainy season.

2. The area east and south of Ziway lake - The dominant type of infiltration is infiltration through faults, fractures and joints. The main factors affecting it are porosity and permeability of rocks and rainfall intensity. In this part infiltration capacity ranges from low to high depending on the porosity and permeability of rocks. In the area east of the eastern border faults of the Wonji Fault Belt infiltration capacity is low due to the presence of impervious bed rock cover in the ridges and domes and due to steep slopes, both facilitate surface runoff during rainy periods. In the area south of Ziway lake and between Ziway lake and the eastern boarder faults of Wonji Fault Belt, infiltration capacity is high due to intense faulting and fracturing, which allows water to percolate through them.

3. The area covered by Ziway lake - In this part infiltration is highly affected by the permeability of rocks in the saturated zone beneath the lake to percolate and filtrate the water continuously supplied from the lake. In this part the infiltration capacity of the soil is constant, since lake bed sediments are saturated with water for a long time, which decrease the infiltration capacity with time and reached a constant value.

### 3.5 Water Balance

The water balance equation for a river basin or water body indicates the relative values of inflow, outflow and change in water storage for the area or water body. The water balance principle for hydrological study states that: for any arbitrary volume and during any period of time the difference between total input and output will be balanced by the change of water storage within the volume.

The inflow components of the water balance equation include precipitation( P), surface inflow into the basin( QSi) and ground water inflow into the basin (Qgi). The outflow components of the equation include evaporation ( E).Transpiration (T), surface outflow from the basin ( QSo) and ground water outflow from the basin (Qgo).Therefore, the total water storage in the basin or water body($\Delta$S) can be balanced as follows:

$$\Delta S = \text{inflow} - \text{outflow}$$

$$\Delta S = P + Qsi + Qgi - E - T - Qso - Qgo$$

For the water balance of free water bodies, since there is no transpiration the water balance equation becomes:

$$\Delta S = P + Qsi + Qgi - E - Qso - Qgo$$

The studied area, which is found within the Ziway - Shalla basin, could not be identified with a single large catchement area over which it is possible to conduct water balance study without an additional investigation outside the area. Therefore, only the water balance study of the lake is conducted.

Even if the information available is incomplete to attain the desired degree of precision, it has been tried to conduct a water balance study of the lake by making various assumptions.

Ziway lake covers a surface area of 434 sq.km and has two main surface inflows and a surface outflow. The purpose of the water balance study is to evaluate the change in ground water storage of the lake in annual basis and total of eleven years from 1981 to 1991, by using the following water balance equation,

$$\Delta g = \Delta VL + VE + VB + VIr - VR - VM - VK - VOv$$

$$\Delta g = Vgi - Vgo$$

Vgi = Volume of ground water flow into the lake
Vgo = Volume of ground water flow out of the lake
$\Delta$VL = Change in volume of water from the lake storage
VE = Volume of water evaporated from the lake
VIr = Volume of irrigated water from the lake
VB = Volume of water of Bulbula river
VR = Volume of rainfall water directly precipitated into the lake
VM = Volume of water of Meki river
VK = Volume of water of Ketar river
VOv = Volume of water flow into the lake as over land flow during rainy seasons

The assumptions made to derive the water balance equation for the lake are:

1. All the water measured in Meki for Meki river and in Abura for Ketar river directly flow into the lake without decrease by infiltration and increase by overland flow (in rainy seasons) and all the volume of water measured at Kerkersitu of Bulbula river came from the lake.

2. The irrigated water from the lake ( VIr) can be compensated by the overland flow into the lake during rainy seasons( VOv) on annual basis.

Therefore the water balance equation can be simplified as follows :

$$\Delta g = \Delta VL + VE + VB - VR - VM - VK$$

The change in volume of water from the lake ( ΔVL) is calculated from the gauge height measurements at Bochessa by multiplying the difference between gauge height measurements of the months of December and January by the total area of the lake ($434 \times 10^6$ sq. metres) for the years from 1981 to 1991.

Table 3.4 Change in volume of Ziway lake

| Year | Gauge Height Difference ( Dec - Jan ) | Change in volume of water in $10^6$ $m^3$ |
|---|---|---|
| 1981 | 0.70 | 303.80 |
| 1982 | 0.06 | 26.04 |
| 1983 | 0.70 | 303.80 |
| 1984 | -0.57 | -247.38 |
| 1985 | 0.06 | 26.04 |
| 1986 | 0.40 | 173.60 |
| 1987 | 0.03 | 13.02 |
| 1988 | 0.54 | 234.36 |
| 1989 | 0.02 | 8.68 |
| 1990 | 0.72 | 312.48 |
| 1991 | 0.05 | 21.70 |
| Total | 2.71 | 1176.14 |

Evaporated water from the lake is taken from pan evaporation measurements at Ziway station (Appendix 2) by multiplying with a correction factor of 0.75 and the total area of the lake.

Total annual rainfall directly falling into the lake (column 5 of table 3.5) was computed by multiplying the value at Ziway station from 1981 to 1991 with the total area of the lake.

The total volume of water from the three river gauging stations of Meki, Bulbula and Ketar were taken from Appendix 3 from the year 1981 to 1991.

Finally, from the balance equation the change in ground water storage of the lake has been determined for each year from 1981 to 1991 ( table 3.5) and for the total of eleven years.

Table 3.5 Water Balance of Ziway Lake From 1981 to 1991

| Year | ΔVL | VE | VB | VR | VM | VK | Δg |
|---|---|---|---|---|---|---|---|
| 1981 | 303.80 | 653.99 | 144.34 | 430.62 | 339.30 | 573.55 | -241.34 |
| 1982 | 26.04 | 588.53 | 79.07 | 386.30 | 237.23 | 345.24 | -275.13 |
| 1983 | 303.80 | 450.74 | 281.82 | 375.02 | 333.65 | 579.96 | -252.27 |
| 1984 | -247.38 | 667.77 | 103.05 | 269.95 | 115.61 | 251.30 | -113.42 |
| 1985 | 26.04 | 628.80 | 21.10 | 286.09 | 172.32 | 296.36 | -78.83 |
| 1986 | 173.60 | 597.41 | 105.64 | 233.32 | 219.29 | 430.81 | -6.77 |
| 1987 | 13.02 | 745.30 | 62.89 | 239.96 | 216.37 | 278.98 | +76.9 |
| 1988 | 234.36 | 741.94 | 112.36 | 306.97 | 229.55 | 527.87 | +24.27 |
| 1989 | 8.68 | 647.52 | 126.90 | 412.78 | 219.80 | 288.32 | -137.8 |
| 1990 | 312.48 | 683.88 | 159.69 | 299.20 | 231.02 | 511.33 | +114.5 |
| 1991 | 21.70 | 677.15 | 159.36 | 337.22 | 271.00 | 332.56 | -82.54 |
| Total | 1176.14 | 7083.03 | 1356.25 | 3577.43 | 2585.14 | 4425.28 | -972.43 |
| Average | 106.92 | 643.91 | 123.30 | 325.22 | 235.01 | 402.30 | -88.40 |

Unit are all in $10^6$ $m^3$

VL - Change in volume of the lake
VE - Volume of water evaporated from the lake
VB - Volume of water of Bulbula river at Kerkersitu
VR - Volume of water directly precipitated in to the lake
VM - Volume of water of Meki river at Meki
VK - Volume of water of Ketar river at Abura
Δg - Change in ground water storage within the lake

From table 3.5 we can see that the mean annual volume of water that leaves the lake as groundwater is 88.4 x $10^6$ $m^3$. However this groundwater outflow show significant annual variation from 1981 to 1991 which mainly depends on the amount of rainfall directly falling into the lake and the total rainfall in the western and eastern highlands bordering the Main Ethiopian Rift which supply the runoff of Meki and Ketar rivers . The positive values in 1987, 1988 and 1990 indicate that the lake received a considerable amount of recharge as groundwater inflow. This inflow is most probably through the fractures from the eastern side of the lake. In the western part it is insignificant since there is a great soil moisture deficit large amount of water is needed to escape from the field capacity of the soils and flow into the lake as groundwater.

In an area where there is a continuous supply of water for a long time the soil in the aeration zone saturated and the infiltration capacity decreases with time and becomes a constant value depending on the permeability of the rocks in the saturated zone. From this we can depict that the sediments within Ziway lake have a constant infiltration capacity since they are saturated with water for a long time.

By taking the annual mean groundwater outflow from the lake ( 88.4 x $10^6$ $m^3$ ) the infiltration capacity of the lake bed sediments is calculated to be 0.0233 mm/ hour which is also the permeability of the rocks in the saturated zone within the lake.

# CHAPTER FOUR

# GROUND WATER HYDROGEOLOGY

## 4.1 General

The main controlling factors of groundwater distribution in rocks are lithology, structure and grain size.

In clastic sedimentary rocks permeability depends on grain size, shape of grain and sorting. Coarse grained rounded and well sorted materials are very good aquifers while fine grained and poorly sorted materials are aquicludes.

In consolidated sedimentary rocks, since primary permeability is reduced by cementing materials the occurrence of aquifers depends on fracturing by secondary processes. Highly fractured consolidated sedimentary rocks are good aquifers while unfructured rocks are aquifuges.

In the case of volcanic rocks the occurrence of aquifers mainly depend on structure and the process resulting those rocks. Volcanic rocks resulting from explosive magmatic activity, like pumice falls and scoria have very high intergranular permeability while in lava flows primary permeability is mainly due to jointing at the time of flowing . Therefore fracturing is the main factor in such type of rocks to be aquifers. In volcanic lava flows, cinder cones and spatter cones, weathering mostly have a negative effect on permeability of rocks by filling the openings in the lava flows and intergranular spaces in cinder and spatter cones, while in tuffs and ignimbrites it may have a positive effect by separating different layers forming these rocks.

In general the aquifers in the studied area are divided into three main groups

1. Aquifers mainly characterised by primary permeability in rocks which include: lacustrine sediments, alluvial, pumice falls, scoria cones and hyaloclastites. These deposits usually represent important aquifers in many places within the area. However, lacustrine sediments composed of fine and poorly sorted particles are characterised by low permeability.

2. Aquifers mainly characterised by secondary permeability due to rock fracturing and weathering. This group consists of ignimbrites and tuffs, the permeability of these rocks mainly depends on the intensity of faults and fractures. In places of intense faulting and fracturing they are good aquifers otherwise they are typical aquicludes.

3. Aquifers characterised by both primary and secondary rock permeability. In the area this group includes: basaltic lava flows, rhyolitic pumice flow and obsidian lava flows. Generally these rocks form moderate to good aquifers, in places of intense faulting and fracturing they are very good aquifers.

## 4.2 Hydrogeology of Different Rock Units in the Studied Area

In the studied area the permeability of different rock units ranges from low to high and is mainly controlled by lithology and structure.

The high permeability units are basaltic lava flows, scoria and hyaloclastites and highly faulted and fractured ignimbrites while the low permeability units are Chillalo trachytes and welded ignimbrites.

The aquifer characteristics of these different rock units in the area is described below.

### 4.2.1 Alluvial and Lacustrine Sediments

In the studied area alluvial sediments are found along the channels of Meki and Ketar rivers and made of materials ranging from clays to gravel which are deposited by the action of Meki and Ketar rivers either on their channels or on the adjacent flood plains owing to channel flows and over bank flooding. Alluvial sediments made of gravel and sands form very good aquifers while those made of clay and silt are aquicludes.

Lacustrine sediments found west, north, north-east and south-west of Ziway lake are dominantly composed of silt and clay size materials with some volcano clastic sediments and tuffs. Lacustrine sediments generally show anisotropic permeability due to the variation in grain size both horizontally and vertically. On the surface they are considered to have low permeability, Since the fine grained materials are dominant and they are poorly sorted.

Therefore, this upper units serve as semi- confining layers in many of the wells in these rocks ( see lithologic logs of BW20 and BW35 at appendix 12). But a few aquifers in these rocks are unconfined since the upper units are dominantly composed of coarse grained rocks (see lithologic logs of BW2, BW10, BW30 and BW40).

The permeability of these rocks ranges between low to high, the higher permeability aquifers are mostly made of coarse grained volcano - sedimentary materials and well sorted.

### 4.2.2 Rhyolitic Pumice and Obsidian Lava Flows

Pumice falls are characterised by high intergranular permeability while pumice flows associated with rhyolites are characterised by low to moderate permeability. In the studied area pumice is found around and Southeast of Bora mountain and around Tullu Moje mountain, which are poorly welded and associated with ash and rhyolite ( poorly sorted) which result in moderate ground water potential.

In general obsidian lava flows are considered to be less permeable unless they are highly fractured. In the studied area obsidian lava flows occur only on the slopes of Aluto volcano and they are found interbeded with pumice and ashes and affected by minor fracturing which result in a secondary permeability in this rock.

### 4.2.3 Basaltic Lava Flows, Cones and Hyaloclastites

These rocks are found just east and north-east of lake Ziway up to the eastern border faults of the Wonji Fault Belt.

From hydrogeological point of view basalts can have a very wide range of permeability. Basaltic rocks relatively dense, unfructured and unjointed have low permeability while basaltic rocks heavily weathered and /or fractured have high permeability, and also the permeability in between the two extreme cases also occur according to the degree of weathering and fracturing.

In the studied area basaltic lava flows occur in places where faulting is intense which result in a secondary permeability and its ground water potential ranges from moderate to high.

Naturally cinder and spatter scoracious cones have primary intergranular porosity which made these rocks a very good aquifers. In the studied area these basaltic cones occur east of Ziway lake mostly associated with basaltic lava flows.
Faulting and fracturing were intense in this part of the area which result in fracture porosity in addition to their intergranular porosity resulting from coarse grained fragments due to explosive eruptions. Therefore the ground water potential of these rocks in the area is very high.

Since hyaloclastites are results of explosive activity generally they are highly permeable. In the studied area they are found in southern shore of Ziway lake and east of Ziway lake, associated with basaltic lava flows and cones. Due to the fact that they are the results of explosive activity and in the area faulting is intense, basaltic hyaloclastites in the area have a very high groundwater potential.

### 4.2.4 Ignimbrites

From the hydrogeological point of view ignimbrites can have permeability ranging from low to high according to its type ( Poorly welded or well welded ), degree of weathering and degree of fracturing.

In the studied area two types of ignimbrites were identified, poorly welded and well welded. In the western part of the area ignimbrites are well welded associated with thinly layered pumice, which result in low permeability. In addition to this faulting is relatively scarce in this part of the area, therefore ignimbrites in the western part of the area have from low to moderate groundwater potential.

In the area east of Ziway lake up to the eastern border fault of the Wonji Fault Belt ignimbrites are less welded and intercalated with big pumice fragments, which increases permeability. In this part of the area faulting is very intense (Which result in secondary permeability), therefore ignimbrites in this part of the area have high groundwater potentials.

In the area east of the eastern boarder faults of the Wonji Fault Belt, ignimbrites are dominantly well welded and less fractured which result in ground water potential ranging between low to moderate according to the degree of fracturing.

#### 4.2.5 Trachytes

In the studied area this rock is found in the slopes of Chillalo mountain ( which is found at the eastern escarpment of the Main Ethiopian Rift ). Due to the fact that trachytic lava flow have no primary permeability and faulting is scarce in this part of the area these rocks have low groundwater potentials. In the lower parts of the mountain affected by minor faulting and fracturing low permeability are most probably due to the filling of this secondary discontinuities by weathering materials from the upper part of trachyte dome .

### 4.3 Well and Spring Inventory

The water wells are used for the extraction of groundwater to fill domestic, municipal, industrial and irrigation need. In the studied area wells are mainly used for domestic and municipal needs.

There are many hand dug and bore wells in the studied area. About 50 of them were observed during the field period. From these phreatimeteric measurements were done only for a few hand dug wells due to the fact that most of the bore wells are either connected with pumps or sealed due to failure of chemical quality of the waters for drinking. However the hydrodynamic data of these wells were found from the drilling organisation of most of these wells and from hydrogeological literature in the area which is presented in Appendix 9 and their location is found on Fig 4.1. The measurements of the features in appendix 9 were taken in different periods most of them are at the time of drilling. The location of most of the wells are determined by the author at the time of field observation.

#### 4.3.1 Hand Dug Wells

Many hand dug wells in the studied area, mainly around the towns of the eastern part of the area. From the observed dug wells the total depth varies from 3 to 40 meters and their diameter varies from 0.7 to 1.25 meters. Except a few dug wells which are fitted with surface pump, most of them are equipped with pulley.

The depth of static water level below the ground surface ranges from 1.75 to 37.4 meters. According to the information gathered from the owners of these wells the depth of water level varies in different seasons of the year, decrease during the rainy season and increase during the dry seasons which indicates that the main recharge of these wells is coming from rainfall.

#### 4.3.2 Bore Wells

More than sixty five bore wells in the studied area, most of them are in the western part of the lake and they are mainly used for domestic water supply .

In the western part most of them fitted with wind mills except Ziway Prison and Gubiba wells, which are fitted with electrical pumps, while in the eastern part all are equipped with electrical pumps.

The yield of bore wells varies from less than 0.03 to 9 l /Sec, however their pump yields of most of these bore wells are less than their well yields. The diameter of bore wells varies from 12.5 cm to 31.1 cm and their total depth ranges from 25 meters to 200 metres except BW43 which have 250 metres depth. The static water level varies from 18 to 130 metres below the ground surface.

Most of the bore wells are within unconfined and semi confined aquifers made of lacustrine sediments and ignimbrites except a few wells within basalts. Pumping and recovery test data are found non of these wells while lithological log data of many wells (particularly in the western part) are available ( see Appendix 12).

### 4.3.3 Springs

In the studied area only two cold springs and two thermal springs ( Tulu Gudo Island) are found.

Gonde springs - are contact type, found in hill side ignimbrites overlain by Chillalo trachytes and their approximate flow is about 30 l/ s and they are locally used for irrigation and domestic purposes .

Burkitu springs - are depression springs, which are found within a graben made of ignimbrites and their approximate flow is about 10.5 l/s and their use is locally for irrigation and domestic purposes.

Tulu Gudo Springs - are volcanic springs rise to the surface along fractures without gravitational forces due to their high temperatures. Their high temperature is from a shallow magma chamber in the area. Their approximate flow is about
0.1 l/s for TS1 and small for TS2, due to the fact that man have not been live in the island, these springs are not used for human beings.

# CHAPTER FIVE

# HYDROCHEMISTRY

## 5.1 Sampling and Analyses

In hydrogeological investigation of an area chemical, physical and bilogical properties of both surface and ground water are very important. Therefore, investigations were extended to these aspects of the waters.

Samples were collected from bore wells, hand dug wells, rivers and Ziway lake from April 1 to 5 and on June 4 and 5 by using 100 ml plastic bottles and 250 ml glass bottles. Sampling sites were selected so as to be representative of the entire area and to fill the gap of knowledge of previous hydrogeochemical investigations.

For the bore wells and hand dug wells samples were collected from the tap connected with the pumps within the wells. River samples were taken only from the three main rivers in the area Meki, Ketar and Bulbula between five to ten kilometres far from Ziway Lake. For Ketar river one additional sample were taken at Feti, the Southeast border of the area, since it drains a wide area in the basin. For Ziway lake three samples were collected one at the swampy area north of the lake and two from western and southern shore of the lake.

Temperature and electrical conductivity of water were measured in the field by using thermometer and conductivity metre respectively. Field measurement of pH was done only in the first field trip. At the time of the second field trip pH measurement was not done due to equipment failure.

Chemical analyses was carried out on major cations like sodium, potassium, calcium and magnesium and major anions, chloride and fluoride. Sulphate and bicarbonate were not determined due to the absence of chemicals in the Department laboratory.

Chemical analyses of fluoride and chloride were carried out by using electrode method in Chemistry Department and that of sodium, potassium, calcium and magnesium were carried out by using atomic absorption spectrophotometer in Geology Department of Addis Ababa University. The results of the analyses are given in appendix 10.
Bacteriological tests for the collected samples were not carried out due to sampling and analysis problems, since it needed short time to transport samples for analysis.

## 5.2 Geochemical Characteristics

The geochemical characteristics of both surface and ground water of the studied area were discussed below by using results of this work and previous analyses results by different authors and organisations.

### 5.2.1 pH

pH of natural waters mainly fall between 6 to 8.5 ( Hem, 1992) and it is controlled by interrelated chemical reactions that produce or consume hydrogen ions. The main ones are the reaction of dissolved $CO_2$ with water, dissociation reactions of acidic solutes and hydrolysis reactions.

The pH values of waters in the studied area ranges between 7 to 8.9. Therefore, the pH values of all waters are within the range of nneutral to weakly alkaline solutions.

The values of pH in natural waters are one of the controlling factors for the deposition and dissolution of major ions. Carbonate species in natural waters are controlled by pH. In acidic natural waters the carbonate species is mainly in the form of carbonic acid ($H_2CO_3$). At pH between 7 and 10 more than 90% of the carbonate species is in the form of bicarbonate ion ($HCO_3^-$), and in natural water pH greater than 11, carbonate ion ($CO_3^{2-}$) dominates. Accordingly, almost all the carbonate species that occur in the waters of the area are present as bicarbonate ion.

pH also affects the concentration of silica in natural waters. In acidic water the solubility of silica is low. In water with pH value between 7 and 10 silica is highly soluble. This is confirmed by high concentration of silica in water of the area, ranges between 40 and 120 mg/l ( Appendix 10).

### 5.2.2 Electrical Conductivity ( EC) and Total Dissolved Solids ( TDS)

Electrical conductivity is the ability of a substance to conduct an electric current and it is usually measured in microsiemens per centimetre or micromhos per centimetre, both are numerically equal values.

In aqueous solutions EC depends on the amount of charged ions in the solution, the higher the concentration of these ions the higher the electrical conductivity. Therefore the EC measurement provides an indication of ionic concentration.

The value of EC generally increase with temperature, between $20^0$c and $30^0$c an increase in $1^0$c increases the EC by two percent on average ( Hem, 1992 ). Therefore the EC values in table 5.2 and appendix 10 were measured in the field with different temperatures and computed by the above formula to make it uniform at $25^0$c.

There is also a relationship between EC and TDS of natural waters as follows:

TDS in ppm = A EC in µs/ cm

Figure 5.1 is a plot of TDS VS EC of water in the area, by using the least square method of slope calculation, the value of A is calculated and get a result of 0.88. Therefore the relation between TDS and EC in the ground water of the area is given as follows:

TDS in ppm = 0.88 x EC in µs/cm

TDS in Appendix 10 was determined by adding major cations, major anions and undissociated silica ( $SiO_2$ ). Wide range of TDS value has been found in waters of the area ( table 5.2) which ranges from 140 to 2280 ppm. Surface water in the area have relatively lower TDS than ground water.

In the studied area high TDS water are found in the wells at the western part of the lake, most are within the lacustrine sediments, indicates that high TDS resulting from high degree of water - rock interaction. This also confirmed by high TDS value of Chefe Jila well, south-east of Ziway lake. It is located within the lacustrine sediments, unlike the nearby wells in ignimbrites.

Surface and ground waters of an area can be classified in reference to table 5.1 based on TDS.

Table 5.1

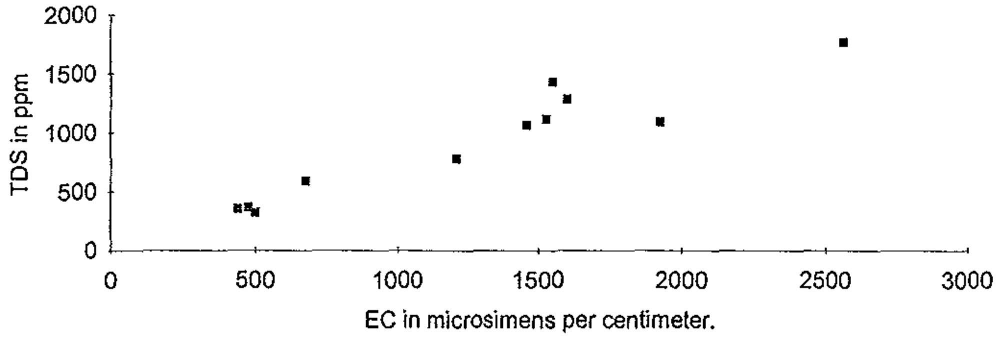
| TDS in PPM | Water type |
|---|---|
| 0 - 1 ,000 | Fresh water |
| 1,000 - 10,000 | Brackish water |
| 10,000 - 100,000 | Saline water |
| > - 100,000 | Brine |

Based on the above table all surface water and ground water east of Ziway lake, except Chefe Jila well and swampy area at the northern shore of Ziway lake are fall into fresh water category. However, ground water west of Ziway lake are mainly fall into brackish water category except a few wells which fall into fresh water category.

Table 5.2 TDS and EC values of surface and ground waters of the area

| Ref No | TDS in ppm | EC in μs/cm |
|---|---|---|
| BW8 | 590 | 673 |
| BW10 | 1062 | 1459 |
| BW13 | 1278 | 1601 |
| BW20 | 1769 | 2563 |
| BW23 | 778 | 1210 |
| BW24 | 1430 | 1550 |
| BW35 | 1118 | 1526 |
| DW4 | 1087 | 1923 |
| B1 | 318 | 498 |
| M1 | 353 | 438 |
| Z1 | 364 | 475 |

Fig 5.1 A plot showing the relation between TDS and EC of waters in the area




### 5.2.3 Hardness

The hardness of natural waters are mainly due to the presence of calcium and magnesium and usually expressed on as equivalent concentration of calcium carbonate. Hardness can be computed by multiplying the sum of milliequivalents per litre of calcium and magnesium by 50, which is simplified as follows:

$$H = 50\ (0.04990\ Ca^{2+} + 0.8229\ Mg^{2+})$$

$Ca^{2+}$ and $Mg^{2+}$ are in mg /l

Durfor and Becker ( 1964) used the following classification of natural water according to their $CaCO_3$ hardness.

Table 5.3

| Hardness Range ( mg/l of $CaCO_3$ ) | Description |
|---|---|
| 0 - 60 | Soft |
| 61 - 120 | Moderately Hard |
| 121 - 180 | Hard |
| > 180 | Very Hard |

Surface and ground water in the area ranges between soft to very hard, dominantly they fall into moderately hard category (Appendix 10) .The maximum value is 252 at Gerbi well which is found at Ziway state farm in the south-western shore of the lake. This is due to cation exchange reactions of calcium with sodium since in irrigated areas the exchange reactions between $Na^{+}$ and $Ca^{2+}$ extensively fluctuates with time (Hem, 1992). This can be confirmed by relatively low concentration of $Na^{+}$ in the same well, which substitute $Ca^{2+}$ in residual solutes from the irrigation water that was used by the crop or evaporated from the soil.

### 5.2.4 Major Constituents

The main undissociated specious in both surface and subsurface waters in the studied area is silica. The major cations are sodium ($Na^+$), potassium ($K^+$), calcium ($Ca^{2+}$) and magnesium ($Mg^{2+}$). Among these sodium is dominant in most of the waters. The major anions are bicarbonate ($HCO_3^-$), chloride ($Cl^-$ ), fluoride ($F^-$) and sulphate ($SO_4^{2-}$) , from these bicarbonate is the dominant anion in all surface and ground waters in the area.

**Silica ($SiO_2$)**

In natural waters silica present as undissociated specious $SiO_2$ and most of the dissolved silica in natural waters result from the chemical break down of silicate minerals.

In the studied area silica concentration ranges between 40 mg/l at Ziway lake and 120 mg/l at a well one kilometre south of Kulumsa. As we can see from the lithological log of BW56, south of Kulumsa (Appendix 12), this high concentration is mainly derived from dissolution of feldspars within weathered ignimbrites. Relatively low silica of lake Ziway as compared with the nearby wells is partly due to low temperature and partly due to the extraction of silica by organisms to use for their shells and skeletons.

**Sodium($Na^+$) and Potassium($K^+$)**

In the studies area sodium is the dominant cation in most of the ground water, it reaches up to 646 mg/l at Semoye Chelemo well (BW20). As we can see from lithologic log of BW20( Appendix 12), clay and volcanic ash are dominant which are the source of high sodium in the well. In the area high sodium is due to high rock - water interaction, which is confirmed by higher values in wells within lacustrine sediments and lower in welded ignimbrites and basalts (Appendix 10).

In rivers of the area $Na^+$ is low this is because the main source of sodium in water is dissolution of sodium containing minerals and river water have no long time interaction with rocks.

The low concentration of sodium in Ziway lake is due to the reason that the main recharge of the lake is dominantly from surface runoff and rainfall (both have low sodium concentration). Ground water inflow in to the lake is very low ( see chapter 3, water balance).

In the studied area the concentration of potassium follows the same trend as sodium (higher in ground water and low in surface water ) but it is always less than sodium. This is due to three reasons: first potassium containing minerals (i.e. sanidine) are more resistant for weathering than sodium containing minerals (e.g. plagiolcase); second potassium is less abundant than sodium in the acid peralkaline rocks.

**Calcium($Ca^{2+}$) and Magnesium($Mg^{2+}$)**

Calcium ( $Ca^{2+}$) ranges between 0 and 91 mg/l for surface and ground waters in the studied area. The maximum value is at Gerbi well, which is located south-west shore of the lake within an irrigated area. This high value is due to the fact that recharge of the

In the studied area it varies between 0 and 338 mg/l, and generally associated with volcanic activity in the area but the anomalous concentration of 338 mg/l in BW20 is due to locally highly oxidising conditions, probably by human activity, which oxidise the reduced forms of sulphur.

To verify the dominant type of water in the area based on the chemical analyses results of major cations and anions, Trilinear diagram was used (fig 5.4). From Fig. 5.4 and Appendix 11, almost all the ground water in the lowlands of the area are sodium bicarbonate type except BW3 and DW2, whic are calcium sodium bicarbonate type. These samples have been collected very near to Meki river and indicate considerable influence from the river. The ground water in the eastern escarpment, including the two cold springs, are calcium sodium bicarbonate type. When we consider surface water Ketar river is calcium bicarbonate type, Meki river is calcium sodium bicarbonate type and Bulbula river and Ziway lake are sodium bicarbonate type.

Fig 5.4.a Trilinear diagram plot of water from wells

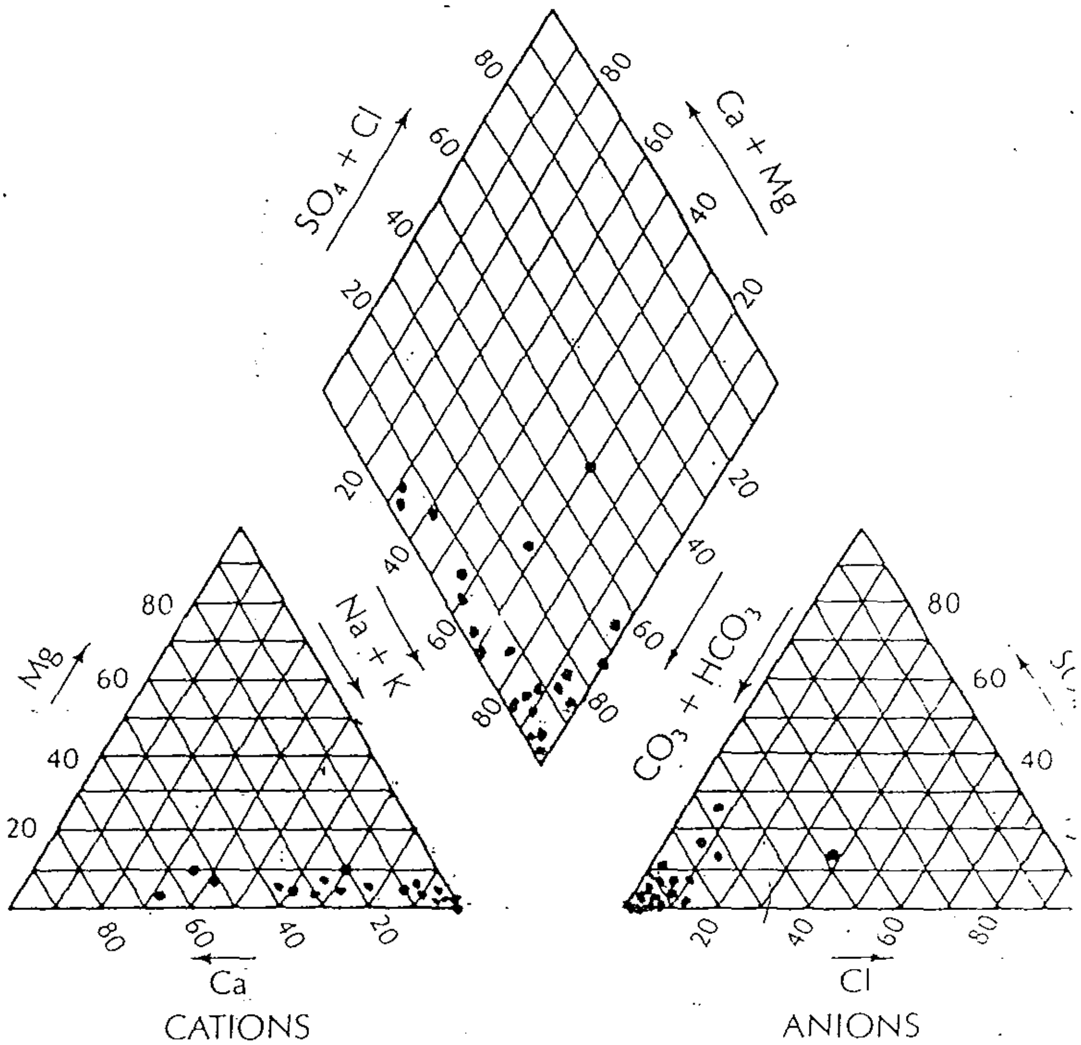
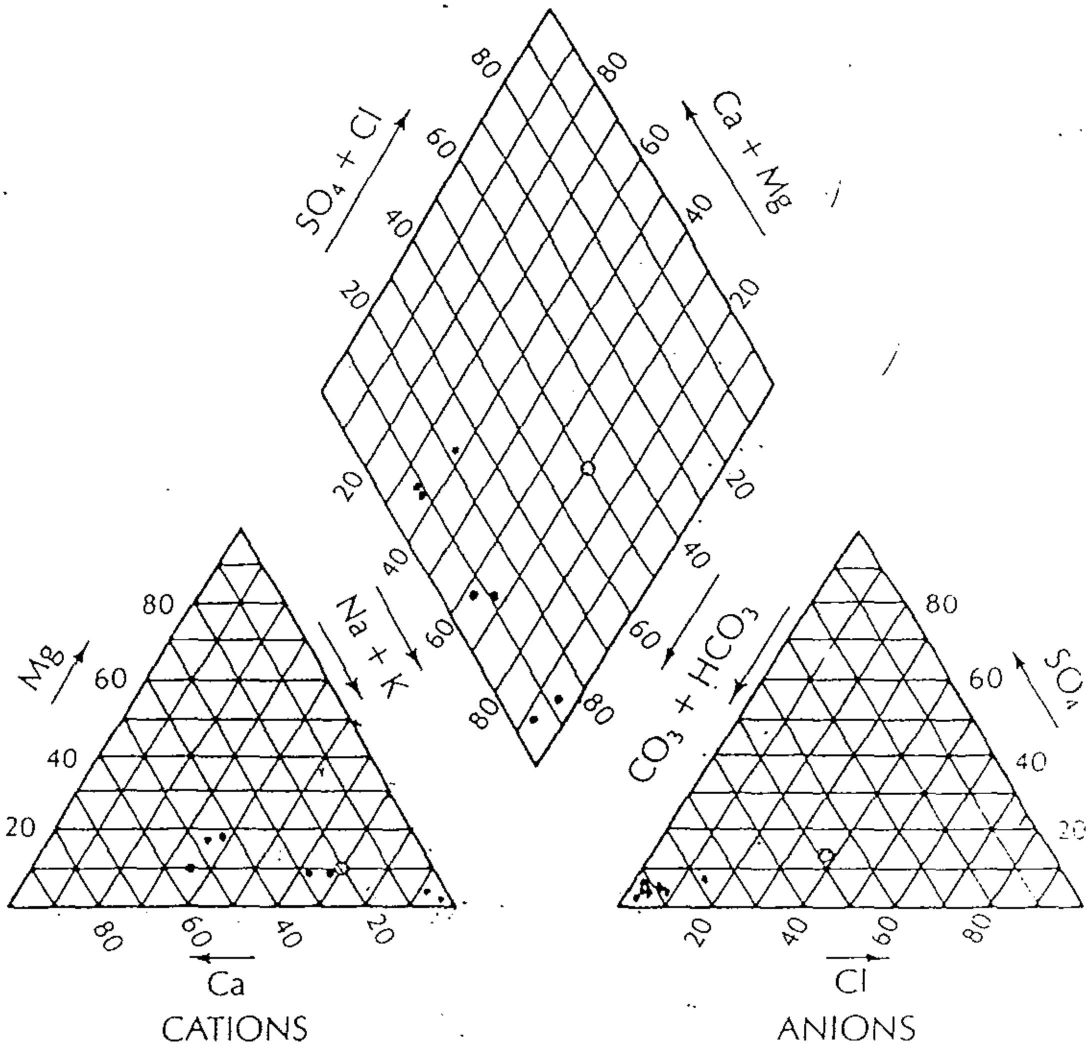


Fig 5.4.b Trilinear diagram plot of surface and spring water



## 5.3 Water Quality

Water quality is a consequence of the natural physical and chemical state of the water as well as any alterations that may have occurred as a consequence of human activity and it is determined by the solutes and gases dissolved in the water as well as the matter suspended in and floating on the water.

In this part the water quality criteria of surface and ground water of the studied area were discussed in comparison with international water quality standards acceptable to a specific use.

### 5.3.1 Water Quality Criteria for Domestic Use

Chemical analyses results of the water in the studied area were compared with the international standard for drinking water quality set by World Health Organisation ( WHO, 1984).

The pH in the water of the area is within the acceptable limit of 7 to 8.5 except the water from three wells ( BW20, BW23, and BW24) . Temperature of most of the ground water measured in the field have values higher than the acceptable limit $25^0$c which indicates there is a less potability of most ground waters in respect to temperature.

Total dissolved solids (TDS) of all surface waters in the area are below the maximum acceptable limit 1000 mg/l but most of the ground waters in the area except ground waters in the eastern escarpment, have more than 1000 mg/l TDS which implies that ground water in the area have a poor quality for drinking in respect to TDS. With respect to hardness as $CaCO_3$ all surface and ground water in the area are below the maximum recommended value 500 mg/l.

The major cations in all the waters in the area fall within the standard limits (table 5.4) except sodium in many ground waters in the western part of the lake which exceed the maximum allowable concentration ( 200 mg/l).

In respect to the anions chloride and sulphate all surface and ground waters of the area fall within the acceptable limits. When we consider bicarbonate ion, surface waters are within the acceptable limit but most of ground waters have been observed above the maximum allowable limit 500 mg/l .

Table 5.4 Drinking water quality standards, WHO (1984)

| Parameters | Min - Max. (Recommended Maximum) |
|---|---|
| Temperature | 12 - 25 $^0$c |
| pH | 6.5 - 8.5 |
| TDS | 500 - 1000 mg/l |
| Conductivity | 400 - 1250 μs/cm |
| Hardness($CaCO_3$) | 500 mg/l |
| Calcium | 10 - 200 mg/l |
| Magnesium | 5 - 50 mg/l |
| Sodium | 20 - 200 mg/l |
| Potassium | 10 - 12 mg/l |
| Sulphate | 400 mg/l |
| Chloride | 5 - 250 mg/l |
| Fluoride | 0.7 - 1.5 mg/l |
| Bicarbonate | 150 - 500 mg/l |
| Nitrate | 45 mg/l |
| Iron | 0.3 mg/l |
| Manganese | 0.1 mg/l |

In the studied area the main problem of water for drinking is fluoride ion which is almost in all of the ground water above the maximum allowable value 1.5 mg/l except ground waters in the eastern escarpment and in Meki town north of Meki river. Fluoride concentration reaches up to 24 mg/l in Boromo, which is located about 20 km West of Ziway town near the road to Butajira.

It is known that prolonged intake of water with a concentration of fluoride of 2 mg/l and above can cause mottled enamel and skeletal fluorisis. This effect is observed in the people of the area particularly in the western part of Ziway town.

The source of fluoride in the Main Ethiopian Rift in general is believed to be the fumarolic or geothermal activity but particularly in the studied area higher values are mainly related with high water-rock interaction and low calcium concentration.

In general the quality of surface waters for drinking purposes is good in the studied area while ground waters have very poor quality for drinking, and need treatment before using. However in most parts of the area they are directly used by the people without any type of chemical treatment.

### 5.3.2 Water Quality Criteria for Agricultural Purposes

Water required for agricultural purposes includes that consumed by livestock and used for irrigation.

Most animals can tolerate water with higher in dissolved solids concentration (5,000 - 10,000 mg/l) than which is considered satisfactory for humans. However for some ions the water quality criteria for livestock give similar concentrations with that of human beings. The maximum allowable limit of fluoride for livestock is 2 mg/l (Hem, 1992).

As a result, all the water in the area met the standard limit for livestock consumption in respect to TDS but in respect to fluoride almost all the ground water in the area, except the ground waters in the eastern escarpment have more than the maximum allowable limit for livestock.

Features of the chemical composition that affect irrigation include total dissolved solids, the concentrations of certain potentially toxic constituents ( mainly boron) and the relative proportions of some of the constituents present ( percent sodium and sodium adsorption ratio).

Total dissolved solids is the primary feature in dealing with irrigation quality. However specific permissible limits are not stated since the tolerance of the irrigated area for TDS is affected by nature and composition of soil, topography of the land, the amount of water used, the climate of the region and the kinds of crops grown. Generally waters with excessive concentration of total dissolved solids are not suitable for irrigation.

The toxicity of boron in the irrigation water varies with the type of crop, but in general for the most sensitive crops for boron the maximum permissible concentration of boron developed by US Salinity Laboratory Staff (1954) is 1 mg/l.

Because of the effect of sodium on the physical properties of the soil to reduce its permeability by reacting with the soil, the concentration of sodium is an important factor in evaluating the quality of water for irrigation.

percent sodium ( % Na) for irrigation water is defined by:

$$\% Na = \frac{(Na+k)\ 100}{Ca + Mg + Na + K}$$

where concentrations are in meq/l.

The values of percent sodium and electrical conductivity of the waters in the area are listed in table 5.6. The electrical conductivity of some surface and ground waters taken from other sources are computed from the total dissolved solids by using the relation TDS in ppm = 0.88 EC in μs/cm as previously designed for the waters of the area.

Based on percent sodium and electrical conductivity the quality classification of water for irrigation is given in table 5.5. From tables 5.5 and 5.6 it can be concluded that most of the ground waters in the western part of the area are unsuitable for irrigation. However in this part four wells have doubtful quality, three wells have permissible quality and two wells have good quality. The wells in the eastern escarpment have excellent quality for irrigation.

Table 5.5 Classification of water for irrigation based on percent sodium( Wilcox 1955)

| Percent Sodium | EC in μs/cm | Water Class |
|---|---|---|
| < 20 | < 250 | Excellent |
| 20 - 40 | 250 - 750 | Good |
| 40 - 60 | 750 - 2000 | Permissible |
| 60 - 80 | 2000 - 3000 | Doubtful |
| > 80 | > 3000 | Unsuitable |

When we consider surface waters: Ketar river has excellent quality, Meki river has good quality and Bulbula river and Ziway lake have poor qualities for irrigation.

If water used for irrigation is high in sodium and low in calcium the calcium in the soil is replaced by sodium and can destroy the soil structure owing to dispersion of the clay particles. The danger of high - sodium water for irrigation can be evaluated by using Sodium Adsorption Ratio (SAR) which is defined by:

$$SAR = \frac{Na^+}{\{(Ca^{2+} + Mg^{2+})/2\}^{1/2}}$$

where the ionic concentrations are expressed in meq/l.

SAR values of both surface and ground waters in the area are listed in table 5.6. From this table and figure 5.6, most of ground waters west of Ziway lake have high to very high sodium hazard with two wells medium sodium hazard and three wells low sodium hazard. In the eastern part of Ziway lake all the ground waters have low sodium hazard except a hand dug well at Chefe Jila which has high sodium hazard. All waters from the rivers ( Meki, Ketar and Bulbula ) and Ziway lake have low sodium hazard.

Table 5.6 % Na and SAR of waters in the studied area

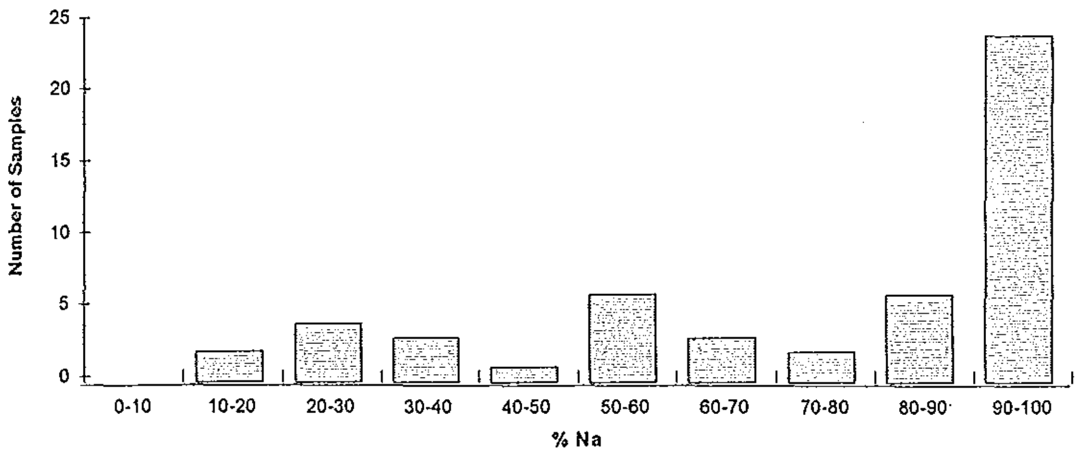
| Ref. No | Location | EC in µs/cm | %Na | SAR | Water Class w.r.t. % Na | Water Class w.r.t. SAR |
|---|---|---|---|---|---|---|
| BW1 | MEKI TOWN [L.V.I.A] | 627 | 30.1 | 0.94 | good | A |
| BW3 | MEKI MUNICIPALITY | 658 | 54.1 | 2.7 | permissible | A |
| BW5 | GARABA GARSO | 1622 | 94.1 | 15.2 | unsuitable | C |
| BW7 | ATE FNURI | 784 | 94.2 | 14.4 | unsuitable | C |
| BW8 | LALUNA DERO | 673 | 64.8 | 2.9 | doubtful | A |
| BW10 | CHOROKE | 1459 | 99.4 | 47.6 | unsuitable | D |
| BW11 | KORKE ADI | 1703 | 98.4 | 30.8 | unsuitable | D |
| BW13 | GURA GERMEGI | 1601 | 97.0 | 22.4 | unsuitable | D |
| BW14 | ABONNO 1 | 1872 | 95.7 | 27.2 | unsuitable | D |
| BW15 | BADA GOSA | 2592 | 97.7 | 32.0 | unsuitable | D |
| BW17 | MAGO | 2794 | 99.8 | 113.8 | unsuitable | D |
| BW18 | ZIWAY BEKELE MOLLA | 1061 | 86.3 | 10.2 | unsuitable | B |
| BW20 | SEMOYE CHELEMO | 2563 | 98.5 | 38.0 | unsuitable | D |
| BW21 | ELKANA METROMOFA | 2111 | 98.2 | 29.4 | unsuitable | D |
| BW23 | GUBIBA | 1210 | 100 | large | unsuitable | D |
| BW24 | GALO FECHASA | 1550 | 98.2 | 44.0 | unsuitable | D |
| BW25 | HESBAWI BATELE | 1503 | 77.6 | 7.7 | unsuitable | B |
| BW26 | ZIWAY PRISON | 1786 | 84.8 | 7.3 | unsuitable | B |
| BW27 | KOSHE | 836 | 82.7 | 7.3 | unsuitable | B |
| BW29 | ZIWAY TOWN | 1311 | 90.0 | 13.7 | unsuitable | C |
| BW31 | ZIWAY PHILADELPHIA | 915 | 50.9 | 1.3 | permissible | A |
| BW33 | GUSH GULLA | 1350 | 94.9 | 21.0 | unsuitable | D |
| BW34 | WORGA GARBI | 2366 | 95.6 | 19.6 | unsuitable | D |
| BW35 | BOROMO | 1526 | 97.7 | 25.0 | unsuitable | D |
| BW37 | WOYSO MACHO | 2357 | 100 | large | unsuitable | D |
| BW38 | SHISHO TABO | 1278 | 98.4 | 24.7 | unsuitable | D |
| BW39 | ADAMITULU | 1151 | 97.8 | 24.3 | unsuitable | D |
| BW40 | GARBI | 1286 | 62.9 | 5.2 | doubtful | A |
| BW48 | WAJI | 196 | 50.3 | 1.22 | permissible | A |

Table 5.5 continued

| | | | | | | |
|---|---|---|---|---|---|---|
| BW49 | ELEAS | 246 | 35.3 | 0.69 | good | A |
| BW56 | SOUTH OF KULUMSA | 503 | 26.8 | 0.78 | good | A |
| DW1 | NORTH OF MEKI | 1838 | 90.9 | 18.3 | unsuitable | D |
| DW2 | MEKI TOWN | 560 | 26.8 | 0.90 | good | A |
| DW3 | CHEFE | 985 | 73.2 | 6.0 | doubtful | B |
| DW4 | ABONNO | 1923 | 98.1 | 28.6 | unsuitable | D |
| DW5 | WOLIMBULA | 2218 | 100 | large | unsuitable | D |
| DW6 | ABOSA | 2052 | 92.3 | 21.3 | unsuitable | D |
| DW8 | CHEFE JILA | 1785 | 84.3 | 12.3 | unsuitable | C |
| DW9 | ABURA | 406 | 47.2 | 1.15 | permissible | A |
| DW10 | NORTH OF ABURA | 463 | 61.2 | 2.54 | doubtful | A |
| CS1 | GONDE | 159 | 30.1 | 0.41 | good | A |
| CS2 | BURKITU | 210 | 27.9 | 0.47 | good | A |
| TS1 | TULU GUDO ISLAND | 1596 | 88.7 | 12.43 | unsuitable | C |
| TS2 | TULU GUDO ISLAND | 2050 | 95.8 | 27.19 | unsuitable | D |
| B1 | BULBULA RIVER | 498 | 58.6 | 1.76 | permissible | A |
| K1 | KETAR RIVER | 203 | 13.9 | 0.20 | excellent | A |
| M1 | MEKI RIVER | 438 | 27.6 | 0.66 | good | A |
| NS1 | N. SHORE OF ZIWAY | 2788 | 91.5 | 15.5 | unsuitable | D |
| Z1 | ZIWAY LAKE | 475 | 53.2 | 1.47 | permissible | A |

A - low sodium hazard
B - medium sodium hazard
C - high sodium hazard
D - very high sodium hazard

**Fig 5.5 The number of water samples in the area in different ranges of % Na**



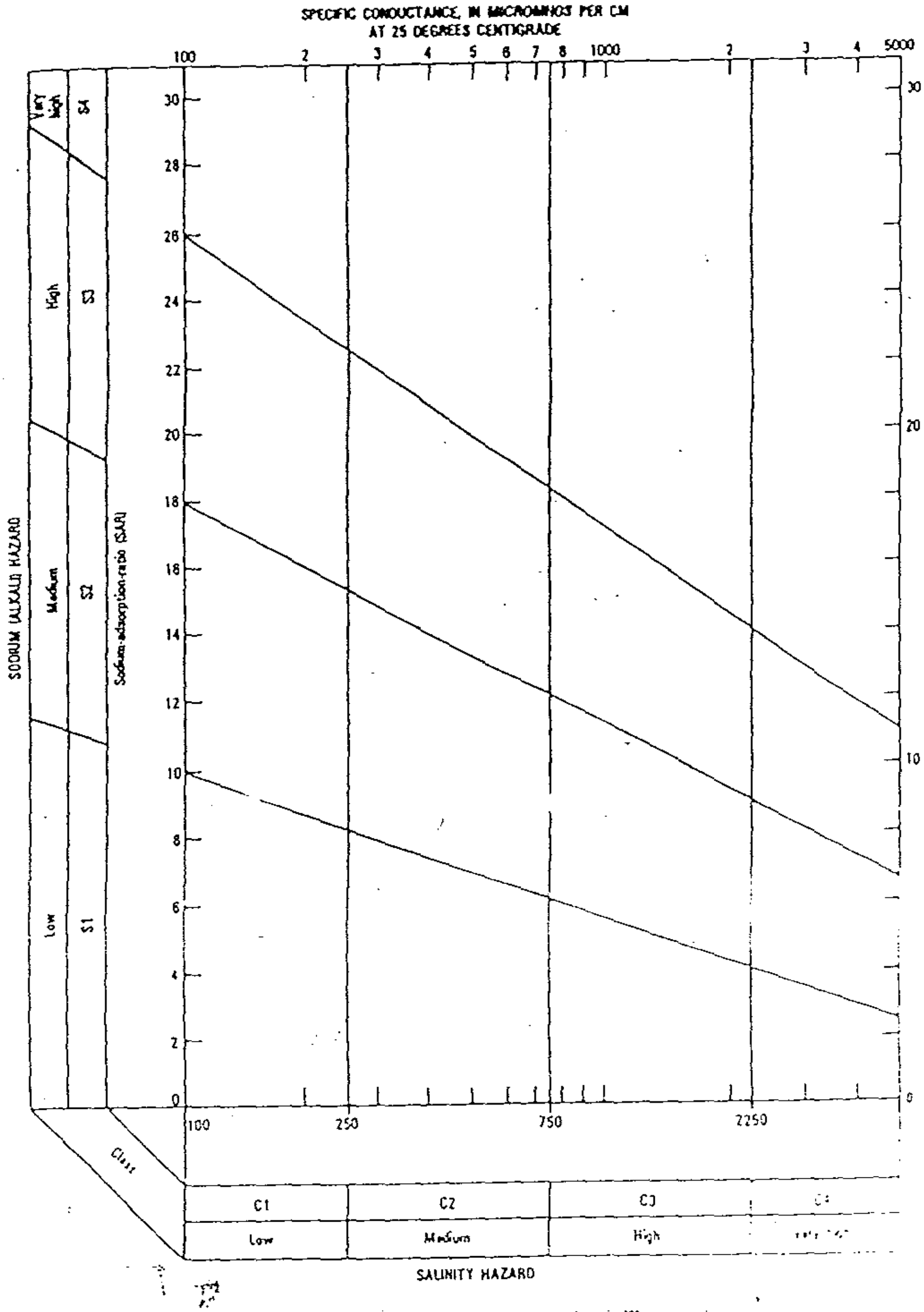



Fig 5.6 Classification of water for irrigation based on SAR

### 5.3.3 Water Quality Criteria For Industry

The quality requirements for industrial water supplies range widely and almost every industrial application has its own standards. For some uses such as 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, for processes such as the manufacture of high - grade paper or pharmaceuticals, water approaching or equalling the quality of distilled water is required.

Water quality requirements for certain industries are given in Table 5.7 ( US Federal Water Pollution Control Administration, 1968 ). The standard given in Table 5.6 represent maximum values permitted in the water at the point of use, after any necessary treatment. The absence of an entry in the table indicates either that no limit for the constituent or that the constituent cannot attain objectionable levels if the water meets the other specifications.

Water used for processing food or beverages must also meet the drinking water standards in addition to the requirements depicted in table 5.7.

Most of the ground water in the area have poor quality for the following industries: - for food and beverage processing due to their high fluoride and high TDS values.
- for chemical pulp and paper due to their high silica concentration.
- for wood chemicals due to their high bicarbonate and high TDS values
- for hydraulic cement manufacture due to their high silica and high TDS concentrations.

However, it is technically possible to treat any water in the studied area to give it a composition suitable for specific uses, but it is necessary to calculate the amount of water involved and the cost before constructing any type of industries in the area.

Water of the rivers( Meki, Ketar and Bulbula) and Ziway lake meet most quality requirements in table 5.7.

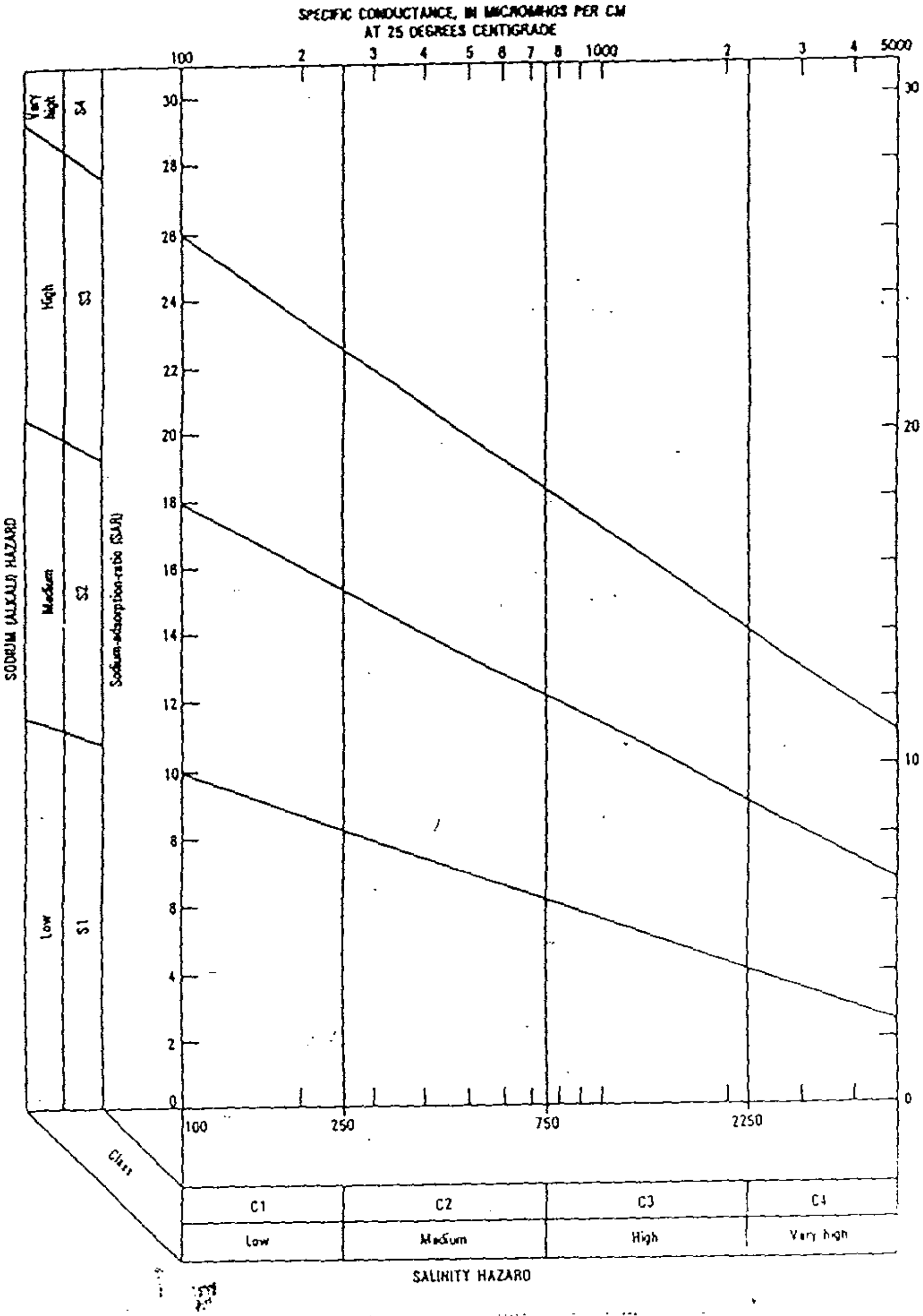



Fig 5.6 Classification of water for irrigation based on SAR

Table 5.7 Water quality requirements for selected industries and processes

| Constituent | T(S,B,D) | CPP | | WC | SR | PP | CDFFV | SDB | LT | HCM |
|---|---|---|---|---|---|---|---|---|---|---|
| | | UB | BL | | | | | | | |
| Silica | - | 50 | 50 | 50 | - | - | 50 | - | - | 35 |
| Iron | 0.1 | 1.0 | 0.1 | 0.3 | 0.1 | 1 | 0.2 | 0.3 | 0.3 | 25 |
| Manganese | 0.01 | 0.5 | 0.05 | 0.2 | 0.1 | - | 0.2 | 0.05 | 0.2 | 0.5 |
| Calcium | - | 20 | 20 | 100 | 80 | 75 | - | 100 | - | - |
| Magnesium | - | 12 | 12 | 50 | 36 | 30 | - | - | - | - |
| Bicarbonate | - | - | - | 250 | - | - | - | - | - | - |
| Sulphate | - | - | - | 100 | - | - | 250 | 500 | 250 | 250 |
| Chloride | - | 200 | 200 | 500 | - | 300 | 250 | 500 | 250 | 250 |
| Fluoride | - | - | - | - | - | - | 1 | 1.5 | - | - |
| Nitrate | - | - | - | 5 | - | - | 10 | - | - | - |
| Hardness($CaCO_3$) | 25 | 100 | 100 | 900 | 350 | 350 | 250 | - | soft | - |
| Alkalinity($CaCO_3$) | - | - | - | 200 | 150 | - | 250 | 85 | - | 400 |
| pH | 2.5 - 10.5 | 6 - 10 | 6 - 10 | 6.5 - 8.0 | 6.2 - 8.3 | 6 - 9 | 6.5 - 8.5 | - | 6 - 8 | 6.5 - 8.5 |
| Dissolved solids | 100 | - | - | 1,000 | - | 1,000 | 500 | - | - | 600 |
| Colour(units) | 5 | 30 | 10 | 20 | 20 | - | 5 | 10 | 5 | - |
| Temp. ($^0$F) | - | - | 95 | - | - | - | - | - | - | - |
| Suspended solids | 5 | 10 | 10 | 30 | 5 | 10 | 10 | - | - | 500 |

Concentrations are in mg/l.
T(S,B,D) - Textiles(scouring, bleaching and dyeing)
PP - Petroleum products
LT - Leather tanning( general finishing processes)
CDFFV - canned, dried, and frozen fruits and vegetables
CPP - Chemical pulp and paper(UB - unbleached and BL - bleached)
SDB - Soft - drinks bottling
HCM - Hydraulic cement manufacture
WC - Wood chemicals
SR - Synthetic rubber

# CHAPTER SIX

# CONCLUSION AND RECOMMENDATION

## 6.1 Conclusions

The studied area is covered by recent to Pliocene volcanic rocks and lacustrine sediments and it was highly affected by faults and fractures which result in a great variation in altitude in the area, ranges from 1636 metres up to 4080 metres above sea level .Due to this variation of altitude the hydrological, hydrogeological and hydrochemical properties show a great variation within the studied area. In relation to these properties the area can be divided in to two: Lowlands and Highlands.

The main hydrological parameters rainfall, evapotranspiration and runoff show significant seasonal variation. The effective annual depth of rainfall in the area is 936.62 mm. More than 75% of the total annual rainfall in the area is in the five months May through September with big rains in the highlands. However the total annual rainfall did not show a great variation for the last 27 years both in the lowlands and the highlands.

The annual potential evapotranspiration, 893.64 mm in the lowlands and 695.83 mm in the highlands is higher than the annual actual evapotranspiration 735.87 mm in the lowlands and 639.06 mm in the highlands. The less difference in actual and potential evapotranspiration in the highlands is due to lower daily temperatures in the highlands. Because of high potential evapotranspiration and low rainfall in the lowlands the amount of water contributing to runoff and aquifer recharges from the lowlands is very low (18.2 mm) while in the highlands the amount of water contribution to runoff and groundwater recharge is higher (541.39 mm).

The greater amount of water entering into the lake has been came from runoff of Meki and Ketar rivers their annual mean are 235 x $10^6$ $m^3$ and 402.3 x $10^6$ $m^3$ respectively.

The only surface runoff that leaves the area is through Bulbula river which gets its discharge almost totally from Ziway lake and its annual mean is 123.3 x $10^6$ $m^3$.

The mean annual volume of water infiltrated into lake bed sediments or leaves the lake as ground water outflow is 88.4 x $10^6$ $m^3$ which gives the infiltration capacity of the lake bed sediments 0.0233 mm / hour.

The water balance study of Ziway lake indicate that from the total inflow of the lake 66.2% is from runoff and 33.8% is from direct rainfall and from the total outflow of the lake 75.3% is lost by evaporation, 14.4% leaves as surface runoff and the rest 10.3% leaves as groundwater.

Groundwater potentials of volcanic rocks and sediments in the studied area ranges from low to high. The most important aquifers are scoracious cones and hyaloclastites which are mainly found in the eastern shore of the lake and the poorest aquifers in the area are trachytes which are found in the eastern border of the area, around the slopes of Chillalo mountain.

The aquifers in the area can be classified in to three groups based on the nature of permeability.
1. Aquifers characterised by primary permeability include lacustrine sediments , alluvial, pumice falls, scoria cones and hyaloclastites
2. Aquifers characterised by secondary permeability include ignimbrites and tuffs.
3. Aquifers characterised by both primary and secondary permeability include rhyolitic pumice flows, basaltic lava flow and obsidian lava flows.

Most of the aquifers in the area exist as a semi-confined condition and others are as confined and unconfined conditions. Clays, ashes, loams, silts and fresh volcanic rocks are serve as a confining and semi-confining layers in the area. From these clays are the most important confining layers particularly in the western part of the area.

Ground water flow direction is towards the lake from the west, north, east and south-east part of the area and out of the lake at the southern and south-western part of the area.

From hydrochemical point of view the common properties of both surface and ground waters throughout the studied area are high bicarbonate, high sodium and high silica concentrations. However the total dissolved solids and some ions like fluoride show a wide range within the waters of the area. Most of the water samples are sodium bicarbonate type except the ground water in the eastern escarpment and Meki river which are calcium sodium bicarbonate type. Ketar river is calcium bicarbonate type.

Water of rivers and Ziway lake have low total dissolved solids and low fluoride concentrations which have good qualities for drinking.

Most of the ground waters in the lowlands of the area have high total dissolved solids and high fluoride concentrations.

The major problem for drinking water quality in the waters of the area is its fluoride content, in most cases above the recommended limit ( 1.5 mg/l), which causes dental fluorisis in many of the residents in the lowlands of the area.

The source of this high fluoride concentration is related with three causes.
1. the addition by active volcanic and fumarolic activities in the area.
2. by the high water - rock interaction in the area, particularly interaction of water with volcanic ash.
3. by the low calcium concentration in the area, which restricts the precipitation of fluoride as fluorite ( $CaF_2$).

When we consider the quality of water for agricultural and industrial purposes all ground waters in the eastern highlands and all surface waters have generally good qualities . However, most of ground waters from the lowlands have poor qualities due to their high sodium and high total dissolved solids.

## 6.2 Recommendations

The following recommendations are forwarded in order to alleviate existing different hydrogeological and hydrochemical problems in the studied area and for proper management of water resources for continuously increasing demand of quality and quantity of water in the future.

1. In the area west of Ziway lake mean annual potential evapotranspiration exceeds mean annual precipitation resulting low mean annual recharge to the groundwater but discharge from few potential aquifers is high. Therefore it is recommendable to conduct isotope hydrology study in the area to determine the age of the groundwater and to identify if there is recent infiltration or volcanic water contribution to recharge the groundwater storage.

2. Although many wells have been constructed in many peasant villages of the area most of them have very low yields and a few wells are abandoned. Therefore before drilling bore wells it is necessary to conduct both hydrogeological and geophysical investigations to select localities with high ground water potentials and to determine depth to ground water and thickness of aquifers.

3. Construction of bore wells by penetrating the full thickness of aquifer and pumping and recovery tests would be helpful to increase the yield of the well and to design the proper management of the wells according to their yield.

4. Almost all bore wells in the area do not have an inlet for water level measurements. It will be better to leave open bore wells for water level observations and pumping tests and also useful to install automatic water level recorders in some bore wells in the area in order to determine seasonal water level fluctuations.

5. It is advantageous to continue windmill installing practices in the western part of the area in all peasant villages where electricity is not available.

6. In the towns and villages near to perennial rivers and Ziway lake exploitation of these water resources is very recommendable since they have relatively good chemical qualities and great potentials for different purposes.

7. In places where very high total dissolved solids and high fluoride contents of groundwater, construction of reservoirs and ponds to collect rain water and overland flow during rainy seasons would be helpful.

8. Detail chemical and isotopic investigations of waters and reservoir rocks would be necessary in order to understand the contribution of each sources for high fluoride contents and to conduct chemical water balance of the area.

9. Fumaroles are present in the area around Aluto and Bora mountains. Therefore it is advantageous to use fumarolic steam chemistry to determine the contribution of fumarolic activity for high fluoride in the area.

10. To prevent contamination of groundwater, particularly in the towns, by various liquid and solid wastes all possible pollution sources of water must be properly located.

11. Due to their poor qualities and low yields most of the ground waters in the area are not recommended for irrigation, good potential water resources for irrigation in the area are Ziway lake, Ketar river and Meki river.

12. Even if it is possible to treat all surface and groundwater in the area to make suitable for many type of industries, treatment cost and the amount of water needed by the planned industry must be calculated before establishing new industries in the area.

13. Generally in the studied area, except in the western and eastern borders there are abundant surface and ground water resources. Therefore it is necessary to plan and design these exploitable water resources for proper uses in the future according to their quality and quantity.

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Appendices

1. Rainfall Data
2. Temperature and Evaporation Data
3. Runoff Data
4. Lake Level Fluctuation Data
5. Calculation of Effective Uniform Depth of Precipitation
6. Latitude Factor for Thornthwaite Evapotranspiration Calculation
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12. Lithological Log Data

# Appendix 1

## Rainfall Data

Monthly Total Rainfall in mm of Ziway Station

| YEAR | JAN | FEB | MAR | APR | MAY | JUNE | JULY | AUG | SEP | OCT | NOV | DEC | TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1970 | 66.5 | 0 | 70.2 | 43.6 | 21.2 | 86 | 9.2 | 9.4 | 93.7 | 35.6 | 0 | 0 | 435.4 |
| 1971 | 6.8 | 1 | 30.4 | 100.8 | 67 | 143.6 | 116.2 | 114.4 | 27.8 | 0 | 3.4 | 1.6 | 613 |
| 1972 | 0 | 0 | 0 | 178.9 | 78.2 | 46.9 | 124.8 | 132.3 | 67.1 | 31.4 | 0 | 0 | 659.6 |
| 1973 | 0 | 0 | 0 | 9 | 164.4 | 70.5 | 168.8 | 121.2 | 111.4 | 33.8 | 0 | 2.6 | 681.7 |
| 1974 | 3.6 | 5.5 | 152.4 | 1.2 | 67.6 | 75.2 | 118.1 | 218.7 | 213.4 | 0 | 0 | 0 | 855.7 |
| 1975 | 0 | 29.4 | 3.3 | 23.6 | 105.6 | 187.8 | 304.1 | 48.6 | 246.5 | 7.1 | 0 | 0 | 956 |
| 1976 | 0 | 1.8 | 47.3 | 31.8 | 96.2 | 64.2 | 175.3 | 76.2 | 37.1 | 6.9 | 21.9 | 0 | 558.7 |
| 1977 | 63.1 | 9 | 6 | 154.3 | 96.4 | 168.7 | 180.4 | 143.9 | 55.5 | 218.8 | 0 | 0 | 1096.1 |
| 1978 | 10.9 | 178.3 | 45.6 | 65.6 | 13.2 | 181.9 | 61.9 | 221.8 | 93.4 | 45.5 | 1.6 | 5.5 | 925.2 |
| 1979 | 91.9 | 102.4 | 70 | 61.6 | 148.6 | 105.2 | 150 | 98 | 87.9 | 71 | 0 | 6.2 | 992.8 |
| 1980 | 25.8 | 14.9 | 14.4 | 48.3 | 3.6 | 53.8 | 129.3 | 116.8 | 63.4 | 43.6 | 0 | 0 | 513.9 |
| 1981 | 0 | 28.2 | 248.9 | 68.7 | 21.7 | 2.2 | 237.1 | 145.4 | 234.2 | 5.2 | 0 | 0.6 | 992.2 |
| 1982 | 51 | 14.7 | 136.2 | 76.8 | 68 | 16.6 | 117 | 218.7 | 39.3 | 142.3 | 9.5 | 0 | 890.1 |
| 1983 | 34.4 | 56.3 | 85.9 | 100.6 | 152.1 | 43.3 | 153.2 | 146.5 | 64.6 | 27.2 | 0 | 0 | 864.1 |
| 1984 | 0 | 0 | 10.6 | 70.6 | 90.6 | 57.5 | 213 | 116.2 | 63.5 | 0 | 0 | 0 | 622 |
| 1985 | 0.4 | 0 | 30.6 | 105.4 | 118.6 | 40 | 155.7 | 138.2 | 69 | 1.3 | 0 | 0 | 659.2 |
| 1986 | 0 | 53 | 19.7 | 53.7 | 110.3 | 88.4 | 70.5 | 54 | 65.8 | 22.2 | 0 | 0 | 537.6 |
| 1987 | 0 | 29.8 | 56.3 | 47.6 | 219.6 | 16.2 | 67.5 | 54.1 | 44.7 | 17.1 | 0 | 0 | 552.9 |
| 1988 | 3.2 | 20.9 | 1.8 | 49.8 | 13 | 118.9 | 138.2 | 92.9 | 169.3 | 99.1 | 0 | 0.2 | 707.3 |
| 1989 | 4.7 | 50.3 | 195.7 | 129.9 | 2.9 | 101.9 | 120 | 150.5 | 133.1 | 12.5 | 0 | 49.6 | 951.1 |
| 1990 | 0 | 140.8 | 16.6 | 52.1 | 37.8 | 49 | 162.2 | 141.6 | 88.8 | 0.5 | 0 | 0 | 689.4 |
| 1991 | 1.7 | 98.2 | 141 | 12.8 | 26.2 | 114 | 171.9 | 144.3 | 47 | 10.7 | 0 | 9.2 | 777 |
| 1992 | 20.3 | 21.8 | 6.2 | 58.8 | 75.2 | 99.4 | 208.5 | 153.6 | 27.5 | 116.5 | 1.5 | 3.4 | 792.7 |
| 1993 | 42.1 | 127.4 | 0.4 | 100.2 | 128.5 | 68.5 | 223.7 | 147.5 | 49.4 | 71 | 0 | 0 | 958.7 |
| 1994 | 0 | 0 | 24.1 | 9 | 49.1 | 145.6 | 126.4 | 92.9 | 89.6 | 42.3 | 4.6 | 0 | 583.6 |
| 1995 | 0 | 28.8 | 68 | 141.32 | 21.6 | 49.5 | 79.9 | 131.7 | 28.5 | 3.1 | 0 | 11.6 | 564.02 |
| 1996 | 13.8 | 8.2 | 53.9 | 110.4 | 127.1 | 128.4 | 125.4 | 161.5 | 106.4 | 0 | 32.8 | 0 | 867.9 |
| TOTAL | 440.2 | 1020.7 | 1535.5 | 1906.4 | 2124.3 | 2323.2 | 3908.3 | 3390.9 | 2417.9 | 1064.7 | 75.3 | 90.5 | |
| AVR | 16.3 | 37.8 | 56.9 | 70.6 | 78.7 | 86.1 | 144.8 | 125.6 | 89.6 | 39.4 | 2.8 | 3.4 | |

Monthly Total Rainfall in mm of Assela Station

| YEAR | JAN | FEB | MAR | APR | MAY | JUNE | JULY | AUG | SEP | OCT | NOV | DEC | TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1970 | 112 | 35 | 275 | 72 | 77 | 92 | 285 | 225.5 | 187 | 65 | 0 | 0 | 1425.5 |
| 1971 | 29 | 2 | 98 | 153 | 185 | 164 | 191 | 200 | 171 | 38.5 | 25.5 | 27 | 1284 |
| 1972 | 23 | 43 | 85.5 | 256 | 75.5 | 134 | 160.5 | 341 | 117 | 2 | 6.5 | 9 | 1253 |
| 1973 | 2 | 0 | 1 | 40.5 | 194.5 | 172.5 | 127.3 | 195 | 135 | 53 | 0 | 0 | 920.8 |
| 1974 | 14.3 | 35 | 186 | 23 | 122 | 105.5 | 192 | 133.3 | 208.7 | 27 | 0 | 0 | 1046.8 |
| 1975 | 13.9 | 24.5 | 15.7 | 46.5 | 77.5 | 237 | 223 | 284 | 161.1 | 31.5 | 0 | 0 | 1114.7 |
| 1976 | 26.6 | 52.2 | 102.9 | 112.6 | 84.1 | 154.6 | 259.3 | 207.8 | 83.8 | 74 | 48.1 | 21.3 | 1227.3 |
| 1977 | 36 | 16.3 | 113.2 | 127.1 | 93.3 | 193.7 | 220.5 | 234 | 182.4 | 112.2 | 0 | 27.5 | 1356.2 |
| 1978 | 14.8 | 152.6 | 83.5 | 49.7 | 153 | 124.8 | 285.3 | 213.6 | 153.9 | 76.1 | 81.5 | 8.1 | 1396.9 |
| 1979 | 44 | 34.2 | 87.8 | 52 | 160.2 | 103.5 | 228.8 | 322.6 | 290.7 | 82.4 | 0 | 16.7 | 1422.9 |
| 1980 | 18.7 | 81.3 | 109.6 | 129.3 | 138.9 | 134 | 202.3 | 173 | 166.1 | 66.8 | 12.7 | 0 | 1232.7 |
| 1981 | 0 | 18.8 | 166.2 | 145.5 | 47 | 80.4 | 200.5 | 191.1 | 280.5 | 47 | 10 | 0 | 1187 |
| 1982 | 22.1 | 66.4 | 75.6 | 94.1 | 142.6 | 131.6 | 168.3 | 391.8 | 213.8 | 48.3 | 50.1 | 17.3 | 1422 |
| 1983 | 5.8 | 78.6 | 81.3 | 210.1 | 255.8 | 145.4 | 196.7 | 203.4 | 183.5 | 36.1 | 9.6 | 4.3 | 1410.6 |
| 1984 | 0.3 | 5.7 | 11.3 | 23.6 | 327.2 | 135.7 | 156.5 | 209.1 | 244.9 | 1.6 | 0 | 0 | 1115.9 |
| 1985 | 14.9 | 1.8 | 48.1 | 175 | 179 | 293.5 | 206.6 | 150.4 | 153.8 | 13.5 | 26.7 | 2.7 | 1266 |
| 1986 | 8.2 | 98.5 | 84.6 | 172.2 | 112.9 | 118 | 246.5 | 166.2 | 256 | 43.1 | 72.3 | 2.3 | 1380.8 |
| 1987 | 0 | 60.1 | 88.4 | 105.9 | 103 | 126.4 | 213.8 | 136.5 | 114.9 | 54.3 | 8 | 13.7 | 1025 |
| 1988 | 14.1 | 52 | 8.4 | 75.3 | 51.1 | 279.5 | 219.3 | 168.2 | 148.1 | 66.5 | 0 | 0 | 1082.5 |
| 1989 | 1.7 | 26.7 | 126.6 | 268.2 | 40.2 | 132.3 | 111.9 | 169.3 | 130 | 53.2 | 13.2 | 88.5 | 1161.8 |
| 1990 | 0 | 111.5 | 93 | 92.1 | 19.8 | 87.1 | 197.8 | 186.4 | 153.7 | 46.2 | 11.2 | 0 | 998.8 |
| 1991 | 0 | 42.4 | 162.1 | 34.4 | 57.6 | 117.6 | 178.8 | 149.1 | 39.1 | 1.5 | 1.2 | 20 | 803.8 |
| 1992 | 36 | 90.8 | 58.3 | 142.1 | 33.5 | 44 | 131.6 | 206.3 | 136 | 63.4 | 22.3 | 38.7 | 1003 |
| 1993 | 13.2 | 22.3 | 20 | 150.8 | 92.8 | 38.7 | 117.9 | 166.3 | 140 | 172.9 | 0 | 0 | 934.9 |
| 1994 | 0 | 0 | 132.9 | 44.9 | 83.8 | 203.8 | 249.7 | 164.5 | 178.1 | 5.5 | 4.2 | 3.5 | 1070.9 |
| 1995 | 0 | 23.2 | 122.4 | 153.8 | 96.7 | 118.9 | 212 | 164.2 | 98.6 | 22 | 0 | 69.5 | 1081.3 |
| 1996 | 69.8 | 16 | 171.7 | 155.9 | 156.5 | 193.9 | 163.5 | 132.7 | 133.9 | 31.5 | 1.9 | 4.3 | 1231.6 |
| TOTAL | 520.4 | 1190.9 | 2609.1 | 3105.6 | 3160.5 | 3862.4 | 5346.4 | 5485.3 | 4461.6 | 1335.1 | 405 | 374.4 | 31856.7 |
| AVR | 19.3 | 44.1 | 96.6 | 115 | 117.1 | 143.1 | 198 | 203.2 | 165.2 | 49.5 | 15 | 13.9 | |

Monthly Total Rainfall in mm of Meki Station

| YEAR | JAN | FEB | MAR | APR | MAY | JUNE | JULY | AUG | SEP | OCT | NOV | DEC | TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1970 | 118.5 | 31 | 49.6 | 4.9 | 59.4 | 20.2 | 117.3 | 155.5 | 120.4 | 17.7 | 0 | 0 | 694.5 |
| 1971 | 0.4 | 0 | 21.8 | 21.2 | 57.8 | 129.6 | 100.8 | 195.6 | 119.8 | 0 | 11.3 | 7 | 665.3 |
| 1972 | 30.8 | 30.7 | 42.3 | 167.3 | 37.4 | 116.5 | 116.6 | 159.3 | 60 | 0 | 0 | 0 | 760.9 |
| 1973 | 12.2 | 43.6 | 54.7 | 60 | 65.8 | 77.6 | 172.6 | 132 | 92.3 | 43 | 7.2 | 1.2 | 762.2 |
| 1974 | 0 | 18.7 | 153.1 | 0.1 | 139.2 | 80.4 | 222 | 157.9 | 205.6 | 4.5 | 0 | 0 | 981.5 |
| 1975 | 2.4 | 7.3 | 12.7 | 69 | 61 | 118 | 321.1 | 61.8 | 83.3 | 5.8 | 11.6 | 0 | 754 |
| 1976 | 0.5 | 1 | 104 | 40.5 | 86.3 | 56.2 | 180.8 | 136.5 | 73.5 | 4.2 | 22.6 | 0 | 706.1 |
| 1977 | 6.3 | 28 | 19.1 | 78.1 | 22.5 | 132.1 | 253.6 | 91.6 | 95 | 223.7 | 38.9 | 0 | 988.9 |
| 1978 | 8.5 | 147.8 | 53.6 | 46.9 | 19.3 | 229.3 | 83.2 | 243.8 | 102.8 | 35.4 | 1.1 | 0 | 971.7 |
| 1979 | 68.9 | 14.8 | 139.9 | 37.7 | 60 | 135.5 | 155.1 | 63.7 | 83.8 | 71.6 | 0 | 0.3 | 831.3 |
| 1980 | 20.4 | 7.2 | 0.6 | 57 | 39.9 | 98.3 | 153.3 | 133.9 | 52.9 | 23 | 0 | 0 | 586.5 |
| 1981 | 0 | 0 | 185.4 | 62.2 | 28.7 | 3 | 204.2 | 218.6 | 119.4 | 343 | 0 | 0 | 1164.5 |
| 1982 | 18.1 | 18.1 | 6.5 | 67.8 | 65.9 | 3.1 | 98.1 | 122.3 | 117 | 65.5 | 9.9 | 2.7 | 595 |
| 1983 | 8.9 | 64.3 | 55.2 | 132.6 | 245.7 | 87.4 | 195.8 | 183.9 | 95.4 | 19.8 | 0 | 0 | 1089 |
| 1984 | 0 | 8.6 | 1.8 | 7.7 | 153 | 57.6 | 193 | 233.1 | 68 | 0 | 0 | 0 | 722.8 |
| 1985 | 0 | 0 | 6.3 | 58.4 | 86.2 | 8.9 | 225.9 | 195.4 | 115.3 | 0 | 0 | 0 | 696.4 |
| 1986 | 0 | 167.6 | 31.1 | 58.2 | 101.2 | 157.9 | 211.2 | 67.1 | 105.7 | 38 | 0 | 0 | 938 |
| 1987 | 0 | 13.9 | 116.5 | 66.1 | 231.2 | 27.2 | 111.9 | 167.6 | 67.3 | 2.3 | 0 | 0 | 804 |
| 1988 | 0.7 | 51 | 16 | 83.2 | 20.3 | 129.1 | 143.4 | 134.6 | 99.9 | 51.6 | 0 | 0 | 729.8 |
| 1989 | 3 | 36.9 | 112.5 | 84.8 | 14.5 | 122.7 | 122.7 | 173.7 | 109.9 | 48.9 | 0 | 0 | 829.6 |
| 1990 | 0 | 257.5 | 7.7 | 83 | 13.6 | 17.2 | 215.8 | 211.8 | 79.9 | 18.6 | 0 | 0 | 905.1 |
| 1991 | 0 | 49.2 | 173.5 | 0.1 | 11.6 | 2.8 | 66.8 | 171.3 | 21 | 7.6 | 0 | 11.7 | 515.6 |
| 1992 | 18.3 | 54.7 | 2.2 | 68.6 | 56.3 | 47.9 | 290.8 | 243.3 | 76.2 | 59.8 | 0 | 16.5 | 934.6 |
| 1993 | 31.4 | 31.4 | 1.4 | 120.2 | 61.4 | 65 | 188.2 | 147.4 | 46.1 | 56.9 | 0.4 | 0 | 749.8 |
| 1994 | 0 | 0 | 29.1 | 14.1 | 63.7 | 129 | 250.2 | 96.7 | 44.3 | 0 | 5.1 | 0 | 632.2 |
| 1995 | 0 | 0.7 | 34.6 | 80.6 | 72.4 | 19 | 90.9 | 46.6 | 84 | 32.6 | 3.8 | 1.4 | 466.6 |
| 1996 | 14.7 | 111 | 36.1 | 29.1 | 38.5 | 43 | 154.1 | 280.4 | 135.2 | 36.1 | 0 | 0 | 878.2 |
| TOTAL | 364 | 1195 | 1467.3 | 1599.4 | 1912.8 | 2114.5 | 4639.4 | 4225.4 | 2474 | 1209.6 | 111.9 | 40.8 | 21354.1 |
| AVR | 13.5 | 44.3 | 54.3 | 59.2 | 70.8 | 78.3 | 171.8 | 156.5 | 91.6 | 44.8 | 4.2 | 1.5 | 790.89 |

## Appendix 2

## Temperature and Evaporation Data

Monthly Mean Temperature in $^{0}C$ of Ziway Station

| YEAR | JAN | FEB | MAR | APR | MAY | JUNE | JULY | AUG | SEP | OCT | NOV | DEC | TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1970 | 19.9 | 21.2 | 20.6 | 21.3 | 22.9 | 23.9 | 23.6 | 20.5 | 17.7 | 17.9 | 18.3 | 18.7 | 246.5 |
| 1971 | 16.7 | 18.7 | 17.7 | 17.4 | 16.5 | 15.8 | 19.4 | 18.1 | 18.8 | 19.7 | 18.2 | 19.8 | 216.8 |
| 1972 | 14.8 | 15.3 | 17.2 | 18.4 | 18.5 | 19 | 18.6 | 18.4 | 18.5 | 19.3 | 19.5 | 18.5 | 216 |
| 1973 | 17.7 | 20.2 | 22.1 | 22.5 | 21.6 | 21.1 | 19.9 | 20.2 | 19.7 | 18.7 | 19.3 | 16.9 | 239.9 |
| 1974 | 18.9 | 19.8 | 20.3 | 20.4 | 21 | 20.3 | 18.5 | 19.8 | 18.6 | 18.4 | 17.5 | 17.5 | 231 |
| 1975 | 19 | 20.2 | 21.2 | 19.9 | 21.8 | 20.3 | 18.8 | 19.1 | 19.5 | 19 | 18.3 | 18.5 | 235.6 |
| 1976 | 17.6 | 20.1 | 20.5 | 20.7 | 20.9 | 20.7 | 19.2 | 18.7 | 18.9 | 19 | 18.5 | 17.3 | 232.1 |
| 1977 | 19.7 | 18.9 | 20.7 | 21.1 | 21.2 | 20.3 | 19.4 | 19.4 | 19.4 | 19.5 | 19.4 | 18.4 | 237.4 |
| 1978 | 18.9 | 19.4 | 21 | 21.2 | 21.3 | 21 | 19.3 | 19.4 | 19.3 | 19.7 | 19.2 | 18.8 | 238.5 |
| 1979 | 19 | 20.1 | 20.5 | 21.2 | 21.3 | 20.8 | 19.5 | 19.6 | 19.6 | 19.4 | 18.7 | 19.1 | 238.8 |
| 1980 | 19.3 | 21 | 21.7 | 21.7 | 22.3 | 21.1 | 19.6 | 19.8 | 19.8 | 19.6 | 19.2 | 17.9 | 243 |
| 1981 | 19.5 | 20.6 | 20.5 | 20.5 | 21.4 | 21.1 | 19.4 | 19.4 | 19 | 19.1 | 18.4 | 17.6 | 236.5 |
| 1982 | 20 | 20.5 | 20.8 | 20.5 | 20.8 | 20.8 | 19.6 | 19 | 19.2 | 18.5 | 19.8 | 19.7 | 239.2 |
| 1983 | 19.5 | 21.4 | 22.8 | 21.4 | 21.2 | 20.3 | 19.4 | 19.1 | 18.7 | 18.4 | 18.2 | 18.1 | 238.5 |
| 1984 | 17.5 | 18 | 20.4 | 21 | 21.3 | 20.2 | 19.9 | 19.4 | 19.3 | 18.9 | 19.8 | 18.8 | 234.5 |
| 1985 | 19.2 | 19.8 | 20.7 | 20.6 | 20.8 | 21 | 18.9 | 18.4 | 19.1 | 18.6 | 18.3 | 17.1 | 232.5 |
| 1986 | 17.4 | 18.6 | 19.7 | 20.5 | 21.1 | 18.9 | 18.5 | 18.9 | 18.9 | 19.4 | 19.2 | 18.1 | 229.2 |
| 1987 | 19.1 | 20.6 | 22.3 | 21.8 | 21.7 | 21.4 | 21.1 | 21 | 21.2 | 21.3 | 19.8 | 19.7 | 251 |
| 1988 | 20.2 | 21.9 | 22.8 | 22.7 | 23 | 21.7 | 19.8 | 20.4 | 20.6 | 19.8 | 18.1 | 18.7 | 249.7 |
| 1989 | 18.7 | 20.4 | 21.7 | 20.6 | 21.6 | 21.1 | 19.9 | 20.2 | 20.2 | 19.5 | 19.8 | 19.1 | 242.8 |
| 1990 | 19.7 | 20.9 | 21 | 21.8 | 22.8 | 21.7 | 19.9 | 19.6 | 20.7 | 19.8 | 20 | 18.7 | 246.6 |
| 1991 | 21 | 21.3 | 21.8 | 21.9 | 23 | 22.6 | 19.6 | 19.8 | 20.3 | 19.8 | 19.2 | 19.2 | 249.5 |
| 1992 | 19.9 | 21.1 | 23.2 | 23.1 | 22.8 | 21.8 | 19.8 | 19.7 | 19.6 | 19.7 | 18.9 | 18.7 | 248.3 |
| 1993 | 19.8 | 19.5 | 21.2 | 21.9 | 22.9 | 21.4 | 20 | 20.2 | 19.4 | 19.8 | 19.1 | 18.3 | 243.5 |
| 1994 | 19.4 | 20.3 | 21.1 | 22 | 22.7 | 20.9 | 19.8 | 20 | 20 | 19.9 | 19.3 | 18.2 | 243.6 |
| 1995 | 19.2 | 21.7 | 22.2 | 22.1 | 22.8 | 22.9 | 20.6 | 20.5 | 20.3 | 20.9 | 19.7 | 20.4 | 253.3 |
| 1996 | 20.5 | 21.5 | 22.6 | 22.4 | 21.6 | 20.5 | 20 | 20.1 | 20.2 | 19.6 | 19.2 | 18.5 | 246.7 |
| TOTAL | 512.1 | 543 | 568.3 | 570.6 | 580.8 | 562.6 | 532 | 528.7 | 526.5 | 523.2 | 512.9 | 500.3 | 6461 |
| AVR | 18.97 | 20.11 | 21.05 | 21.13 | 21.51 | 20.84 | 19.7 | 19.58 | 19.5 | 19.38 | 19 | 18.53 | 239.3 |

Monthly Mean Temperature in $^0C$ of Assela Station

| YEAR | JAN | FEB | MAR | APR | MAY | JUNE | JULY | AUG | SEP | OCT | NOV | DEC | TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1970 | 14.4 | 14.3 | 15.3 | 16.3 | 16.5 | 15.2 | 14.5 | 14 | 14.4 | 14.7 | 13.9 | 13.2 | 176.7 |
| 1971 | 12.6 | 14.9 | 15.1 | 15.7 | 15.1 | 14.7 | 14.4 | 13.9 | 13.9 | 14.9 | 14.5 | 11.9 | 171.6 |
| 1972 | 12.8 | 12.4 | 14.8 | 15.4 | 16.2 | 15.4 | 14.3 | 14.5 | 14.2 | 14.5 | 13.5 | 12.9 | 170.9 |
| 1973 | 13.6 | 14.9 | 16.9 | 17.5 | 16.6 | 15.8 | 13.5 | 12.6 | 13.5 | 14.5 | 14.4 | 13.1 | 176.9 |
| 1974 | 13.7 | 14.7 | 15.4 | 15.7 | 16.2 | 14.7 | 14.4 | 14.6 | 14.1 | 14.2 | 12.3 | 12.5 | 172.5 |
| 1975 | 12.5 | 14.2 | 16 | 13.2 | 13.6 | 11.9 | 11 | 11 | 12 | 14.3 | 14 | 12.8 | 156.5 |
| 1976 | 13.1 | 13.9 | 14.6 | 15.2 | 15.7 | 14.1 | 13.6 | 13.1 | 13.1 | 13.6 | 12.1 | 12 | 164.1 |
| 1977 | 13 | 13 | 14.2 | 14.8 | 14.8 | 14 | 13.5 | 13.2 | 13 | 13.6 | 11.4 | 11.5 | 160 |
| 1978 | 13.2 | 12.9 | 14.2 | 15.4 | 15.2 | 15.5 | 14.3 | 14.2 | 13.8 | 14 | 14.3 | 12.7 | 169.7 |
| 1979 | 15.1 | 14.1 | 15.2 | 16 | 16.1 | 15.6 | 14.4 | 14 | 13.1 | 13.7 | 12.3 | 12.9 | 172.5 |
| 1980 | 13.5 | 14.3 | 16.1 | 15.8 | 16.2 | 15.3 | 14.7 | 14.8 | 14 | 13.9 | 12.4 | 12.3 | 173.3 |
| 1981 | 12.8 | 13.7 | 14.8 | 14.9 | 15.9 | 15.5 | 14.5 | 13.7 | 13.1 | 13.2 | 12.2 | 11.6 | 165.9 |
| 1982 | 13.2 | 14 | 14.6 | 14.6 | 15.4 | 15.2 | 13.7 | 13.2 | 13 | 13.1 | 12.7 | 14.3 | 167 |
| 1983 | 12.1 | 13.9 | 15.2 | 15.6 | 15.6 | 14.9 | 14.1 | 13.6 | 13.8 | 14 | 13.1 | 13.3 | 169.2 |
| 1984 | 12.7 | 12.7 | 14 | 15.9 | 16.3 | 14.4 | 13.7 | 13.8 | 13.7 | 13.7 | 13.3 | 13.6 | 167.8 |
| 1985 | 13.4 | 14.2 | 15.4 | 15 | 14.8 | 14.8 | 13.6 | 13.5 | 13.8 | 14 | 12.8 | 12.3 | 167.6 |
| 1986 | 13.7 | 14.6 | 15.1 | 15.2 | 15.9 | 15 | 14.3 | 14.7 | 13.6 | 14.1 | 13.2 | 12.9 | 172.3 |
| 1987 | 13.3 | 14.7 | 15.3 | 15.1 | 16.3 | 14.9 | 15.1 | 15.5 | 15.4 | 16.8 | 15.3 | 15 | 182.7 |
| 1988 | 14.4 | 16.1 | 17.8 | 18 | 17.9 | 16.8 | 16.5 | 15.8 | 16 | 16.1 | 13.9 | 14.4 | 193.7 |
| 1989 | 14.4 | 15.3 | 16 | 16 | 16.7 | 16.4 | 15.9 | 15.6 | 15.2 | 15.8 | 15.5 | 15.2 | 188 |
| 1990 | 14.6 | 16.1 | 15.5 | 16.8 | 17.8 | 16.9 | 15.2 | 15 | 14.8 | 14.7 | 14.7 | 13.4 | 185.5 |
| 1991 | 16.5 | 17.2 | 17.5 | 17.9 | 18.2 | 18.3 | 15.8 | 16.1 | 16 | 15.9 | 14.6 | 14.2 | 198.2 |
| 1992 | 14.9 | 17 | 18 | 17.3 | 17.9 | 18.2 | 16 | 15.9 | 16.1 | 15.6 | 15.2 | 15.7 | 197.8 |
| 1993 | 16.4 | 15.2 | 16.5 | 17.8 | 18 | 17.3 | 16.4 | 16.2 | 16.2 | 16.1 | 14.8 | 15.1 | 196 |
| 1994 | 15 | 18.7 | 18.3 | 18.9 | 17.9 | 16.7 | 15.8 | 15.8 | 15.3 | 16.7 | 15.8 | 14.1 | 199 |
| 1995 | 15.4 | 17.4 | 17.7 | 17.8 | 17.5 | 17.8 | 17.1 | 16.7 | 16.3 | 16.6 | 14.7 | 15.4 | 200.4 |
| 1996 | 15.6 | 15.5 | 18 | 17.4 | 16.9 | 16.2 | 16.4 | 16 | 16.3 | 15.9 | 15.6 | 15 | 194.8 |
| **TOTAL** | 375.9 | 399.9 | 427.5 | 435.2 | 441.2 | 421.5 | 396.7 | 391 | 387.7 | 398.2 | 372.5 | 363.3 | 4810.6 |
| **AVR** | 13.92 | 14.81 | 15.83 | 16.12 | 16.34 | 15.61 | 14.69 | 14.48 | 14.03 | 14.75 | 13.8 | 13.46 | 178.17 |

Monthly total pan evaporation in mm of Ziway station

| YEAR | JAN | FEB | MAR | APR | MAY | JUNE | JULY | AUG | SEP | OCT | NOV | DEC | TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1981 | 183.2 | 137.9 | 206.1 | 169.2 | 143.7 | 176 | 133.4 | 126.5 | 204.54 | 172.12 | 184.16 | 172.37 | 2009.19 |
| 1982 | 133.78 | 128.06 | 186.66 | 82.06 | 156.7 | 163.5 | 135.5 | 216.5 | 138.1 | 214.2 | 142.9 | 110.1 | 1808.06 |
| 1983 | 95.97 | 109 | 110.54 | 105.66 | 113.03 | 122.55 | 99.79 | 77.44 | 97.53 | 120.77 | 172.2 | 160.29 | 1384.77 |
| 1984 | 177.74 | 168.59 | 218.79 | 211.36 | 168.83 | 166.7 | 148.76 | 120.71 | 133.61 | 187.79 | 159.48 | 189.15 | 2051.51 |
| 1985 | 188.68 | 183 | 226.96 | 150.32 | 137.17 | 180.91 | 111.55 | 128.85 | 124.34 | 180.1 | 150.84 | 169.06 | 1931.78 |
| 1986 | 165.9 | 123.17 | 171.63 | 143.46 | 136.14 | 141.24 | 130.67 | 134.28 | 146.73 | 168.25 | 178.6 | 195.3 | 1835.37 |
| 1987 | 192.4 | 146.5 | 213.48 | 165.62 | 153.76 | 220.54 | 189.16 | 170.63 | 171.46 | 203.22 | 236.16 | 226.76 | 2289.69 |
| 1988 | 209.71 | 206.8 | 287.45 | 173.34 | 251.28 | 198.4 | 119.6 | 131.7 | 130.2 | 171 | 199 | 200.9 | 2279.38 |
| 1989 | 196.7 | 180.4 | 183.1 | 130.9 | 211 | 164.7 | 130.6 | 125.3 | 116.8 | 182.9 | 206.5 | 160.39 | 1989.29 |
| 1990 | 198.59 | 111.18 | 178.97 | 176.95 | 221.06 | 206.35 | 139.83 | 120.25 | 125.75 | 205.55 | 200.97 | 215.58 | 2101.03 |
| 1991 | 213.52 | 151.18 | 153.94 | 191.43 | 214.19 | 179.6 | 126.7 | 118.9 | 141.8 | 197.27 | 188.6 | 203.2 | 2080.33 |
| TOTAL | 1956.1 | 1645.7 | 2137.6 | 1700.3 | 1906.8 | 1920.4 | 1465.5 | 1471.0 | 1530.86 | 2003.1 | 2019.4 | 2003.1 | |
| AVR | 177.84 | 149.62 | 194.33 | 154.57 | 173.35 | 174.59 | 133.23 | 133.73 | 139.17 | 182.11 | 183.58 | 182.1 | |

# Appendix 3

## Runoff Data

Monthly Runoff in Million Cubic meter of Bulbula River At Kerkersitu (near Adami Tulu)

| YEAR | JAN | FEB | MAR | APR | MAY | JUNE | JULY | AUG | SEP | OCT | NOV | DEC | TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1979 | 11.65 | 9.14 | 8.19 | 9.24 | 5.22 | 4.83 | 8.8 | 28.99 | 47.62 | 48.15 | 32.31 | 18.29 | 232.43 |
| 1980 | 10.47 | 5.49 | 2.41 | 1.6 | 1.5 | 0.456 | 0.504 | 2.25 | 5.24 | 5.4 | 3.1 | 1.01 | 39.43 |
| 1981 | 0.55 | 0.437 | 0.559 | 0.508 | 0.588 | 0.522 | 0.588 | 6.29 | 32.65 | 47.61 | 33.45 | 20.59 | 144.342 |
| 1982 | 8.48 | 4.25 | 2.67 | 1.6 | 1.43 | 0.779 | 0.69 | 5.55 | 17.52 | 21.1 | 9 | 6 | 79.069 |
| 1983 | 5.15 | 3.13 | 2.16 | 2.41 | 4.04 | 11.51 | 15.38 | 35.36 | 63.58 | 54.62 | 54.25 | 30.23 | 281.82 |
| 1984 | 29.09 | 15.33 | 8.38 | 3.66 | 1.81 | 1.14 | 1.78 | 7.77 | 14.29 | 11.74 | 5.59 | 2.47 | 103.05 |
| 1985 | 1.04 | 0.75 | 0.67 | 0.5 | 0.47 | 0.46 | 0.47 | 0.84 | 5.2 | 6.86 | 2.57 | 1.27 | 21.1 |
| 1986 | 0.672 | 0.571 | 0.565 | 0.548 | 0.575 | 0.49 | 0.612 | 3.38 | 28.46 | 26.74 | 24.63 | 18.4 | 105.643 |
| 1987 | 1.76 | 0.633 | 0.6 | 1.51 | 2.16 | 6.26 | 4.36 | 6.44 | 10.65 | 14.82 | 8.51 | 5.19 | 62.893 |
| 1988 | 3.19 | 2.16 | 1.74 | 1.75 | 1.694 | 1.711 | 1.764 | 3.92 | 13.21 | 37.55 | 27.52 | 16.15 | 112.359 |
| 1989 | 8.87 | 4.768 | 3.025 | 3.791 | 2.05 | 2.11 | 2.74 | 7.39 | 27.37 | 36.37 | 18.4 | 10.02 | 126.904 |
| 1990 | 1.1 | 1.12 | 3.73 | 8.63 | 7.35 | 2.12 | 3.25 | 12.92 | 39.72 | 32.67 | 27.22 | 19.86 | 159.69 |
| 1991 | 9.288 | 3.3 | 1.81 | 0.7 | 0.81 | 0.34 | 1.1 | 12.27 | 48.93 | 41.81 | 25.05 | 13.98 | 159.388 |
| 1992 | 5.95 | 2.02 | 0.66 | 0.29 | 0.042 | 0.008 | 0.114 | 12.23 | 58.94 | 67.18 | 50.12 | 30.88 | 228.434 |
| 1993 | 18.24 | 12.6 | 5.85 | 2.91 | 9.2 | 14.88 | 23.16 | 54.34 | 72.16 | 64.77 | 44.95 | 29.9 | 352.96 |
| 1994 | 21.28 | 12.12 | 8.88 | 2.6 | 0.13 | 0.1 | 0.08 | 10.55 | 38.85 | 48.58 | 36.3 | 27.42 | 206.89 |
| 1995 | 13.96 | 5.59 | 4.01 | 1.21 | 4.8 | 2.6 | 2.87 | 10.17 | 24.22 | 18.87 | 22.63 | 15.2 | 126.13 |
| TOTAL | 150.74 | 83.409 | 55.909 | 43.457 | 43.869 | 50.316 | 68.262 | 220.66 | 548.61 | 584.84 | 425.6 | 266.86 | |
| AVR | 8.867 | 4.906 | 3.289 | 2.556 | 2.581 | 2.96 | 4.02 | 12.98 | 32.27 | 34.40 | 25.035 | 15.70 | |
| m3/sec | 3.31 | 2.02 | 1.23 | 0.99 | 0.96 | 1.14 | 1.5 | 4.85 | 13.13 | 12.84 | 10.34 | 6.3 | |

Monthly Runoff in Million cubic meter of Ketar River at Abura

| YEAR | JAN | FEB | MAR | APR | MAY | JUNE | JULY | AUG | SEP | OCT | NOV | DEC | TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1970 | 10.97 | 6.94 | 37.81 | 32.28 | 24.38 | 8.13 | 62.76 | 233.68 | 129.64 | 44.7 | 10.56 | 8.5 | 610.35 |
| 1971 | 6.55 | 5.24 | 5.71 | 7.86 | 12.33 | 30.06 | 78.38 | 107.42 | 74.46 | 35.46 | 11.92 | 8.35 | 383.74 |
| 1972 | 7.42 | 9.27 | 9.72 | 20.6 | 20.4 | 10.09 | 62.23 | 102.65 | 49.98 | 17.99 | 9.55 | 7.07 | 326.97 |
| 1973 | 5.72 | 4.75 | 4.2 | 4.06 | 6.59 | 6.62 | 35.67 | 108.8 | 88.34 | 43.64 | 8.34 | 5.75 | 322.48 |
| 1974 | 5.81 | 4.49 | 11.22 | 13.44 | 8.21 | 11.27 | 37.45 | 91.37 | 73.09 | 19.38 | 6.47 | 5.53 | 287.73 |
| 1975 | 5.15 | 4.16 | 3.53 | 5.27 | 5.3 | 11.9 | 65.76 | 245.84 | 174.46 | 38.39 | 8.42 | 6.76 | 574.94 |
| 1976 | 5.78 | 4.88 | 5.14 | 34.51 | 10.79 | 6.96 | 32.06 | 120.23 | 72.88 | 12.82 | 11.85 | 6.35 | 324.25 |
| 1977 | 8.79 | 7.78 | 6.95 | 14.74 | 13.55 | 12.76 | 54.82 | 134.49 | 111.64 | 88.11 | 64.13 | 10.99 | 528.75 |
| 1978 | 7.08 | 7.04 | 14.85 | 7 | 9.6 | 9.43 | 89.63 | 155.37 | 55.71 | 46.01 | 11.62 | 7.94 | 421.28 |
| 1979 | 12.74 | 21.17 | 19.95 | 23.92 | 27.35 | 20.31 | 58.72 | 121.96 | 60.05 | 32.49 | 11.26 | 8.24 | 418.16 |
| 1980 | 6.9 | 6.48 | 6.23 | 6.14 | 6.6 | 10.09 | 45.43 | 104.11 | 48.38 | 21.2 | 7.4 | 6.6 | 275.56 |
| 1981 | 5.99 | 5.31 | 11.01 | 56.6 | 25.97 | 7.33 | 33.7 | 172.05 | 148.05 | 90.84 | 9.33 | 7.37 | 573.55 |
| 1982 | 7.29 | 6.28 | 6.57 | 14.03 | 14.66 | 10.28 | 33.62 | 135.33 | 52.33 | 41.22 | 11.78 | 11.85 | 345.24 |
| 1983 | 9.21 | 7.14 | 10.42 | 25.06 | 44.28 | 61.58 | 31.9 | 178.5 | 108.24 | 82.12 | 12.4 | 9.11 | 579.96 |
| 1984 | 8.97 | 5.25 | 6.72 | 10.25 | 8.43 | 16.28 | 46.52 | 68.36 | 58.74 | 9.54 | 6.14 | 6.1 | 251.3 |
| 1985 | 5.35 | 4.29 | 4.59 | 8.46 | 21.3 | 8.37 | 44.9 | 91.19 | 58 | 40 | 5.03 | 4.88 | 296.36 |
| 1986 | 4.96 | 6.746 | 9.14 | 13.22 | 15.37 | 25.66 | 75.46 | 138.05 | 91.51 | 35.18 | 8.79 | 6.72 | 430.806 |
| 1987 | 4.93 | 4.37 | 13.05 | 46.96 | 26.23 | 38.3 | 26.85 | 51.81 | 44.22 | 19.75 | 6.14 | 5.37 | 287.98 |
| 1988 | 4.96 | 5.31 | 5.4 | 5.97 | 6.74 | 7.07 | 61.58 | 266.32 | 89.48 | 54.44 | 13.39 | 7.21 | 527.87 |
| 1989 | 6.44 | 5.69 | 6.24 | 16.56 | 15.53 | 10.18 | 32.83 | 67.11 | 75.57 | 32.49 | 8.97 | 10.71 | 288.32 |
| 1990 | 6.77 | 26.19 | 53.57 | 55.33 | 14.24 | 11.17 | 48.36 | 141.96 | 90.83 | 43.69 | 12.86 | 6.36 | 511.33 |
| 1991 | 5.77 | 5.42 | 9.88 | 13.97 | 7.38 | 8.73 | 37.64 | 121.77 | 92.68 | 16.45 | 6.65 | 6.22 | 332.56 |
| 1992 | 5.4 | 6.17 | 4.71 | 7.7 | 8.21 | 8.38 | 21.92 | 176.9 | 139.9 | 67.18 | 11.82 | 7.58 | 465.87 |
| 1993 | 7.27 | 15.6 | 5.88 | 13.23 | 30.61 | 29.98 | 43.96 | 141.5 | 92.55 | 53.9 | 18.58 | 7.23 | 460.29 |
| 1994 | 5.74 | 4.64 | 4.39 | 4.21 | 15.95 | 11.02 | 61.26 | 184.5 | 127.2 | 18.81 | 7.28 | 5.48 | 450.48 |
| 1995 | 4.18 | 3.83 | 21.27 | 18.73 | 14.58 | 6.58 | 33.96 | 129.67 | 153.77 | 12.3 | 6.09 | 5.65 | 410.61 |
| TOTAL | 176.14 | 194.43 | 298.15 | 480.1 | 414.58 | 398.53 | 1257.3 | 3590.9 | 2361.7 | 1018.1 | 306.77 | 189.92 | |
| AVR | 6.77 | 7.50 | 11.42 | 18.42 | 15.945 | 15.328 | 48.36 | 138.11 | 90.835 | 39.158 | 11.799 | 7.305 | |
| m3/sec | 2.53 | 3.08 | 4.27 | 7.11 | 5.95 | 5.91 | 18.06 | 53 | 27.33 | 16.31 | 4.96 | 2.75 | |

Monthly Runoff in Million cubic meter of Meki River at Meki

| YEAR | JAN | FEB | MAR | APR | MAY | JUNE | JULY | AUG | SEP | OCT | NOV | DEC | TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1970 | 10.8 | 3.84 | 46.09 | 6.08 | 6.69 | 4.53 | 69.69 | 111.45 | 52.57 | 16.18 | 4.18 | 2.334 | 334.434 |
| 1971 | 1.99 | 1.112 | 1.47 | 5.57 | 13.64 | 45.77 | 82.85 | 103.28 | 54.08 | 7.92 | 2.58 | 1.06 | 321.322 |
| 1972 | 1.088 | 12.31 | 113.88 | 32.8 | 24.99 | 10.33 | 37.81 | 87.65 | 36.16 | 9.06 | 1.597 | 0 | 367.675 |
| 1973 | 0.192 | 0.002 | 0 | 0.018 | 1.633 | 2.69 | 46.83 | 65.38 | 59.52 | 31.83 | 2.609 | 0.252 | 210.956 |
| 1974 | 0.529 | 0 | 4.82 | 2.82 | 3.27 | 6.72 | 58.39 | 67.34 | 72.84 | 19.76 | 2.31 | 0.494 | 239.293 |
| 1975 | 0.297 | 0.577 | 0.02 | 1.57 | 1.177 | 11.56 | 72.77 | 73.44 | 116.36 | 32.33 | 5.09 | 1.327 | 316.518 |
| 1976 | 0.703 | 0.216 | 6.41 | 5.19 | 15.71 | 5.39 | 39.72 | 50.42 | 36.1 | 5.46 | 14.6 | 1.99 | 181.909 |
| 1977 | 6.69 | 9.52 | 1.768 | 9.05 | 26.68 | 16.76 | 83.6 | 77.02 | 48.7 | 47.81 | 63.43 | 7.59 | 398.618 |
| 1978 | 1.22 | 4.18 | 14.1 | 3.12 | 1.99 | 9.99 | 35.39 | 78.58 | 41.86 | 38.2 | 12.59 | 1.88 | 243.1 |
| 1979 | 7.95 | 14.16 | 21.19 | 54.05 | 35.32 | 7.72 | 63.46 | 80.12 | 36.05 | 34.16 | 10.31 | 3.1 | 367.59 |
| 1980 | 2.16 | 2.41 | 3.4 | 5.66 | 4.04 | 11.84 | 44.36 | 56.43 | 24.71 | 11.65 | 2.12 | 1.41 | 170.19 |
| 1981 | 1.07 | 1.177 | 36.66 | 51.92 | 32.12 | 14.32 | 44.24 | 80.71 | 58.75 | 13.68 | 1.6 | 3.05 | 339.297 |
| 1982 | 2.46 | 4.29 | 3.46 | 18.21 | 19.06 | 6.55 | 22.11 | 80.54 | 24.97 | 44.24 | 6.69 | 4.65 | 237.23 |
| 1983 | 1.417 | 6.67 | 12.36 | 30.77 | 48.11 | 36.19 | 26.56 | 89.43 | 55.42 | 20.16 | 4.18 | 2.38 | 333.647 |
| 1984 | 1.647 | 1.209 | 1.2 | 0.82 | 6.95 | 11.87 | 26.81 | 26.28 | 34.25 | 2.89 | 0.914 | 0.774 | 115.614 |
| 1985 | 0.591 | 0.437 | 0.449 | 4.38 | 17.3 | 3.27 | 24.4 | 72.72 | 40.24 | 7.22 | 0.865 | 0.448 | 172.32 |
| 1986 | 0.248 | 1.251 | 2.319 | 12.67 | 6.83 | 4.21 | 42.31 | 94.08 | 49.68 | 5.07 | 0.507 | 0.112 | 219.287 |
| 1987 | 0.019 | 0.68 | 20.6 | 47.3 | 46.23 | 37.9 | 20.12 | 16.8 | 18.87 | 6.73 | 1.01 | 0.108 | 216.367 |
| 1988 | 0.093 | 1.02 | 0.397 | 7.95 | 5.94 | 7.87 | 41.99 | 62.27 | 58.23 | 33.79 | 7.55 | 2.45 | 229.55 |
| 1989 | 0.371 | 5.88 | 8.83 | 25 | 7.91 | 10.13 | 40.63 | 41.13 | 47.25 | 26.04 | 4.26 | 2.37 | 219.801 |
| 1990 | 0.878 | 27.45 | 54.08 | 57.02 | 14.14 | 15.04 | 45.72 | 53.02 | 39.33 | 17.2 | 4.8 | 2.34 | 331.018 |
| 1991 | 1.33 | 6.28 | 19.2 | 7.41 | 2.38 | 9.8 | 65.57 | 93.5 | 52.18 | 9.31 | 2.25 | 1.79 | 271 |
| 1992 | 2.38 | 13.48 | 5.77 | 12.86 | 11.27 | 8.36 | 58.73 | 136.74 | 84.86 | 33.37 | 7.737 | 4.243 | 379.8 |
| 1993 | 2.483 | 2.382 | 2.65 | 34.857 | 46.977 | 31.946 | 67.478 | 144.14 | 51.605 | 57.06 | 11.586 | 2.41 | 455.574 |
| 1994 | 2.166 | 1.21 | 1.636 | 0.792 | 6.42 | 14.08 | 63.18 | 153.94 | 121.27 | 4.588 | 2.58 | 0.632 | 372.494 |
| 1995 | 2.03 | 4.87 | 15.31 | 17.52 | 26.21 | 21.13 | 56.34 | 121.48 | 59.2 | 23.14 | 6.8 | 2.01 | 356.04 |
| TOTAL | 52.802 | 126.61 | 398.06 | 455.40 | 432.98 | 365.96 | 1281.058 | 2117.89 | 1375.05 | 558.84 | 184.745 | 51.204 | |
| AVR | 2.031 | 4.87 | 15.31 | 17.516 | 16.653 | 14.076 | 49.271 | 81.457 | 52.887 | 21.494 | 7.106 | 1.969 | |
| m3/sec | 0.76 | 2 | 5.72 | 6.76 | 6.22 | 5.43 | 18.23 | 30.41 | 20.4 | 8.03 | 2.74 | 0.74 | |

# Appendix 4

## Lake Level Fluctuation of Ziway Lake

Monthly Mean Gauge Height in meters of Ziway Lake at Bochesa

| YEAR | JAN | FEB | MAR | APR | MAY | JUNE | JULY | AUG | SEP | OCT | NOV | DEC | Dec-Jan |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1975 | 0.73 | 0.62 | 0.48 | 0.32 | 0.22 | 0.13 | 0.28 | 0.78 | 1.46 | 1.64 | 1.45 | 1.23 | 0.5 |
| 1976 | 1.07 | 0.92 | 0.81 | 0.72 | 0.68 | 0.6 | 0.65 | 0.95 | 1.23 | 1.16 | 1.04 | 0.92 | -0.15 |
| 1977 | 0.83 | 0.79 | 0.63 | 0.55 | 0.54 | 0.51 | 0.72 | 1.12 | 1.48 | 1.65 | 1.78 | 1.68 | 0.85 |
| 1978 | 1.53 | 1.37 | 1.36 | 1.19 | 1 | 0.86 | 1 | 1.46 | 1.68 | 1.74 | 1.55 | 1.37 | -0.16 |
| 1979 | 1.24 | 1.2 | 1.13 | 1.15 | 1.09 | 1.06 | 1.18 | 1.49 | 1.72 | 1.66 | 1.52 | 1.37 | 0.13 |
| 1980 | 1.18 | 1.05 | 0.91 | 0.79 | 0.62 | 0.52 | 0.56 | 0.81 | 1 | 1.01 | 0.83 | 0.65 | -0.53 |
| 1981 | 0.54 | 0.43 | 0.38 | 0.6 | 0.63 | 0.5 | 0.49 | 0.99 | 1.45 | 1.63 | 1.42 | 1.24 | 0.7 |
| 1982 | 1.11 | 0.94 | 0.86 | 0.79 | 0.77 | 0.68 | 0.66 | 0.99 | 1.3 | 1.37 | 1.31 | 1.17 | 0.06 |
| 1983 | 1.02 | 0.91 | 0.81 | 0.89 | 0.94 | 1.21 | 1.23 | 1.65 | 2.17 | 2.17 | 1.96 | 1.72 | 0.7 |
| 1984 | 1.44 | 1.31 | 1.09 | 0.9 | 0.8 | 0.78 | 0.81 | 1.14 | 1.31 | 1.24 | 1.04 | 0.87 | -0.57 |
| 1985 | 0.72 | 0.6 | 0.46 | 0.35 | 0.35 | 0.26 | 0.27 | 0.68 | 1.03 | 1.06 | 0.91 | 0.78 | 0.06 |
| 1986 | 0.58 | 0.52 | 0.48 | 0.41 | 0.38 | 0.36 | 0.63 | 0.92 | 1.09 | 1.23 | 1.1 | 0.98 | 0.4 |
| 1987 | 0.82 | 0.72 | 0.69 | 0.69 | 0.78 | 1.06 | 1.1 | 1.16 | 1.2 | 1.14 | 1 | 0.85 | 0.03 |
| 1988 | 0.65 | 0.53 | 0.39 | 0.24 | 0.2 | 0.19 | 0.28 | 0.67 | 1.13 | 1.4 | 1.33 | 1.19 | 0.54 |
| 1989 | 1.02 | 0.92 | 0.81 | 0.82 | 0.78 | 0.7 | 0.76 | 0.99 | 1.26 | 1.36 | 1.22 | 1.04 | 0.02 |
| 1990 | 0.92 | 0.87 | 1.09 | 1.21 | 1.19 | 1.08 | 1.12 | 1.46 | 1.74 | 1.68 | 1.48 | 1.64 | 0.72 |
| 1991 | 1.12 | 1 | 0.98 | 0.93 | 0.82 | 0.69 | 0.79 | 1.24 | 1.65 | 1.57 | 1.35 | 1.17 | 0.05 |
| 1992 | 1.07 | 0.98 | 0.87 | 0.74 | 0.67 | 0.66 | 0.89 | 1.28 | 1.7 | 1.74 | 1.57 | 1.41 | 0.34 |
| 1993 | 1.3 | 1.21 | 1.07 | 0.95 | 1.05 | 1.13 | 1.25 | 1.6 | 1.8 | 1.8 | 1.65 | 1.47 | 0.17 |
| 1994 | 1.29 | 1.15 | 0.96 | 0.84 | 0.72 | 0.71 | 0.82 | 1.33 | 1.71 | 1.77 | 1.46 | 1.34 | 0.05 |
| 1995 | 1.21 | 1.09 | 0.95 | 0.89 | 1.01 | 0.96 | 0.91 | 1.2 | 1.46 | 1.41 | 1.2 | 1.06 | -0.15 |
| TOTAL | 21.39 | 19.13 | 17.21 | 15.97 | 15.24 | 14.65 | 16.4 | 23.91 | 30.57 | 31.43 | 28.17 | 25.15 | |
| AVR | 1.02 | 0.91 | 0.82 | 0.76 | 0.73 | 0.7 | 0.78 | 1.14 | 1.46 | 1.5 | 2.01 | 1.2 | |

## Appendix 5

### Calculation of Effective Uniform Depth of Rainfall

| A | B | C | D | E |
|---|---|---|---|---|
| Station | Mean Annual Precipitation (mm) | Area (sq. km) | Percent of the total area | Weighted Precipitation (mm) **(B x D)** |
| Meki | 790.89 | 567.2 | 16.83 | 133.11 |
| Ziway | 751.78 | 1399.7 | 41.53 | 312.21 |
| Assela | 1179.88 | 1403.1 | 41.64 | 491.30 |
| Total | 2722.55 | 3370.0 | 100.00 | **936.62** |

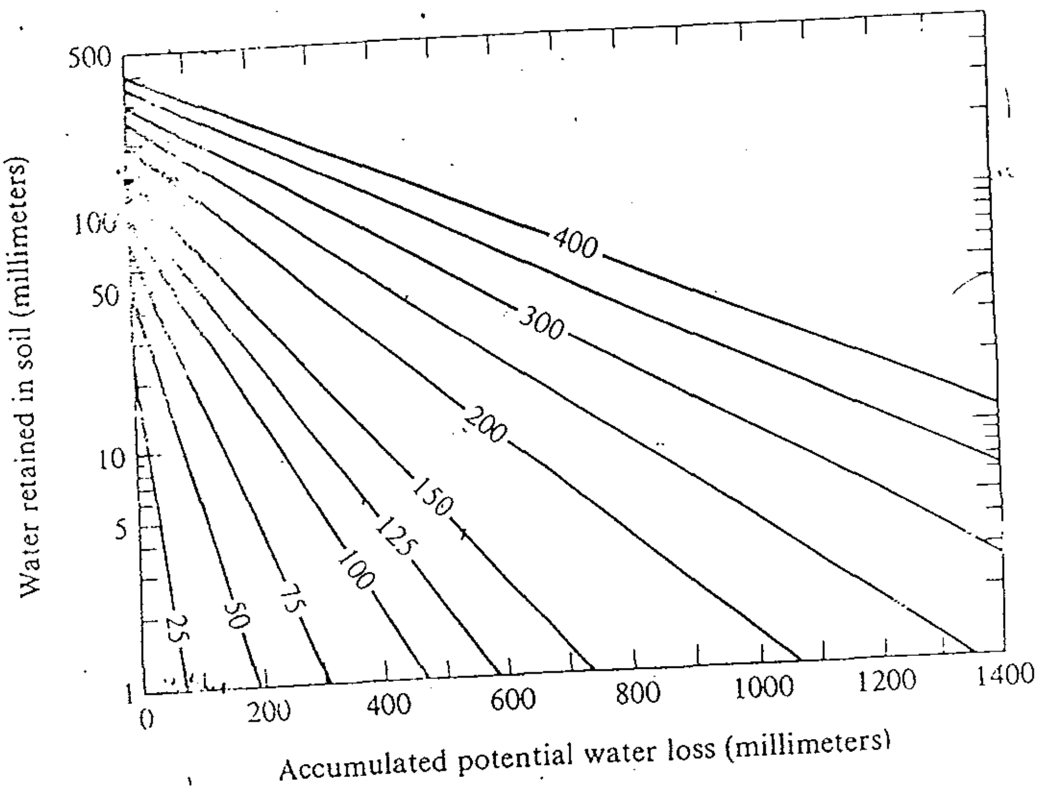
# Appendix 6

## Latitude Factor For Thornthwaite Evapotranspiration Calculation

| Latitude | Jan | Feb | Mar | Apr | May | June | July | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $60^0$N | 0.54 | 0.67 | 0.97 | 1.19 | 1.33 | 1.56 | 1.55 | 1.33 | 1.07 | 0.84 | 0.58 | 0.48 |
| $50^0$N | 0.71 | 0.84 | 0.98 | 1.14 | 1.28 | 1.36 | 1.33 | 1.21 | 1.06 | 0.90 | 0.76 | 0.68 |
| $40^0$N | 0.80 | 0.89 | 0.99 | 1.10 | 1.20 | 1.25 | 1.23 | 1.15 | 1.04 | 0.93 | 0.83 | 0.78 |
| $30^0$N | 0.87 | 0.93 | 1.00 | 1.07 | 1.14 | 1.17 | 1.16 | 1.11 | 1.03 | 0.96 | 0.89 | 0.85 |
| $20^0$N | 0.92 | 0.96 | 1.00 | 1.05 | 1.09 | 1.11 | 1.10 | 1.07 | 1.02 | 0.98 | 0.93 | 0.91 |
| $10^0$N | 0.97 | 0.98 | 1.00 | 1.03 | 1.05 | 1.06 | 1.05 | 1.04 | 1.02 | 0.99 | 0.97 | 0.96 |
| 0 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| $10^0$S | 1.05 | 1.04 | 1.02 | 0.99 | 0.97 | 0.96 | 0.97 | 0.98 | 1.00 | 1.03 | 1.05 | 1.06 |
| $20^0$S | 1.10 | 1.07 | 1.02 | 0.98 | 0.93 | 0.91 | 0.92 | 0.96 | 1.00 | 1.05 | 1.09 | 1.11 |
| $30^0$S | 1.16 | 1.11 | 1.03 | 0.96 | 0.89 | 0.85 | 0.87 | 0.93 | 1.00 | 1.07 | 1.14 | 1.17 |
| $40^0$S | 1.23 | 1.15 | 1.04 | 0.93 | 0.83 | 0.78 | 0.80 | 0.89 | 0.99 | 1.10 | 1.20 | 1.25 |
| $50^0$S | 1.33 | 1.19 | 1.05 | 0.89 | 0.75 | 0.68 | 0.70 | 0.82 | 0.97 | 1.13 | 1.27 | 1.36 |

## Appendix 8

## Soil Moisture Graph



# Appendix 9

## Description of wells and Springs

Bore Wells

| Ref. No | Name of Well | Longitude | Latitude | Elevation ASL(m) | Total Depth (m) | SWL BGS (m) | DWL BGS (m) | Yield (l/s) | Drow-down (m) | Diameter (mm) | Casing Length (m) | Screen Length (m) | Drilling Year | Lithology |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| BW1 | MEKI TOWN[L.V.I.A] | $38^{0}49.370'$ | $8^{0}09.004'$ | 1660 | - | - | - | - | - | - | - | - | - | Lac. Sediment |
| BW2 | MEKI TOWN KEBLE 03 | $38^{0}48.565'$ | $8^{0}09.004'$ | 1660 | 78 | 28 | 29 | 3 | - | - | - | - | 1997 | Lac. Sediment |
| BW3 | MEKI MUNICIPALITY | $38^{0}49.100'$ | $8^{0}08.850'$ | 1665 | 85 | 55 | - | - | - | 254 | - | - | - | Lac. Sediment |
| BW4 | MEKI BEKLE MOLLA | $38^{0}49.100'$ | $8^{0}08.600'$ | 1665 | - | 24 | - | - | - | 270 | - | - | - | Lac. Sediment |
| BW5 | GARABA GARSO | $38^{0}47.599'$ | $8^{0}09.485'$ | 1670 | 75 | 60 | - | - | - | 125 | - | - | 1987 | Lac. Sediment |
| BW6 | ATE METI | $38^{0}46.200'$ | $8^{0}09.851'$ | 1680 | 80 | 65 | - | - | - | 125 | - | - | 1987 | Lac. Sediment |
| BW7 | ATE FNURI | $38^{0}44.969'$ | $8^{0}09.616'$ | 1700 | 90 | 75 | 78 | 3 | 3 | 150 | 90 | 6 | 1992 | Lac. Sediment |
| BW8 | LALUNA DERO | $38^{0}43.349'$ | $8^{0}09.601'$ | 1725 | 100 | 85 | - | - | - | 125 | - | - | 1994 | Lac. Sediment |
| BW9 | DUGDA | $38^{0}38.400'$ | $8^{0}09.320'$ | 1920 | 122 | 91 | - | 2 | 3.6 | 203 | - | - | - | Lac. Sediment |
| BW10 | CHOROKE | $38^{0}44.501'$ | $8^{0}07.685'$ | 1700 | 93 | 78 | 82 | 4 | 3.5 | 150 | 93 | 6 | 1991 | Lac. Sediment |
| BW11 | KORKE ADI | $38^{0}47.100'$ | $8^{0}07.358'$ | 1660 | 51 | 30 | - | - | - | 125 | - | - | 1987 | Lac. Sediment |
| BW12 | CHALALEKI | $38^{0}45.308'$ | $8^{0}05.055'$ | 1680 | 54 | 33 | - | - | - | 125 | - | - | 1986 | Lac. Sediment |
| BW13 | GURA GERMEGI | $38^{0}45.147'$ | $8^{0}04.925'$ | 1675 | 47 | 35 | 38 | 3 | 3 | 150 | 47 | 6 | 1991 | Lac. Sediment |
| BW14 | ABONNO 1 | $38^{0}44.629'$ | $8^{0}04.409'$ | 1670 | 50 | 35 | 38 | 3 | 3.5 | 150 | 50 | 6 | 1991 | Lac. Sediment |

| Ref. No | Name of Well | Longitude | Latitude | Elevation ASL(m) | Total Depth (m) | SWL BGS (m) | DWL BGS (m) | Yield (l/s) | Drow-down (m) | Diameter (mm) | Casing Length (m) | Screen Length (m) | Drilling Year | Lithology |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| BW15 | BADA GOSA | 38°43.558' | 8°03.619' | 1680 | 72 | 54 | - | - | - | 125 | - | - | 1986 | Lac. Sediment |
| BW16 | TUCHI GABRIEL | 38°43.395' | 8°02.995' | 1680 | 75 | 53 | - | - | - | 125 | - | - | 1986 | Lac. Sediment |
| BW17 | MAGO | 38°43.035' | 8°02.596' | 1680 | 53 | 50 | - | - | - | 150 | - | - | 1986 | Lac. Sediment |
| BW18 | ZIWAY BEKELE MOLLA | 38°42.950' | 7°55.510' | 1640 | 46 | 27 | - | - | - | 203 | - | - | - | Lac. Sediment |
| BW19 | NEGALLING | 38°42.934' | 8°01.256' | 1675 | 40 | 30 | - | - | - | 125 | - | - | 1987 | Lac. Sediment |
| BW20 | SEMOYE CHELEMO | 38°40.722' | 8°01.062' | 1700 | 100 | 55 | - | - | - | 150 | - | - | 1994 | Lac. Sediment |
| BW21 | ELKANA METROMOFA | 38°42.851' | 8°00.497' | 1655 | 45 | 35 | - | - | - | 125 | - | - | 1987 | Lac. Sediment |
| BW22 | EDO KONTOLA | 38°43.161' | 7°59.211' | 1645 | 37 | 18 | - | - | - | 125 | - | - | 1987 | Lac. Sediment |
| BW23 | GUBIBA | 38°36.777' | 8°01.520' | 1790 | 199 | 129 | - | - | - | 150 | - | - | 1994 | Ignimbrite |
| BW24 | GALO FECHASA | 38°39.382' | 7°59.479' | 1700 | 108 | 81 | - | - | - | 150 | - | - | 1994 | Lac. Sediment |
| BW25 | HESBAWI BATELE | 38°42.740' | 7°57.343' | 1645 | 25 | 22 | - | - | - | 125 | - | - | 1987 | Lac. Sediment |
| BW26 | ZIWAY PRISON | 38°42.274' | 7°56.186' | 1645 | 61 | 34 | 38 | 5.5 | 4 | 150 | 61 | 6 | 1990 | Lac. Sediment |
| BW27 | KOSHE | 38°32.000' | 7°59.920' | 1880 | 180 | 50 | - | - | - | 152 | - | - | - | Ignimbrite |
| BW28 | FAKA | 38°31.220' | 7°57.740' | 1940 | 131 | 49 | - | - | - | 305 | - | - | - | Ignimbrite |
| BW29 | ZIWAY TOWN | 38°42.742' | 7°56.062' | 1640 | 60 | 33 | 35 | 5.5 | 2 | 150 | 60 | 6 | 1990 | Lac. Sediment |
| BW30 | WORGA BATALE | 38°42.014' | 7°56.134' | 1655 | 61 | 39 | 41 | 4 | 2.5 | 150 | 61 | 6 | 1991 | Lac. Sediment |
| BW31 | ZIWAY PHILADELPHIA | 38°42.605' | 7°56.186' | 1640 | 46 | 32 | 35 | 3 | 3 | - | 46 | 6 | 1990 | Lac. Sediment |

| Ref. No | Name of Well | Longitude | Latitude | Elevation ASL(m) | Total Depth (m) | SWL BGS (m) | DWL BGS (m) | Yield (l/s) | Drow-down (m) | Diameter (mm) | Casing Length (m) | Screen Length (m) | Drilling Year | Lithology |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| BW32 | ZIWAY MUNICIPALITY | 38$^{0}$43.150' | 7$^{0}$55.900' | 1640 | 70 | - | - | - | - | 203 | - | - | - | Lac. Sediment |
| BW33 | GUSH GULLA | 38$^{0}$41.950' | 7$^{0}$55.557' | 1665 | 56 | 42 | 44 | 4 | 2.5 | 150 | 56 | 6 | 1991 | Lac. Sediment |
| BW34 | WORGA GARBI | 38$^{0}$41.427' | 7$^{0}$55.226' | 1670 | 73 | 45 | - | - | - | 150 | - | - | 1995 | Lac. Sediment |
| BW35 | BOROMO | 38$^{0}$38.626' | 7$^{0}$54.819' | 1685 | 117 | 81 | - | - | - | 150 | - | - | 1994 | Lac. Sediment |
| BW36 | WOLEYIE | 38$^{0}$39.950' | 7$^{0}$52.690' | 1670 | 99 | 53 | - | - | - | 311 | - | - | - | Lac. Sediment |
| BW37 | WOYSO MACHO | 38$^{0}$38.316' | 7$^{0}$50.073' | 1695 | 105 | 82 | - | - | - | 125 | - | - | 1988 | Lac. Sediment |
| BW38 | SHISHO TABO | 38$^{0}$40.435' | 7$^{0}$50.184' | 1680 | 85 | 66 | - | - | - | 125 | - | - | 1988 | Ignimbrite |
| BW39 | ADAMI TULU | 38$^{0}$42.202' | 7$^{0}$51.945' | 1650 | 65 | 41 | 44 | 5.5 | 3 | | 65 | 6 | 1990 | Lac. Sediment |
| BW40 | GARBI | 38$^{0}$42.826' | 7$^{0}$53.012' | 1645 | 36 | 21 | 23 | 5 | 2 | 150 | 36 | 6 | 1991 | Lac. Sediment |
| BW41 | SOUTH OF CHEFE JILA | 38$^{0}$51.310' | 7$^{0}$49.000' | 1750 | 136 | 108 | - | - | - | 250-150 | - | - | - | Lac. Sediment |
| BW42 | NORTH OF CHEFE JILA | 38$^{0}$51.850' | 7$^{0}$52.090' | 1640 | - | - | - | - | - | 250-150 | - | - | - | Lac. Sediment |
| BW43 | CHEFE JILA | 38$^{0}$52.530' | 7$^{0}$51.210' | 1692 | 70 | 52 | - | 1.3 | 0 | 250-150 | - | - | - | Lac. Sediment |
| BW44 | EAST OF CHEFE JILA | 38$^{0}$53.600' | 7$^{0}$50.780' | 1712 | - | - | - | - | - | 250-150 | - | - | - | Ignimbrite |
| BW45 | EGO(NORTH OF KERSA) | 38$^{0}$57.340' | 7$^{0}$40.020' | 2550 | 250 | - | - | 0 | - | 250-150 | - | - | - | Ignimbrite |
| BW46 | NINO(NORTH OF KERSA) | 38$^{0}$58.190' | 7$^{0}$35.950' | 2525 | 200 | - | - | 0 | - | 250-150 | - | - | - | Ignimbrite |
| BW47 | WORASENI | 39$^{0}$06.540' | 7$^{0}$47.120' | 2450 | 168 | - | - | 0 | - | 250-150 | - | - | - | Ignimbrite |
| BW48 | WAJI | 39$^{0}$07.730' | 7$^{0}$52.440' | 2600 | 115 | 72 | - | 1.7 | 0.5 | 250-150 | - | - | - | Ignimbrite |

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| BW49 | ELEAS | 39$^0$07.570' | 7$^0$54.098' | 2510 | 152 | 48 | - | 0.03 | 24 | 250-150 | - | - | - | Ignimbrite |
| BW50 | ASSELA (Near Police HQ.) | 39$^0$07.410' | 7$^0$56.290' | 2360 | 128 | 59 | - | 0.2 | - | 250-150 | - | - | - | Ignimbrite |
| BW51 | WEST OF ASSELA | 39$^0$06.920' | 7$^0$56.750' | 2240 | 97 | - | - | 0 | - | 250-150 | - | - | - | Ignimbrite |
| BW52 | ASSELA | 39$^0$08.600' | 7$^0$57.000' | 2360 | 150 | - | - | 0 | - | 250-150 | - | - | - | Basalt |
| BW53 | SOUTH OF ABURA(6 km) | 39$^0$00.410' | 7$^0$59.260' | 1720 | - | - | - | - | - | 250-150 | - | - | - | Ignimbrite |
| BW54 | DENEBA | 39$^0$05.130' | 8$^0$00.000' | 1800 | 70 | 23 | - | 2.7 | 0 | 250-150 | - | - | - | Ignimbrite |
| BW55 | GORA(SOUTH OF KULUMSA) | 39$^0$09.670' | 7$^0$59.200' | 2250 | 105 | 80 | - | 1.1 | 0.25 | 250-150 | - | - | - | Ignimbrite |
| BW56 | SOUTH OF KULUMSA | 39$^0$09.715' | 8$^0$00.470' | 2210 | 120 | 78 | - | 0.03 | 12 | 250-150 | - | - | - | Ignimbrite |
| BW57 | SE OF KULUMSA | 39$^0$11.115' | 8$^0$00.020' | 2220 | 113 | - | - | 0 | - | 250-150 | - | - | - | Ignimbrite |
| BW58 | WEST OF KULUMSA | 39$^0$08.960' | 8$^0$01.330' | 2200 | 126 | - | - | 9 | - | 250-150 | - | - | - | Ignimbrite |
| BW59 | NW OF KULUMSA | 39$^0$09.190' | 8$^0$02.000' | 2180 | 165 | - | - | 0 | - | 250-150 | - | - | - | Ignimbrite |
| BW60 | ABURA SCHOOL | 39$^0$01.000' | 8$^0$02.300' | 1667 | 63 | 27 | - | 5.8 | 0 | 250-150 | - | - | - | Lac. Sediment |
| BW61 | REYE | 39$^0$01.890' | 8$^0$03.490' | 1687 | 64 | 43 | - | 1.4 | 0 | 250-150 | - | - | - | Basalt |
| BW62 | LADETE | 39$^0$00.900' | 8$^0$04.280' | 1700 | 91 | 43 | - | 5 | 0.7 | 250-150 | - | - | - | Basalt |
| BW63 | KURBAYI | 39$^0$02.940' | 8$^0$05.070' | 1695 | 78 | 53 | - | 1.8 | 0 | 250-150 | - | - | - | Lac. Sediment |
| BW64 | GONJI | 39$^0$01.250' | 8$^0$06.000' | 1695 | 102 | 83 | - | 1.6 | 3 | 250-150 | - | - | - | Basalt |
| BW65 | ARBA | 39$^0$04.070' | 8$^0$08.880' | 1670 | 160 | 128 | - | 1.3 | 0 | 250-150 | - | - | - | Lac. Sediment |

Hand Dug Wells

| Ref. No | Name of Well | Longitude | Latitude | Elevation ASL(m) | Total Depth (m) | SWL BGS (m) | Diameter (mm) | Drilling Year | Lithology |
|---|---|---|---|---|---|---|---|---|---|
| DW1 | NORTH OF MEKI | $38^0$51.300' | $8^0$10.475' | 1670 | 30.9 | 30.8 | 1100 | - | Lac. Sediment |
| DW2 | MEKI TOWN | $38^0$48.920' | $8^0$08.800' | 1656 | 26.6 | 26.1 | 700 | - | Lac. Sediment |
| DW3 | CHEFE | $38^0$51.80' | $8^0$06.50' | 1640 | 5.5 | 4.3 | 650 | - | Alluvium |
| DW4 | ABONNO 2 | $38^0$44.748' | $8^0$04.027' | 1665 | - | 21.6 | 520 | - | Lac. Sediment |
| DW5 | WOLIMBULA | $38^0$43.291' | $8^0$01.767' | 1660 | 36 | 35 | 800 | 1987 | Lac. Sediment |
| DW6 | ABOSA | $38^0$43.250' | $8^0$01.200' | 1650 | 27.6 | 26.6 | 800 | - | Alluvium |
| DW7 | SOUTH OF ABOSA | $38^0$43.080' | $8^0$00.510' | 1650 | 22.6 | 22.6 | - | - | Alluvium |
| DW8 | CHEFE JILA | $38^0$50.720' | $7^0$51.150' | 1640 | 3 | 1.7 | 1250 | - | Alluvium |
| DW9 | ABURA | $39^0$00.480' | $8^0$02.625' | 1690 | - | 25.8 | 640 | - | Lac. Sediment |
| DW10 | NORTH OF ABURA | $39^0$00.120' | $8^0$02.860' | 1700 | 25.2 | 24.9 | 1000 | - | Alluvium |

Springs

| Ref. No | Name of Spring | Longitude | Latitude | Elevation ASL(m) | Temp. ($^0$c) | Approximate Flow(l/s) | Mode of Emergence | Lithology |
|---|---|---|---|---|---|---|---|---|
| CS1 | Gonde | $39^0$11.745' | $8^0$01.525' | 2265 | - | 30 | Contact | Ignimbrite |
| CS2 | Burkitu | $39^0$05.777' | $7^0$59.630' | 2120 | - | 10.5 | Depression | Ignimbrite |
| TS1 | Tulu Gudo | - | - | - | 60 | 0.1 | Volcanic | Basalt |
| TS2 | Tulu Gudo | - | - | - | 78 | Small | Volcanic | Basalt |

BW - Bore Well
DW- Hand Dug Well
CS - Cold Spring
TS - Thermal Spring

SWL - Static Water Level
DWL - Dynamic Water Level
ASL - Above Sea Level
BGS - Below Ground Surface

# Appendix 10

## Chemical Analyses Results of Waters in The Studied Area

Bore Wells

| Ref. No | Name of Well | Date | EC in μs/cm | pH | Alkalinity as $CaCO_3$ | Hardness as $CaCO_3$ | $SiO_2$ | $Na^+$ | $K^+$ | $Ca^{2+}$ | $Mg^{2+}$ | $Cl^-$ | $F^-$ | $HCO_3^-$ | $SO_4^{2-}$ | TDS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| BW1 | MEKI TOWN [L.V.I.A] | July 1997 | 627 | 7.8 | | 136 | | 25.2 | 2.83 | 42 | 7.58 | 10.5 | 1.37 | | | |
| BW3 | MEKI MUNICIPALITY * | May 1981 | - | 7.8 | | 139 | 75 | 73 | 4 | 46 | 6 | 14.0 | 1.3 | 355 | 3 | 579 |
| BW5 | GARABA GARSO | July 1997 | 1622 | 7.8 | | 15 | | 175 | | 4.8 | 3.2 | 74.6 | 6.84 | | | |
| BW7 | ATE FNURI # | May 1993 | - | 7.3 | 340 | 20 | 88 | 152 | 8 | 5 | 2 | 13.0 | 7.0 | 415 | neg | 690 |
| BW8 | LALUNA DERO | July 1997 | 673 | 7.9 | # 320 | 73 | # 100 | 56.5 | 9.48 | 24 | 3.24 | 3.0 | 4.03 | # 390 | # neg | 590 |
| BW10 | CHOROKE | July 1997 | 1459 | 8 | # 550 | 2 | # 89 | 175 | 13 | neg | 0.56 | 50.3 | 6.49 | # 672 | # 55.3 | 1062 |
| BW11 | KORKE ADI | July 1997 | 1703 | 8.3 | | 7 | | 191 | 11.7 | 1.4 | 0.83 | 13.6 | 8.86 | | | |
| BW13 | GURA GERMEGI | July 1997 | 1601 | 8.5 | # 780 | 12 | # 95.5 | 180 | 14.5 | 2.5 | 1.4 | 21.0 | 11.24 | # 951.6 | # neg | 1278 |
| BW14 | ABONNO 1 # | May 1993 | - | 8 | 900 | 40 | 88 | 394 | 18 | 6 | 6 | 25 | 12 | 1098 | neg | 1647 |
| BW15 | BADA GOSA | July 1997 | 2592 | 8.2 | | 16 | | 294 | 21.32 | 3.2 | 1.92 | 125.9 | 8.31 | | | |
| BW17 | MAGO | July 1997 | 2794 | 8.1 | | 2 | | 314 | 19.8 | neg | 0.32 | 137.3 | 7.01 | | | |
| BW18 | ZIWAY BEKELE MOLLA * | May 1981 | - | 8 | | 72 | 82 | 200 | 15 | 14 | 9 | 18 | 3.2 | 473 | 5 | 934 |
| BW20 | SEMOYE CHELEMO | July 1997 | 2563 | 8.7 | # 740 | 9 | # 100 | 262 | 13.23 | 3.6 | 0 | 137.3 | 12.34 | # 902.8 | # 338 | 1769 |
| BW21 | ELKANA METROMOFA | July 1997 | 2111 | 7.5 | | 9 | | 196 | 18.2 | neg | 2.09 | 21.0 | 9.41 | | | |

| Ref. No | Name of Well | Date | EC in μs/cm | pH | Alkalinity as $CaCO_3$ | Hardness as $CaCO_3$ | $SiO_2$ | $Na^+$ | $K^+$ | $Ca^{2+}$ | $Mg^{2+}$ | $Cl^-$ | $F^-$ | $HCO_3^-$ | $SO_4^{2-}$ | TDS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| BW23 | GUBIBA | July 1997 | 1210 | 8.8 | # 304 | | # 109 | 149 | 12.72 | neg | neg | 40.47 | 10.93 | # 370.9 | # 84.7 | 778 |
| BW24 | GALO FECHASA # | May 1995 | 1550 | 8.9 | 660 | 16 | 45 | 414.8 | 11.2 | 3.2 | 2 | 53.9 | 14 | 805.2 | 77 | 1430 |
| BW25 | HESBAWI BATELE | July 1997 | 1503 | 7.7 | | 133 | | 206 | 13.23 | 33 | 12.5 | 42.27 | 4.29 | | | |
| BW26 | ZIWAY PRISON | July 1997 | 1786 | 7.6 | | 49 | | 118 | 12.75 | 12.3 | 4.48 | 19.27 | 5 | | | |
| BW27 | KOSHE * | May 1981 | - | 7.9 | | 68 | 113 | 140 | 16 | 19 | 5 | 16 | 2.6 | 418 | 6 | 736 |
| BW29 | ZIWAY TOWN # | Dec 1990 | - | 7.5 | 600 | 64 | 90 | 251.6 | 19.8 | 19.2 | 3.9 | 21.3 | 2.4 | 732 | neg | 1154 |
| BW31 | ZIWAY PHILADELPHIA | July 1997 | 915 | 7.1 | | 81 | | 27.6 | 18.74 | 14.6 | 10.75 | | | | | |
| BW33 | GUSH GULLA # | May 1993 | - | 8 | 630 | 34 | 85 | 280.5 | 17.3 | 8 | 3.4 | 20 | 4.18 | 768.6 | neg | 1188 |
| BW34 | WORGA GARBI | July 1997 | 2366 | 8.3 | | 23 | | 212 | 21.56 | 3 | 3.67 | 84.98 | 15.1 | | | |
| BW35 | BOROMO | July 1997 | 1526 | 8.6 | # 580 | 10 | # 100 | 184 | 11.63 | 4 | 0 | 71.36 | 23.25 | # 707.6 | # 16.5 | 1118 |
| BW37 | WOYSO MACHO | July 1997 | 2357 | 7.8 | | - | - | 251 | 23.46 | neg | 0 | 149.9 | 16.36 | | | |
| BW38 | SHISHO TABO | July 1997 | 1278 | 8.2 | | 5 | | 119 | 10.08 | neg | 1.1 | 27.32 | 6.82 | | | |
| BW39 | ADAMI TULU | July 1997 | 1151 | 8.4 | | 8 | | 151 | 9.13 | neg | 1.82 | 20.13 | 6.11 | | | |
| BW40 | GARBI # | May 1993 | - | 7.4 | 460 | 252 | 64 | 190 | 10 | 91 | 6 | 119 | 1.5 | 561 | 88 | 1132 |
| BW48 | WAJI * | May 1981 | - | 7.6 | | 41 | 38 | 18 | 2 | 13 | 2 | 7 | 0.35 | 92 | 0 | 172 |
| BW49 | ELEAS * | May 1981 | - | 7.4 | | 48 | 99 | 11 | 2 | 16 | 2 | 7 | 0.1 | 79 | 0 | 216 |
| BW56 | SOUTH OF KULUMSA * | May 1981 | - | 7.7 | | 152 | 121 | 22 | 6 | 46 | 9 | 7 | 1.2 | 232 | 0 | 443 |

Hand Dug Wells

| Ref. No | Name of Well | Date | EC in μs/cm | pH | Alkalinity as $CaCO_3$ | Hardness as $CaCO_3$ | $SiO_2$ | $Na^+$ | $K^+$ | $Ca^{2+}$ | $Mg^{2+}$ | $Cl^-$ | $F^-$ | $HCO_3^-$ | $SO_4^{2-}$ | TDS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| DW1 | NORTH OF MEKI * | May 1981 | - | - | | 89 | 75 | 400 | 20 | 21 | 9 | 140 | 10 | 930 | 10 | 1617 |
| DW2 | MEKI TOWN * | May 1981 | - | 7.4 | | 183 | 77 | 28 | 5 | 69 | 3 | 8 | 0.7 | 300 | 2 | 493 |
| DW3 | CHEFE * | May 1981 | - | 8 | | 140 | 68 | 165 | 20 | 43 | 8 | 16 | 1.9 | 519 | 23 | 867 |
| DW4 | ABONNO | July 1997 | 1923 | # 8.3 | # 540 | 8 | # 110 | 184 | 15.75 | 1.4 | 1.11 | 20.13 | 8.37 | # 658.8 | # 87.7 | 1087 |
| DW5 | WOLIMBULA | July 1997 | 2218 | 7.7 | | - | - | 212 | 18.2 | neg | neg | 54.93 | 10.33 | - | - | - |
| DW6 | ABOSA * | May 1981 | - | 8 | | 85 | 98 | 456 | 20 | 21 | 8 | 129 | 2.1 | 996 | 74 | 1806 |
| DW8 | CHEFE JILA * | May 1981 | - | 8 | | 147 | 43 | 345 | 33 | 36 | 14 | 48 | 10 | 1007 | 33 | 1571 |
| DW9 | ABURA | July 1997 | 406 | - | | 62 | - | 20.82 | 7.94 | 18 | 4.18 | 8.78 | 2.21 | - | - | - |
| DW10 | NORTH OF ABURA * | May 1981 | - | 7 | | 74 | 77 | 50 | 6 | 23 | 4 | 4 | 2.6 | 237 | 3 | 407 |

Springs

| Ref. No | Name of Spring | Longitude | Latitude | Temp. $(^{0}c)$ | Flow (l/s) | pH | $CO_2$ | $HCO_3$ | K | Na | Ca | Mg | F | Cl | $SO_4$ | $SiO_2$ | Hardness | TDS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CS1 | GONDE * | $39^{0}11.745'$ | $8^{0}01.525'$ | - | 30 | - | 3 | 56 | 3 | 6 | 10 | 3.5 | 0.2 | 10 | 5 | 39 | 39.4 | 140 |
| CS2 | BURKITU * | $39^{0}05.777'$ | $7^{0}59.630'$ | - | 10.5 | - | 3 | 89 | 3 | 8 | 14 | 5 | 0.3 | 3 | 6 | 49 | 55.58 | 185 |
| TS1 | TULU GUDO ISLAND ** | - | - | 60 | 0.1 | 7.6 | 208 | 704 | 25 | 240 | 15 | 8 | 7 | 31 | < 10 | 159 | 70.42 | 1404 |
| TS2 | TULU GUDO ISLAND ** | - | - | 78 | Small | 8.2 | 58 | 988 | 38 | 400 | 8 | 5 | 5 | 95 | 31 | 176 | 40.58 | 1804 |

Surface Waters

| Ref. No | Location | Longitude | Latitude | Date | EC in µs/cm | pH | $CaCO_3$ Hardness | $SiO_2$ | Na | K | Ca | Mg | Cl | F | $HCO_3$ | $SO_4$ | TDS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| B1 | BULBULA RIVER AT KERKERSITU | 38$^0$43.528' | 7$^0$51.335' | July 1997 | 498 | 8.3 ** | 58 | 39 ** | 30.82 | 11.75 | 14.2 | 5.41 | 15.49 | 1.39 | 195 ** | <10 ** | 318 |
| K1 | KETAR RIVER AT ABURA | 39$^0$01.141' | 8$^0$02.003' | July 1997 | 203 | | 90 | | 4.25 | 3.75 | 30 | 3.67 | 4.56 | 0.58 | | | |
| K2 | KETAR RIVER AT FETI | 39$^0$03.361' | 7$^0$84.153' | July 1997 | 117 | | 68 | | 2.06 | 3.91 | 24 | 1.92 | 4.77 | 0.77 | | | |
| M1 | MEKI RIVER AT MEKI | 38$^0$49.285' | 8$^0$09.053' | July 1997 | 438 | 8.5 ** | 122 | 30 ** | 16.83 | 7.62 | 38 | 6.6 | 15.49 | 0.95 | 232 ** | <10 ** | 353 |
| NS1 | NORTH SHORE OF ZIWAY LAKE | 38$^0$55.245' | 8$^0$07.563' | July 1997 | 2788 | | 60 | | 274.1 | 36.64 | 17.7 | 3.74 | 50.33 | 7.72 | | | |
| Z1 | ZIWAY LAKE 01 | 38$^0$43.748' | 7$^0$55.494' | July 1997 | 475 | * 7.6 | 67 | * 41 | 28.14 | 11.14 | 16.8 | 5.94 | 14.83 | 1.22 | * 244 | * 1 | 364 |
| Z2 | ZIWAY LAKE 02 | 38$^0$47.439' | 7$^0$52.265' | July 1997 | 463 | | 67 | | 27.62 | 11.96 | 17.2 | 5.71 | 13.59 | 1.41 | | | |

Unit is mg/l unless otherwise stated
# - Data taken from L.V.I.A
* - Data taken from Tesfaye C. (1982)
** - Data taken from UN 1973
- indicates not analysed
neg - negligible
BW - Bore Well
DW - Dug Well
CS - Cold Spring
TS - Thermal Spring

Chemical Analyses Results in meq/l

| Ref. No | Location | $Na^+$ | $K^+$ | $Ca^{2+}$ | $Mg^{2+}$ | $Cl^-$ | $F^-$ | $HCO_3^-$ | $SO_4^{2-}$ |
|---|---|---|---|---|---|---|---|---|---|
| BW1 | MEKI TOWN [L.V.I.A] | 1.10 | 0.07 | 2.10 | 0.62 | 0.30 | 0.07 | - | - |
| BW3 | MEKI MUNICIPALITY | 3.18 | 0.10 | 2.30 | 0.49 | 0.40 | 0.07 | 5.82 | 0.06 |
| BW5 | GARABA GARSO | 7.61 | 0.34 | 0.24 | 0.26 | 2.10 | 0.36 | - | - |
| BW7 | ATE FNURI | 6.61 | 0.21 | 0.25 | 0.17 | 0.37 | 0.37 | 6.80 | neg |
| BW8 | LALUNA DERO | 2.46 | 0.24 | 1.20. | 0.27 | 0.08 | 0.21 | 6.39 | neg |
| BW10 | CHOROKE | 7.61 | 0.33 | neg | 0.05 | 1.42 | 0.34 | 11.01 | 1.15 |
| BW11 | KORKE ADI | 8.31 | 0.30 | 0.07 | 0.07 | 0.38 | 0.47 | - | - |
| BW13 | GURA GERMEGI | 7.83 | 0.37 | 0.13 | 0.12 | 0.59 | 0.59 | 15.60 | neg |
| BW14 | ABONNO 1 | 17.14 | 0.46 | 0.30 | 0.49 | 0.71 | 0.63 | 18.00 | neg |
| BW15 | BADA GOSA | 12.79 | 0.55 | 0.16 | 0.16 | 3.55 | 0.44 | - | - |
| BW17 | MAGO | 13.66 | 0.51 | neg | 0.03 | 3.87 | 0.37 | - | - |
| BW18 | ZIWAY BEKELE MOLLA | 8.70 | 0.38 | 0.70 | 0.74 | 0.51 | 0.17 | 7.75 | 0.10 |
| BW20 | SEMOYE CHELEMO | 11.40 | 0.34 | 0.18 | 0 | 3.87 | 0.65 | 14.80 | 7.04 |
| BW21 | ELKANA METROMOFA | 8.53 | 0.47 | neg | 0.17 | 0.59 | 0.50 | - | - |
| BW23 | GUBIBA | 6.48 | 0.33 | neg | neg | 1.14 | 0.58 | 6.08 | 1.76 |
| BW24 | GALO FECHASA | 18.04 | 0.29 | 0.16 | 0.17 | 1.52 | 0.74 | 13.94 | 1.60 |
| BW25 | HESBAWI BATELE | 8.96 | 0.34 | 1.65 | 1.03 | 1.19 | 0.23 | - | - |
| BW26 | ZIWAY PRISON | 5.13 | 0.33 | 0.61 | 0.37 | 0.54 | 0.26 | - | - |
| BW27 | KOSHE | 6.07 | 0.41 | 0.95 | 0.41 | 0.45 | 0.14 | 6.85 | 0.13 |
| BW29 | ZIWAY TOWN | 10.95 | 0.51 | 0.96 | 0.32 | 0.60 | 0.13 | 12.00 | neg |
| BW31 | ZIWAY PHILADELPHIA | 1.20 | 0.48 | 0.73 | 0.89 | - | - | - | - |
| BW33 | GUSH GULLA | 12.20 | 0.44 | 0.40 | 0.28 | 0.56 | 0.22 | 12.60 | neg |
| BW34 | WORGA GARBI | 9.22 | 0.55 | 0.15 | 0.30 | 2.40 | 0.80 | - | - |
| BW35 | BOROMO | 8.00 | 0.30 | 0.20 | 0 | 2.01 | 1.22 | 11.60 | 0.34 |
| BW37 | WOYSO MACHO | 10.92 | 0.60 | neg | 0 | 4.23 | 0.86 | - | - |
| BW38 | SHISHO TABO | 5.18 | 0.26 | neg | 0.09 | 0.77 | 0.36 | - | - |
| BW39 | ADAMI TULU | 6.57 | 0.23 | neg | 0.15 | 0.57 | 0.32 | - | - |
| BW40 | GARBI | 8.27 | 0.26 | 4.54 | 0.49 | 3.36 | 0.08 | 9.20 | 1.83 |
| BW48 | WAJI | 0.78 | 0.05 | 0.65 | 0.17 | 0.20 | 0.02 | 1.51 | 0 |
| BW49 | ELEAS | 0.48 | 0.05 | 0.80 | 0.17 | 0.20 | 0.01 | 1.30 | 0 |
| BW56 | SOUTH OF KULUMSA | 0.96 | 0.15 | 2.30 | 0.74 | 0.20 | 0.06 | 3.80 | 0 |

Chemical Analyses Results in meq/l

| Ref. No | Location | $Na^+$ | $K^+$ | $Ca^{2+}$ | $Mg^{2+}$ | $Cl^-$ | $F^-$ | $HCO_3^-$ | $SO_4^{2-}$ |
|---|---|---|---|---|---|---|---|---|---|
| DW1 | NORTH OF MEKI | 17.4 | 0.51 | 1.05 | 0.74 | 3.95 | 0.53 | 15.24 | 0.21 |
| DW2 | MEKI TOWN | 1.22 | 0.13 | 3.44 | 0.25 | 0.23 | 0.04 | 4.92 | 0.04 |
| DW3 | CHEFE | 7.18 | 0.51 | 2.15 | 0.66 | 0.45 | 0.10 | 8.51 | 0.48 |
| DW4 | ABONNO | 8.00 | 0.40 | 0.07 | 0.09 | 0.57 | 0.44 | 10.80 | 1.83 |
| DW5 | WOLIMBULA | 9.22 | 0.47 | neg | neg | 1.55 | 0.54 | - | - |
| DW6 | ABOSA | 19.84 | 0.51 | 2.15 | 0.66 | 3.64 | 0.11 | 16.32 | 1.54 |
| DW8 | CHEFE JILA | 15.01 | 0.84 | 1.80 | 1.15 | 1.35 | 0.53 | 16.51 | 0.69 |
| DW9 | ABURA | 0.91 | 0.20 | 0.90 | 0.34 | 0.25 | 0.12 | - | - |
| DW10 | NORTH OF ABURA | 2.18 | 0.15 | 1.15 | 0.33 | 0.11 | 0.14 | 3.88 | 0.06 |
| CS1 | GONDE | 0.26 | 0.08 | 0.50 | 0.29 | 0.28 | 0.01 | 0.92 | 0.10 |
| CS2 | BURKITU | 0.35 | 0.08 | 0.70 | 0.41 | 0.09 | 0.02 | 1.46 | 0.13 |
| TS1 | TULU GUDO ISLAND | 10.44 | 0.64 | 0.75 | 0.66 | 0.88 | 0.37 | 11.54 | < 0.21 |
| TS2 | TULU GUDO ISLAND | 17.40 | 0.97 | 0.40 | 0.41 | 2.68 | 0.26 | 16.19 | 0.65 |
| B1 | BULBULA RIVER | 1.34 | 0.30 | 0.71 | 0.45 | 0.44 | 0.07 | 3.20 | < 0.21 |
| K1 | KETAR RIVER | 0.19 | 0.10 | 1.50 | 0.30 | 0.13 | 0.03 | - | - |
| K2 | KETAR RIVER | 0.09 | 0.10 | 1.20 | 0.16 | 0.14 | 0.04 | - | - |
| M1 | MEKI RIVER | 0.73 | 0.20 | 1.90 | 0.54 | 0.44 | 0.05 | 3.80 | < 0.21 |
| NS1 | NORTH SHORE OF ZIWAY | 11.92 | 0.94 | 0.88 | 0.31 | 1.42 | 0.41 | - | - |
| Z1 | ZIWAY LAKE 01 | 1.22 | 0.29 | 0.84 | 0.49 | 0.42 | 0.06 | 4.00 | 0.02 |
| Z2 | ZIWAY LAKE 02 | 1.20 | 0.31 | 0.86 | 0.47 | 0.38 | 0.07 | - | - |

## Appendix 11

### Data for Water Classification by Using Trilinear Diagram

| | Cations | | | | Anions | | | |
|---|---|---|---|---|---|---|---|---|
| Ref. No | % Na + K | % Ca | % Mg | Total | % $HCO_3$ | % Cl | % $SO_4$ | Total |
| BW3 | 59.6 | 35.7 | 4.7 | 100 | 95.4 | 3.8 | 0.8 | 100 |
| BW7 | 95.8 | 3 | 1.2 | 100 | 97 | 3 | 0 | 100 |
| BW8 | 71.3 | 25.5 | 3.2 | 100 | 99.2 | 0.8 | 0 | 100 |
| BW10 | 99.5 | 0 | 0.5 | 100 | 86.5 | 6.4 | 7.1 | 100 |
| BW13 | 98.0 | 1.5 | 0.5 | 100 | 97.8 | 2.2 | 0 | 100 |
| BW14 | 97.2 | 1.4 | 1.4 | 100 | 97.8 | 2.2 | 0 | 100 |
| BW18 | 90.2 | 5.9 | 3.9 | 100 | 95.4 | 3.6 | 1 | 100 |
| BW20 | 98.6 | 1.4 | 0 | 100 | 65.6 | 9.9 | 24.5 | 100 |
| BW23 | 100 | 0 | 0 | 100 | 74.7 | 8.2 | 17.1 | 100 |
| BW24 | 98.8 | 0.7 | 0.5 | 100 | 86.0 | 5.8 | 8.2 | 100 |
| BW27 | 86.6 | 10.6 | 2.8 | 100 | 95.0 | 3.6 | 1.4 | 100 |
| BW29 | 92.2 | 6.4 | 1.4 | 100 | 97.2 | 2.8 | 0 | 100 |
| BW33 | 96.4 | 2.6 | 1.0 | 100 | 97.5 | 2.5 | 0 | 100 |
| BW35 | 98.0 | 2.0 | 0 | 100 | 89.0 | 8.9 | 2.1 | 100 |
| BW40 | 67.4 | 30.6 | 2.0 | 100 | 73.0 | 15.5 | 11.5 | 100 |
| BW48 | 57.1 | 37.1 | 5.7 | 100 | 92.9 | 7.1 | 0 | 100 |
| BW49 | 41.9 | 51.6 | 6.5 | 100 | 91.9 | 8.1 | 0 | 100 |
| BW56 | 33.8 | 55.4 | 10.8 | 100 | 97.1 | 2.9 | 0 | 100 |
| DW1 | 93.3 | 4.7 | 2.0 | 100 | 86.1 | 13.0 | 0.9 | 100 |
| DW2 | 31.4 | 65.7 | 2.9 | 100 | 96.8 | 2.6 | 0.6 | 100 |
| DW3 | 78.4 | 18.2 | 3.4 | 100 | 93.0 | 2.9 | 4.1 | 100 |
| DW4 | 98.8 | 0.7 | 0.5 | 100 | 86.0 | 2.6 | 11.4 | 100 |
| DW6 | 94.2 | 4.2 | 1.6 | 100 | 83.0 | 10.8 | 6.2 | 100 |
| DW8 | 88.3 | 8.4 | 3.3 | 100 | 92.6 | 4.4 | 3.0 | 100 |
| DW10 | 67.5 | 27.7 | 4.8 | 100 | 97.2 | 1.6 | 1.2 | 100 |
| CS1 | 39.1 | 43.5 | 17.4 | 100 | 78.9 | 14.1 | 7.0 | 100 |
| CS2 | 36.6 | 46.7 | 16.7 | 100 | 90.8 | 3.1 | 6.1 | 100 |
| TS1 | 92.0 | 5.2 | 2.8 | 100 | 95.0 | 4.2 | 0.8 | 100 |
| TS2 | 97.1 | 1.8 | 1.1 | 100 | 88.7 | 8.5 | 2.8 | 100 |
| B1 | 68.3 | 22.5 | 9.2 | 100 | 89.8 | 7.4 | 2.8 | 100 |
| M1 | 35.7 | 54.3 | 10.0 | 100 | 91.3 | 6.3 | 2.4 | 100 |
| Z1 | 62.8 | 27.4 | 9.8 | 100 | 93.8 | 5.8 | 0.4 | 100 |

## Appendix 12

## Lithological Log Data of Bore Wells in The Studied Area

BW2 - Meki Town Keb.03

| Depth (m) | Lithologic Description |
|---|---|
| 4 | clay |
| 11 | cobble |
| 25 | clay sand |
| 29 | sand |
| 43 | sand and gravel |
| 50 | clay |
| 58 | cobble and sand |
| 72 | sand |
| 78 | rhyolite |

BW8 - Laluna Dero

| Depth (m) | Lithologic Description |
|---|---|
| 3 | Brown clay |
| 12 | pumaceous tuff |
| 21 | clayey volcanic ash |
| 27 | dark welded tuff |
| 36 | sandy clay |
| 45 | fractured and weathered ignimbrite |
| 48 | volcanic ash |
| 66 | fractured and weathered ignimbrite with quartz grains |
| 72 | volcanic ash with rock fragments |
| 78 | fractured and weathered ignimbrite with quartz grains |
| 84 | clayey volcanic ash |
| 94 | clay |
| 100 | weathered ignimbrite |

BW13 - Gura Germagi

| Depth (m) | Lithologic Description |
|---|---|
| 1.2 | sandy clay soil |
| 4 | pumice gravel and sand |
| 16.5 | quartz sand with pumice dust |
| 47 | very fine pumice sand with some blocks of pumice |

BW14 - Abonno 1

| Depth (m) | Lithologic Description |
|---|---|
| 2 | brown sandy clay soil |
| 9 | pumice with sand pebbles |
| 29.5 | volcanic ash with pumice pubbles |
| 39 | fresh tuff with some pumice blocks |
| 50.4 | fine sand with volcanic ash |

BW20 - Semoye Chelemo

| Depth (m) | Lithologic Description |
|---|---|
| 3 | clayey volcanic ash |
| 12 | volcanic ash |
| 27 | clayey volcanic ash |
| 33 | volcanic ash |
| 42 | clayey volcanic ash |
| 48 | weathered ignimbrite |
| 60 | volcanic ash |
| 100 | volcanic ash slightly compacted at the top and sandy at the bottom |

BW23 - Gubiba

| Depth (m) | Lithologic Description |
|---|---|
| 6 | yellowish clay |
| 33 | volcanic ash |
| 42 | sandy volcanic ash |
| 122 | volcanic ash |
| 136 | fractured ignimbrite |
| 166 | slightly fractured welded tuff |
| 178 | highly weathered volcanic rock |
| 187 | slightly fractured ignimbrite |
| 190 | weathered ignimbrite |
| 196 | slightly fractured ignimbrite |
| 199.2 | fractured ignimbrite |

BW24 - Gallo Fechasa

| depth (m) | Lithologic Description |
|---|---|
| 3 | yellowish clay |
| 12 | Volcanic ash with Yellowish clay |
| 18 | loosely compacted volcanic ash |
| 36 | volcanic ash with obsidian fragments |
| 42 | paleosoil and plant roots |
| 48 | volcanic ash |
| 54 | ignimbrite |
| 60 | highly weathered volcanic rock |
| 78 | slightly weathered ignimbrite |
| 84 | volcanic ash with clay |
| 108 | sandy volcanic ash with some rock fragments |

BW26 - Ziway Prison

| depth (m) | Lithologic Description |
|---|---|
| 1 | sandy clay soil and fresh brown tuff |
| 6 | tuff with some sand and pumice |
| 40 | pumice blocks with numerous holes and soft brown tuff |
| 61.5 | soft pumice blocks |

BW29 - Ziway Town

| Depth (m) | Lithologic Description |
|---|---|
| 2 | grey sandy clay soil |
| 4 | soft brown tuff |
| 27 | quartz sand with grey fine pumice |
| 60 | tuff and brown pumice |

BW30 - Worga Batele

| Depth (m) | Lithologic Description |
|---|---|
| 2.5 | sandy clay soil |
| 11 | brown tuff |
| 19 | sand with fine pumice |
| 22 | pumice gravel |
| 61 | quartz sand with pumice |

BW31 - Ziway Philadelphia

| Depth (m) | Lithologic Description |
|---|---|
| 1 | sandy clay soil |
| 4 | brown tuff |
| 33 | sandy quartz with grey fine pumice |
| 42 | tuff with brown pumice |
| 46 | fine brown sandy quartz |

BW39 - Adami Tulu

| Depth (m) | Lithologic Description |
|---|---|
| 1 | brown sandy clay |
| 36 | volcanic ash with fine brown sand |
| 37.5 | volcanic agglomerate |
| 50 | pumaceous tuff |
| 62 | pumice with fine sand |
| 65 | hard tuff and agglomerate |

BW40 - Garbi

| Depth (m) | Lithologic Description |
|---|---|
| 2 | sandy clay soil |
| 36 | black volcanic agglomerate |

BW47 - Woraseni

| Depth (m) | Lithologic Descriptions |
|---|---|
| 7.3 | yellow soft tuff |
| 9.3 | light grey tuff or ignimbrite |
| 19.2 | brown silt |
| 28.7 | light brown sandy clay |
| 34 | light brown silty sand with large grain basalt pieces |
| 50 | grey tuff |
| 55 | red clay fossil soil and basalt flow |
| 93.7 | brown fine to coarse grained sand |
| 99 | grey sandy and silty ash |
| 104.7 | yellow silty ash |
| 134.4 | yellowish silty sand with basalt pieces |
| 141 | brown clayey sand with grain of basalt and tuff pieces |
| 150.5 | dark grey fine sand with some ignimbrite pieces |
| 159 | coarse sand with basalt pieces |
| 168 | brown fine sand |

BW49 - Eleas

| Depth (m) | Lithologic Description |
|---|---|
| 9 | red clay soil |
| 15.1 | white tuff |
| 18.5 | brown sandy clay |
| 23.5 | unwelded brown tuff |
| 35.7 | grey tuff |
| 45.6 | partly vesicular basalt |
| 50 | basalt |
| 80 | grey tuff |
| 84.1 | red clay fossil soil and weathered basalt |
| 103.4 | fresh basalt |

BW50 - Assela(near police HQ)

| Depth (m) | Lithologic Description |
|---|---|
| 3 | brown clayey soil |
| 6 | grey weathered tuff |
| 12 | reddish brown sand |
| 22.9 | dark grey trachybasalt |
| 25.2 | reddish clay |
| 29.6 | dark grey weathered trachybasalt |
| 35.3 | basalt |
| 38.5 | brown sandy clay |
| 40.7 | grey sand of basic composition |
| 51.3 | reddish yellow sandy clay |
| 55.4 | light brown silty sand |
| 60.3 | dark grey weathered basalt |
| 70.4 | gravely sand of basic composition |
| 75.8 | grey gravely sand |
| 87.6 | dark grey basalt |
| 128 | light brown basalt |

BW56 - South of Kulumsa

| Depth (m) | Lithologic Description |
|---|---|
| 5.5 | |
| 12 | reddish weathered ignimbrite |
| 18 | grey fresh ignimbrite |
| | brown silty sand |
| 34 | grey tuff |
| 40 | reddish grey sand of variable grain size |
| 66 | dark grey fresh ignimbrite |
| 101 | grey fresh tuff or ignimbrite |
| 120 | fresh basalt |

BW59 - NW of Kulumsa

| Depth (m) | Lithologic Description |
|---|---|
| 1.7 | yellowish brown silty soil |
| 3 | light grey tuff |
| 6.5 | yellowish brown weathered tuff |
| 13.8 | light grey silty sand |
| 16.8 | yellowish brown weathered tuff |
| 32.1 | greyish tuff or ignimbrite |
| 36.8 | light yellowish brown sandy silt |
| 55.4 | greyish tuff or ignimbrite |
| 60 | brown tuff |
| 84.6 | light grey tuff |
| 100 | reddish brown sandy clay |
| 105 | grey coarse sand |
| 109.5 | white tuff |
| 112.5 | dark grey pumiceous tuff |
| 121 | yellowish white volcanic ash |
| 132.6 | light brown volcanic sand |
| 141.5 | light brown silty sand |
| 158 | scoraceous basalt |
| 165 | brown clayey sand |

BW60 - Abura School

| Depth (m) | Lithologic Description |
|---|---|
| 1.5 | white gravel of pumice with some silt |
| 27.5 | black clay |
| 63.1 | white calcareous clay |

## DECLARATION

I declare that this thesis is my original work and that all sources of material used in the thesis are duly acknowledged.

Haile Gashaw