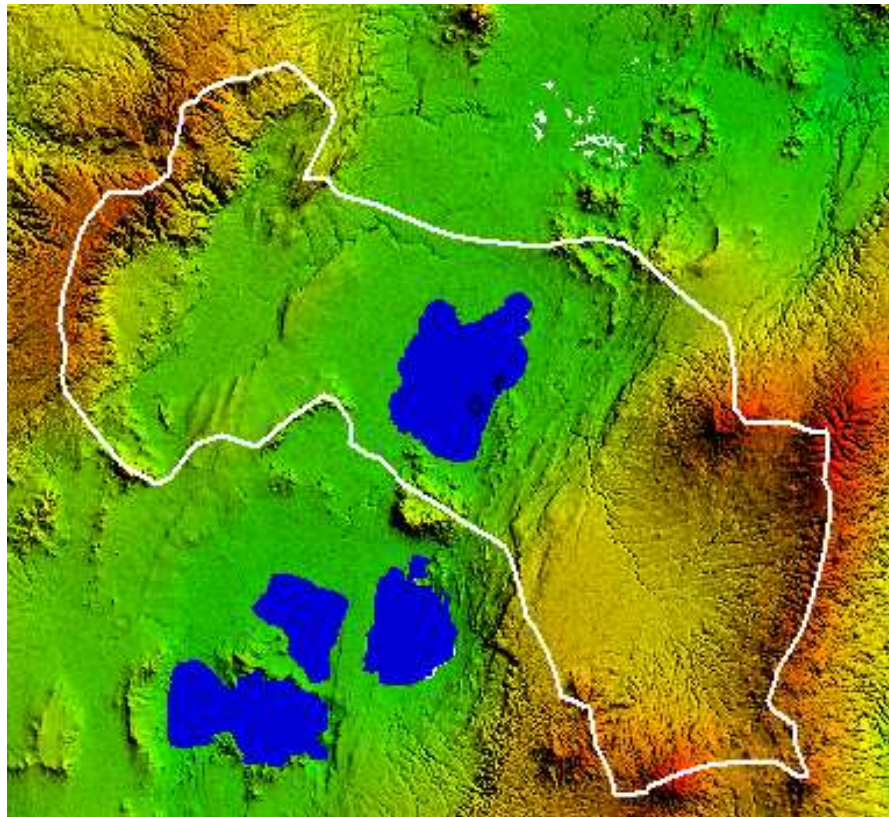


ADDIS ABABA INSTITUTE OF TECHNOLOGY  
DEPARTMENT OF CIVIL AND ENVIROMENTAL ENGINEERING

**GROUNDWATER–SURFACE WATER INTERACTION  
IN THE CASE OF LAKE ZIWAY CATCHMENT**



AN INDEPENDENT PROJECT SUBMITTED TO ADDIS ABABA INSTITUTE OF  
TECHNOLOGY DEPARTMENT OF CIVIL & ENVIROMENTAL ENGINEERING FOR  
THE DEGREE OF MASTERS IN HYDRAULIC ENGINEERING

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## **ABSTRACT**

Lake Zeway catchment is located in the northern part of the Central Main Ethiopian rift valley bounded in west and north by Awash basin; and in east by Wabi shebele catchment. Meki and Katar are the main rivers draining western and eastern part of the catchment respectively and both feed Lake Ziway before outflow to Bulbula River in south west. According to the data collected from the National Meteorological Service Agency area has mean annual precipitation, potential evapotranspiration and actual evapotranspiration of 887mm, 1284mm and 856mm respectively.

Direct groundwater recharge of the catchment was estimated using soil moisture budgeting method.

Groundwater and surface water interaction in the area have been analyzed using groundwater table contour method. The analysis result shows that Meki River in volcano-lacustrine deposit of rift floor and Katar River in Upper and Central Wonji Fault Belt are losing reaches. In the rest of the catchment areas, the rivers and streams are gaining reaches. This facts are important in identifying the reaches which are continuously recharged by the ground water. These reaches are favorable for abstraction because their potential is continuously being recharged. On the other hand for the losing reaches this information helps us to avoid over abstraction.

## CHAPTER ONE

### INTRODUCTION

#### 1.1 Background

Groundwater and surface water are essentially one resource, physically connected by the hydrologic cycle. Although the water law and water policy often consider groundwater and surface water as separate resources, groundwater and surface water are functionally interdependent. Ground water and surface water interactions are controlled by their hydraulic connection. (California Department of Water Resource)

Scientists estimate that there are over 1 billion cubic kilometers of water on this earth which covers nearly three-fourth of the earth's surface. Though this seems an inordinately huge amount, in actual fact, less than 1% is fresh and usable and is found in lakes, ponds, rivers and groundwater. Of the remaining, 97 % is found in oceans and 2 % is locked up in glaciers and icecaps. (Natural Resources Conservation Law by Siaram Bhat).

That is why management of water resources is a crucial issue to sustain life.

In Ethiopia, the National Water Resource Policy is dedicated to promote the efficient management of water resource to attain a sustainable source of consumable water.

According to the Ethiopian Ministry of Water and Energy, Ethiopia has 12 river basins. The Ethiopian rift valley is responsible for the creation of the lake basin and determining the direction of flow of some of rivers that terminate in the rift-valley system.

## **1.2 Statement of the Problem**

Due to increase in population and drastic climate change, the capacity of the readily available water to satisfy the demand is in jeopardy. In lake Zeway catchment, the impact is more pronounced in the downstream areas where there is poor groundwater development and the people have been using surface water for home consumption and their livestock.

In order to allocate the required amount of water, first the total available water resources have to be studied meticulously. Information about the temporal and spatial distribution, as well as dynamics of the resource, is important to plan for areas of more feasible development; and the alternative uses of the available resources. With equal importance, the cause of depletion of available water has to be known and addressed accordingly.

This research is intended to give a different insight on how to deal with these problems.

## **1.3 Research Objectives**

### **1.3.1- General Objective**

The general objective of this study is to analyze and understand ground water-surface water interaction.

### **1.3.2 – Specific Objectives**

The specific objectives are the following:

1. To evaluate groundwater - surface water interaction and indirect groundwater recharge in the catchment, it is called indirect because the source of the recharge is other than direct rainfall.
2. To estimate direct groundwater recharge of Lake Zeway basin. It is called direct because the source of the recharge is direct rainfall.
3. To assess changes in hydrology of the catchment.

## **CHAPTER TWO**

### **LITERATURE REVIEW**

#### **2.1 Groundwater-Surface Interaction Studies around Zeway Catchment**

The Central Ethiopian Rift-Valley, where lake Zeway catchment is located, has been a center of study in many disciplines. For instance geology, volcano-tectonics, hydrogeology, hydrology and water resource potential assessment which directly or indirectly related to the current study. Some of the works are briefly described as follows:

##### **Assessment Of Lake Ziway Water Balance by Amare Mazengia (June 2008)**

The main objective of this study is to assess the water balance components of the Lake Ziway. This activity is performed applying the continuity equation. The monthly water budget of lake Ziway is determined from rainfall, evaporation, estimated inflow from un gauged and gauged inflow and out flow from the lake. Average rainfall for the area was estimated using Thiessen polygon. Evaporation was estimated using Cropwat, Penman combination and Pitche reading. Inflow from the un gauged is developed using area ratio method and for the gauged data was taken from ministry of Water Resources, department of hydrology.

The model was developed using the values from each water balance component and the main components of Lake Ziway water balance quantified are Katar, Meki & Bulbula River runoff, runoff from un-gauged sub-catchment of the lake, precipitation on the lake surfaces, Evaporation from the lake surface and abstractions from the lake.

The simulation of lake level variations (1980-2005) has been conducted through modeling at monthly time stapes. The total annual inflow to the lake is equals 1106.91MCM and the total annual outflow from the lake equals 1,050.35MCM. Final result of the water balance simulation for the lake has shown that 77.5% of the inflow is lost as evaporation.

In conclusion it is recommended to look for an engineering solution that could be economically be used to reduce evaporation, over utilizations and sedimentations.

## **Numerical Groundwater Flow Modeling of the Meki River Catchment, Central Ethiopia by Dereje Birhanu (October 2011)**

This work is summarized as follows. The Meki river catchment aquifer is located in the central Ethiopian rift valley. This unconfined aquifer is one of the most important groundwater reservoirs of the country. A total catchment of 2319 km<sup>2</sup> was selected to study the groundwater flow system using a numerical groundwater flow model (Processing Modflow Pro (Version 8.0.15)). A three dimensional steady-state finite difference groundwater flow model is used to quantify the groundwater fluxes and analyze the subsurface hydrodynamics in the Meki river catchment by giving emphasis to the well field that supplies water to the community. The area is characterized by Quaternary volcanics covered with lacustrine, alluvial, talus, and pyroclastic deposits. The model is calibrated using head observations from 95 wells. The simulation is made in a one layer unconfined aquifer with spatially variable recharge and hydraulic conductivities under well-defined boundary conditions. The calibrated model is used to forecast groundwater flow pattern, the interaction of groundwater and surface water, and evaluate the behavior of the groundwater system under possible future utilization scenarios . A sensitivity analysis conducted indicates that the model is more sensitive to decrease in recharge and increase in hydraulic conductivity but less sensitive to increment or decrement of pumpage.

The simulation result indicates that the groundwater flows from western escarpment to east directions finally join Lake Ziway. Lakes and rivers play important role in recharging the aquifer. Simulations made under different possible future utilization scenarios including increase in pumping rate results in substantial regional groundwater level decline, which will lead to the drying of springs, and shallow hand dug wells. It has also implications of reversal of flow from contaminated rivers in to productive aquifers close to main river courses; decrease in recharge caused more inflow from Lakes as well as increase stream flow but decrease drains, and disappearance of Lake Tuffa results in increased recharge and groundwater outflow through springs. The sensitivity and scenario analysis provided important information on the data gaps and the specific sites to be selected for monitoring that may be of great help for transient model development. This study has laid the foundation for developing detailed predictive groundwater model, which can be readily used for groundwater management practices.

## **Effects of Irrigation Practices and Lacustrine Aquifer Development on Water Availability in Ziway-Abijata Corridor by Tibebe Terefe (February 2007)**

The core idea of this thesis is presented as follows. Water availability is becoming a sensitive issue in the country in general. When it comes to the water stressed regions like the Main Ethiopian Rift the situation is highly aggravated. So it is timely to properly assess the water availability indicators and impact of water utilization for different purposes.

The present study area is located at the floor of the Main Ethiopian Rift, where the interconnected surface water bodies are found in a fine state of balance. The main objective of the study is to evaluate water utilization and its impact on the water resources of the area.

Abstraction from the upstream water resource will have a severe impact on the downstream water bodies. This is evident in the flow regime of River Bulbula. The interconnectivity is not limited to surface water bodies, but there is also strong interaction between surface water bodies and subsurface. So it became evident in this research work that the abstraction from subsurface has got an impact on the overall water resources.

Hydrological data interpretation from stream flow and lake level measurements clearly depicted the trend and status of the water resource in Ziway-Abijata Corridor is at risk. The risk is extreme in the case of downstream closed Lake Abijata.

Since there is no quantitative data on groundwater trend and status, qualitatively speaking still the groundwater resource base is also at risk in the Main Ethiopian Rift in general and the rift floor in particular. The conjunctive nature of the surface and subsurface water resources in the area justifies this condition.

**Streamflow sensitivity to climate and land cover changes: Meki River, Ethiopia**  
**by D. Legesse, T. A. Abiye, C. Vallet-Coulomb, and H. Abate (November 2010)**

In this thesis impacts of climate and land cover changes on stream flow were assessed using a hydrological modeling. The precipitation runoff modeling system of the US Geological Survey was modified in order to consider wetlands as a separate hydrological response unit. Initial model parameters were obtained from a previously modeled adjacent catchment and subsequent calibration and validation were carried out. The model calibration and validation periods were divided into three. The calibration period was a five years period (1981–1986). The validation period was divided into two: validation 1 (1986–1991) and validation 2 (1996–2002). Model performance was evaluated by using joint plots of daily and monthly observed and simulated runoff hydrographs and different coefficients of efficiency. The model coefficients of efficiency were 0.71 for the calibration period and 0.69 and 0.66 for validation periods 1 and 2, respectively. A “delta-change” method was used to formulate climatic scenarios. One land cover change scenario was also used to assess the likely impacts of these changes on the runoff. The results of the scenario analysis showed that the basin is more sensitive to increase in rainfall (+80% for +20%) than to a decrease (–62% for –20%). The rainfall elasticity is 4:1 for a 20% increase in rainfall while it is 3:1 for a 20% reduction. A 1.5°C increase in temperature resulted in a 6% increase in potential evapotranspiration and 13% decrease in streamflow. This indicates that the watershed is more elastic to rainfall increase than temperature. The proposed land cover scenario of converting areas between 2000 to 3000m a.s.l. to woodland also resulted in a significant decrease in streamflow (11.8%). The study showed that properly calibrated and validated models could help understand likely impacts of climate and land cover changes on catchment water balance.

## **Groundwater-Surface water interaction and Analysis of Recent Changes in Hydrologic Environment of Lake Ziway Catchment by Dr. Tenalem Ayenew, Alemu Diribssa (June 2006)**

In this thesis in order to understand the interaction between groundwater and surface water the stated computations were made. The area has mean annual precipitation, potential evapotranspiration and actual evapotranspiration of 887mm, 1284mm and 856mm respectively. Direct groundwater recharge of the catchment was estimated using empirical formula, soil moisture budgeting and groundwater balance methods. The empirical formula gives 67mm; while the results of soil moisture balance and groundwater balance are 57mm and 83mm respectively.

Groundwater and surface water interaction in the area have been analyzed using groundwater table contour, field base river discharge measurements, channel water balance and hydrographic analysis. The analysis result shows that Meki River in volcano-lacustrine deposit of rift floor and Katar River in Upper and Central Wonji Fault Belt are losing reaches. In the rest of the catchment areas, the rivers and streams are gaining reaches.

Annual and monthly lake water balances have been conducted by incorporating available and necessary parameters. In annual basis groundwater outflow is greater than groundwater inflow. The recession in groundwater inflow over outflow is higher in the months of July and August due to time lag between commencement of surface moisture and contribution of groundwater to the lake on one hand and the increase in groundwater outflow due to rising lake level on the other hand.

Assessment of recent changes in hydrologic environment has been analyzed by trends in short and long term precipitation, evaporation, abstraction, rivers discharge, lake level and direct groundwater recharge. All these parameters reveal changes of hydrologic environment; attributed both to climate change and human interference.

## **Assessment Of Water Balance of Lake Ziway and Its Temporal Variation Due To Water Abstraction by Abu Eresso (December 2010)**

The general idea of this thesis is summarized as follows, lake Ziway is locally called “Hara Danbal”, is naturally existing exorheic reservoir situated in Central Rift Valley of Ethiopia with an average water surface area of 440km<sup>2</sup>, 2.5 m average depth and total drainage area of 7488 km<sup>2</sup> and located at 1636 masl. Katar and Meki rivers are two major perennial rivers drained into the lake and Bulbula river spills out from the lake. The lake is currently used for irrigation, domestic water supply, fishing, transportation and recreation. Newly development activities around the lake and uncontrolled water abstraction from the lake have been certainly disturbed the hydrologic balance of the lake. The objective of this study was to analyze the water balance components. This activity was performed applying continuity equation of water Balance Model. The monthly water budget of lake Ziway was determined from inflow components (direct rainfall, Katar and Meki rivers and runoff from un-gauged parts part of the watershed) and outflow components (evaporation, Bulbula river and water abstraction from the lake). Average rainfall over lake Surface was estimated using simple arithmetic mean method and evaporation from the lake was assessed by Penman method while from agricultural land was estimated with CropWat. Gauged inflow, outflow from Bulbula river and lake level data were collected from Ministry of Water Resources, Department of Hydrology and inflow from un-gauged parts of the watershed was computed using area ratio method. Water abstraction from lake was estimated from irrigated land and average seasonal crop water requirements. The model was then developed using the values of each water budget components. The mean annual inflow to the lake was estimated about 1096.83Mm<sup>3</sup> and that of the outflow as 1114.30 Mm<sup>3</sup>. Evaporation consumed about 74.04% of total annual inflows while annual water abstraction consumed about 11.72% of it (inflows). The outflow from the lake to River Bulbula was estimated about 15.84% of total annual inflow components of water budget of the lake. Annual inflow components of lake water budget showed declined trend whereas outflow components (evaporation and abstraction) showed increasing trend. But recent drop in lake level was not only the effect of drought, but water abstraction had a significant role in temporal variation on lake level during average to low rainfall years. The declining of outflow of Bulbula river from this lake and rising in

annual evaporation rate from the lake water surface certainly will be responsible for changing of this Lake to endorheic lake in near future. Therefore, it is recommended to look a solution for minimization of the extent of outflow components (rate of evaporation and over utilizations of water from this lake) for its future sustainability.

### **Summarized Literature Reviews From Various Authors**

In a master plan for water resource and supplies in Chilalo Awraja, Asela, investigated both surface water and groundwater potential of the area. River discharge measurements were taken at different locations in Katar catchment (Wenner, 1972).

In the work entitled ‘Rift valley lakes integrated natural resource development master plan’, groundwater and surface water potential of the area was analyzed (HALCROW, 1989).

In the Ph.D thesis stated that, Central Ethiopian rift’, the general hydrology and hydrogeology of Ziway–Shala basin is analyzed. The study includes evaluation of groundwater and surface water interaction, water balance and recharge estimation of sub catchments (Tenalem Ayenew, 1998).

In the project study of Meki irrigation and rural development, the primary emphasis was given to the assessment of water resource potential in Meki–Abijata basin. Accordingly, hydrological analysis and lake water balance were part of the study (JICA and OIDA, 2001).

In the Ph.D thesis entitled ‘ Analysis of hydrological response of Ziway–Shala basin to changes in climate and human activities’, hydrological analysis, lake water balance, land use and land cover map is presented.

An overall account of the geology, stratigraphy, structural patterns and geological map with an approximate scale of 1:60,000 of the main Ethiopian rift with in 7<sup>0</sup> 00’ to 8<sup>0</sup> 40’N latitudes has been presented by Di Pola (1972).

A regional geological and hydrogeological map of Ziway – Shala basin. The report includes regional classification of rocks in to different permeability groups has been presented by Tesfaye Chernet (1982).

Study of Hydrogeology and Hydrology of lake Ziway area and its surroundings has been presented by Haile Gashew(1998). In this work lake water balance and hydrogeology of part of the current study area were investigated.

Geological Map of the Ziway-Shala Lakes Basin has been presented by Dainelli et al (2001),.

The current study focuses on critically estimating direct groundwater recharge. Monthly basis lake water balance calculation is the new work that supplements existing ones to provide useful information for Policy makers and general public to manage the resource on sustainable basis.

## CHAPTER THREE

### METHODOLOGY

#### 3.1 General Overview Of The Study Area

##### 3.1.1 Location and Accessibility

The study area is the northern part of Central Ethiopian Rift Valley catchment; located partly in Oromia and partly in Southern Nations and Nationality states. It extends from Gurage Mountain in the west via main Ethiopian rift valley to Mount Chilalo, Galema and Kakka of Arsi in its eastern side. The area is about 7414km<sup>2</sup> and bounded between latitude of 7°20'54" to 8°25'56" and longitude of 38°13'02" to 39°24'01".

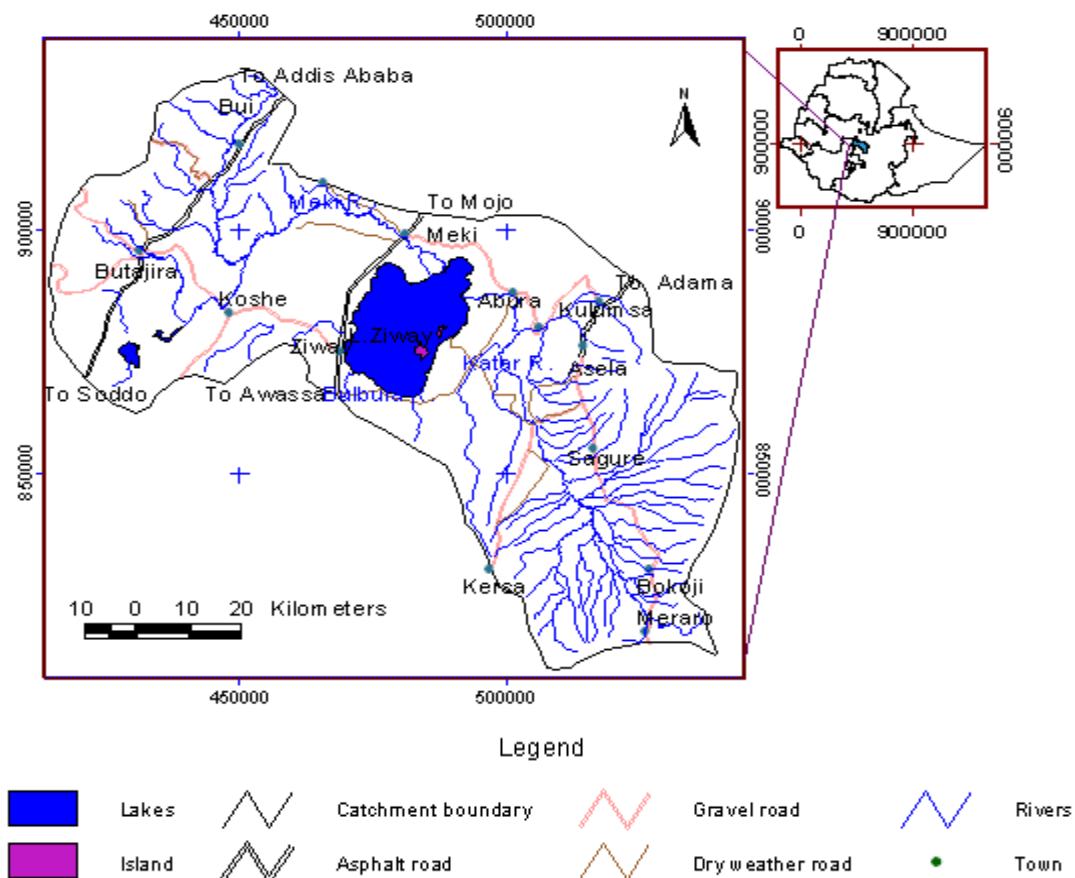


Figure 3.1 Location map of Lake Zeway Catchment (Alemu Diribsa 2006)

In this work, all maps and tables are referenced by Alemu Diribsa.

### **3.1.2 Population**

#### **3.1.2.1 Human**

The total population in the study area was estimated based on the Statistical Abstract, 2005, prepared by Central Statistical Agency. Accordingly, the population size of the catchment area is about 1,479,451 as of July 30,2005.

#### **3.1.2.2 Livestock**

Livestock population of the area was estimated using statistical report of Central Agricultural Census Commission, 2003. Based on the data, total population of cattle, sheep, goat, horse, asses, mule, poultry and beehives residing in the area are 452791, 164707, 93637, 30361, 44799, 3633, 481579 and 26107 respectively.

#### **3.1.3 Climate**

According Makin M.J. et al (1975), climate of the study area consists of three ecological zones: humid to dry humid lands, dry sub-humid or semi arid lands and semiarid or arid lands. Accordingly, highland areas west of Butajira and east of Asela are categorized under humid to dry sub-humid land. The areas east of Butajira around Lake Abay and a strip of land between Lake Ziway and Asela are dry sub-humid lands. The rest of the area which is around the lake is in semiarid or arid zone.

The average annual rainfall of the area varies spatially from about 620mm in lowland to over 1200mm at extreme highland areas. The mean daily temperature also varies between 13.5<sup>0</sup>C and 21.8<sup>0</sup>C in different physiographic areas.

#### **3.1.4 Topography and drainage**

The study area is bounded in the east by Chilalo (4056m a.s.l), Galama(4153 a.s.l) Kakka(4167m a.s.l), Mountains and from the west by Garaghe Mountains( 3609 a.s.l ).

Generally, Lake Ziway basin is divided into three physiographic areas: the high plateaux on either side of the rift, the transitional escarpment and the rift floor. There is a topographic difference of about 2600m between the rift floor and mountains.

Lake Ziway is fed principally by Meki and Katar rivers; from its western and eastern sides respectively (Figure 3.1). Most parts of plateau area are perennial sources of these rivers while the tributaries in the escarpments and rift floor are almost intermittent sources. In addition, the highland is characterized by higher drainage density than the escarpment due to differences in rock permeability, climate and slope.

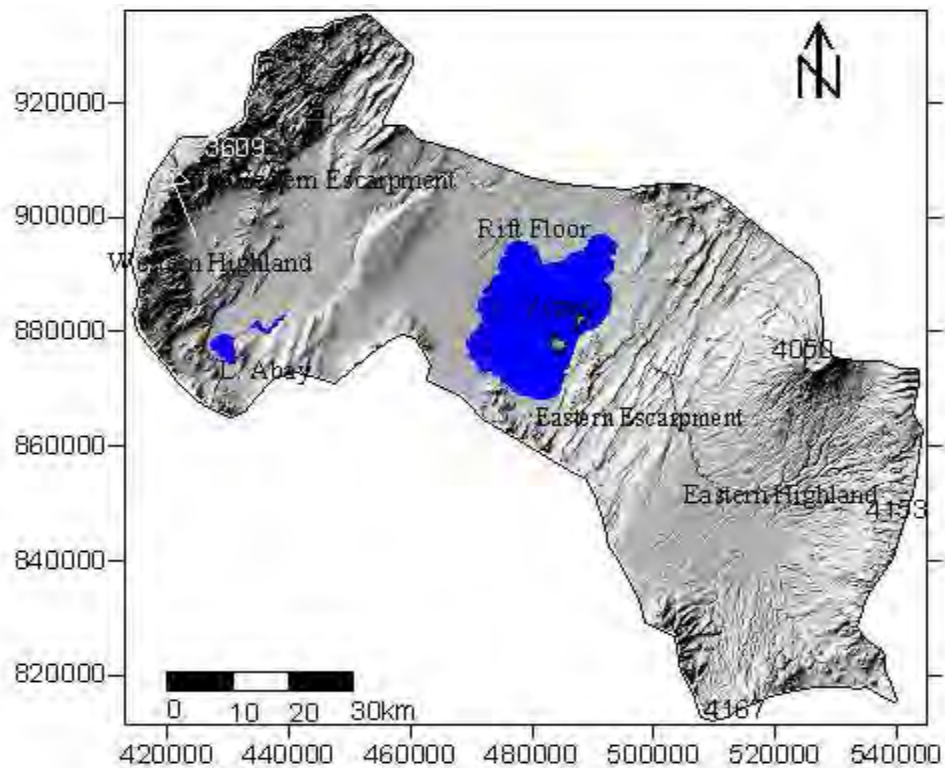


Figure 3.2 Topography of the catchment derived from digital elevation model (Alemu Diribsa 2006)

### 3.1.5 Soil, land use and land cover

#### 3.1.5.1 Soil

Soil in the study area is closely related to parent material and degree of weathering (Makin et al 1976). The main parent materials are basalt, ignimbrite, volcanic ash, pumice, riverine and lacustrine alluvium. Weathering varies from deeply weathered basalt in humid highland areas to unweathered recent alluvial deposits in the drier central part of the rift valley.

Generally, there are four soil types in the area (Makin et al, 1976, Halcro, 1992):

*Type I:* covers predominantly the rift floor and western escarpment on flat to undulating plains with some hills formed on pyroclastic deposits (figure 2.3). Generally, the soils are dark grayish free draining friable silty loom to sandy loam with moderate structure and good moisture storing properties.

*Type II:* is found on steep faulted undulating and rolling low plateau escarpments of the rift zone. The soil is well drained, moderately deep to deep dark gray or brown, friable silty loam to sandy loam with moderate structure and good moisture storing properties.

*Type III:* is well drained deep reddish brown to red friable clays to clay loams with strong structure. This soil type is found on flat to undulating plateau of western margin and dominantly in eastern plain.

*Type IV:* is very thin and shallow soil covering the eastern margin of the study area. The soil is well drained and limited moisture storing property, stony and has no diagnostic horizon (Rigosols/Lithosols according to FAO /UNESCO soil classification)

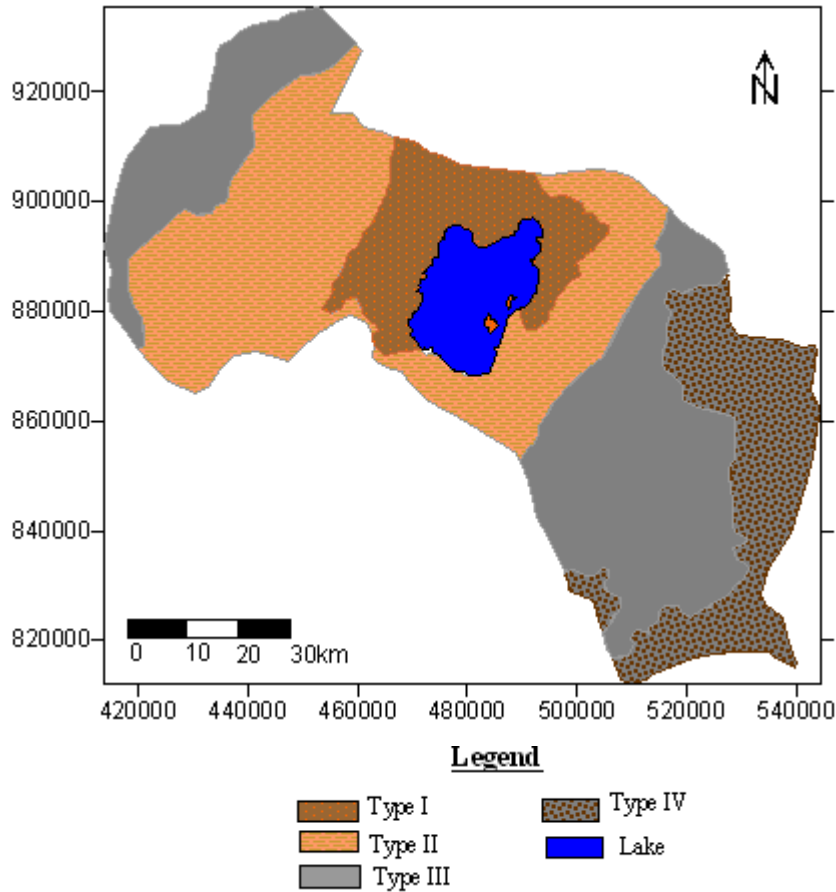


Figure 3.3 Generalized soil map of Lake Ziway catchment (from Makin et al, 976)

### 3.1.5.2 Land use and land cover

The different topographic, climatic, and edaphic conditions determine the ground ecological groups in the catchment, each of which is characterized by particular associations of vegetation (Dagnachew Legesse, 2002).

Land use/land cover map of the area has been prepared based on previous reports with some adjustments being made for recent changes. The detail land cover comprises of numerous groups. However, for its relevance to the objective of study, like estimation of actual evapotranspiration and direct groundwater recharge, the simplified land use and land cover of the area is described as in the following table:

Table 3.1 Aerial distributions of land cover units (Alemu Diribsa 2006)

Class	Cover type	Area%	Area(km)2
1	Permanent water body	6.2	463
2	Marshy and swampy areas	3.1	231
3	Irrigated agriculture	0.8	63
4	Rain fed cultivated land	72.1	5333
5	Dominantly grass land	3.6	266
6	Bushes and shrubs	3.9	293
7	Woodland and afro-alpine vegetation	10.3	765

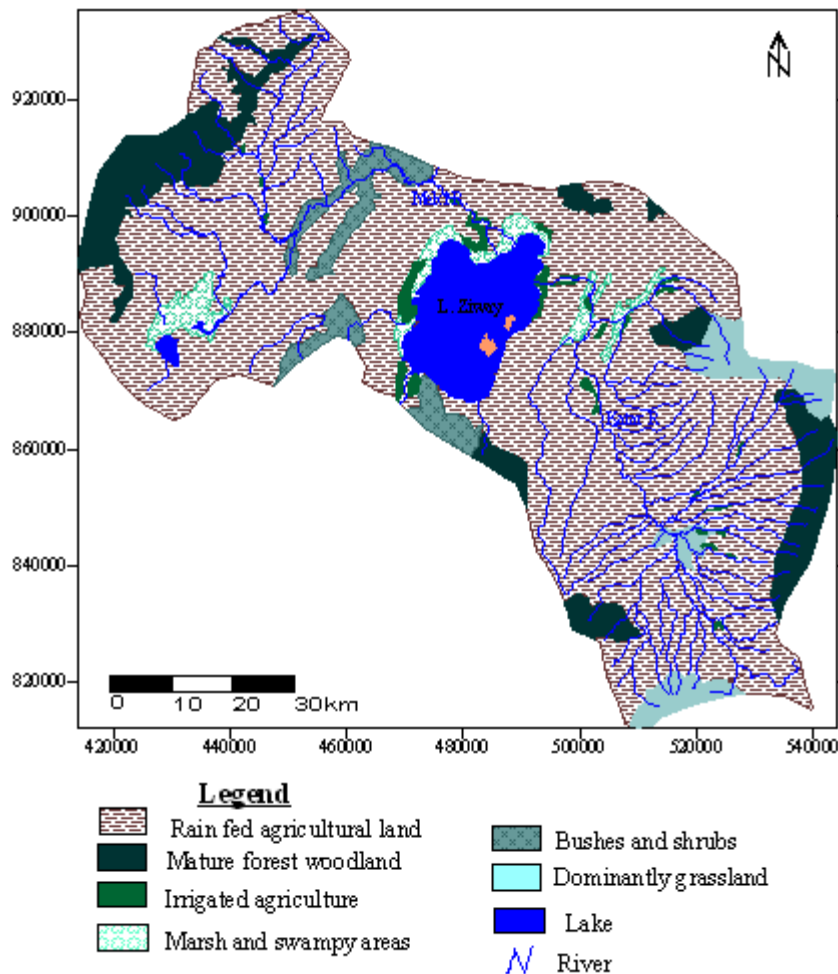


Figure 3.4 Land use/land cover map (Alemu Diribsa 2006)

### **3.2 Data Collection**

- For analysis, river discharge and meteorological data collected from Ministry of Water Resources and National Meteorological Service Agency respectively are used.
- Use groundwater table contour, constructed by Alemu Diribsa using static water level and spring locations collected from Oromia and South Nations and Nationality States Water Resource Bureaus; and previous works have been used.

### **3.3 Data Analysis**

- Analysis of trends in water use was carried out using data obtained from previous works and concerned Agricultural and Rural Development Bureaus, Departments and offices.
- Determination of average areal depth of precipitation over the catchment using Thiessen polygon method which is devised by an American Engineer (Thiessen 1911), this is an objective method. The rainfall measurement at an individual gauges are first weighed by the fraction of the catchment area represented by the gauges, and then summed (Elizabeth Shaw, 1994).
- Estimation of evapotranspiration using Thornthwaite Method. I chose this method because of its familiarity. The method is discussed in detail in chapter two.
- Estimation of rainfall recharge (direct groundwater recharge) using the soil-water balance. This method is essentially a book-keeping procedure which estimates the balance between the inflow and outflow of water.
- Identification of effluent and influent reaches on the main rivers using groundwater table elevation contour map. By constructing groundwater table contour, it is possible to find centers of recharge and discharge along river reaches. Stream is influent (loosing water to subsurface system) as it traverses recharge area; and effluent (gaining water from the subsurface system) as it crosses the discharge area (Freez and Cherry, 1979).
- To calculate water balance, the application of the principle of conservation of mass in hydrology is used.

## **CHAPTER FOUR**

### **HYDROMETEOROLOGY**

#### **4.1. Introduction**

Hydrometeorology is concerned with the study of the atmospheric and land phases of the Hydrologic cycle with emphasis on the interrelations involved (WMO,1963). Therefore, it is the beginning parameter and very essential in water resource evaluation of a given area.

In this study, attempt is made to analyze the mean monthly and annual precipitation, runoff and lake level; and evapotranspiration using other variables of hydrometeorologic data.

#### **4.2 Precipitation**

The seasonal distribution of rainfall over the country is governed by the position of Inter Tropical Convergence Zone, ITCZ (Tenalem Ayenew, 1998; Dagnachew Legesse ,2002).

Accordingly:

- The rainy season from June to September is controlled by ITCZ which lies to north of Ethiopia at that time. Hence, the study area intercepts most of the monsoon rainfall from Atlantic and Indian oceans.
- The dry period, from October to February is when the ITCZ lies to the southern of the country. In these months, the north easterly trade wind traversing Arabia dominates the region and therefore, produces very little or no rainfall in the area.
- During March, the ITCZ is located in south of Ethiopia moving northwards. At that time low pressure is developed in Sudan and Arabia while high pressure develops over Gulf of Aden and Indian Ocean. The high pressure generates a moist easterly air current over southeast Ethiopia producing spring (Bulg) rain from March to May.

Precipitation in the catchment varies with altitude. High altitude areas like Chilalo, Galama, and Guraghe mountains receive mean annual rainfall of over 1200mm while the lake area gets average depth of about 735 mm. However, the correlation coefficient between precipitation and altitude is not very strong due orographic effect and is found to be 0.492.

There is significant orographic effect on the spatial distribution of precipitation over the area. Areas close to mountains of eastern highland get higher mean annual precipitation than areas found far away from the mountainous region even if the later ones are in higher altitudes. One good example of this effect is the difference between Asela and Sagure; where the mean annual precipitation and altitude of the former are 1167mm and 2396m a.s.l respectively, while that of Sagure, are 775mm and 2517m a.s.l. In addition, western half of the area gets higher spring (March to May) rainfall than the eastern half because the Guraghe Mountains act as windward direction to the northward movement of moist air while the eastern mountains are rain shadow at that time.

Precipitation of the study area was analyzed based on 17 stations found in and around the catchment. Most of these stations have monthly records of 25 to 40 years. However, there are few stations with rainfall data of less than 15 years. Due to the likelihood of error in using few year records for precipitation analysis, the data gap of those stations were filled by averaging results obtained by linear regression between the station and the other nearby three stations having higher correlation coefficients (Annex 1).

The average arial depth of precipitation over the catchment has been determined using Thiessen polygon method.

The Thiessen polygon has been constructed using all 17 stations (Figure 4.1) and then the precipitation of each polygon was determined by multiplying the area weighing factor and point precipitation enclosed in the polygon. Accordingly, the catchment gets mean annual precipitation of 887mm.

No	Station	Recording period	Location		Altitude (m.a.s.l.)	Mean monthly precipitation (mm)												
			XUTM	YUTM		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1	Abura	1967-1977	501720	888408	1690	17	34	51	61	54	67	112	95	74	29	12	11	617
2	Arata	1974-2004	506536	882282	1760	12	30	69	71	84	93	133	121	109	42	12	6	781
3	Asela	1966-2004	514750	879412	2396	18	46	95	113	115	133	188	203	159	60	20	15	1167
4	Bokoji	1971-1999	527386	832211	2793	25	51	87	104	102	108	177	187	87	58	15	12	1014
5	Bui	1970-2004	460267	919803	2027	26	46	79	82	73	111	213	199	112	35	8	6	992
6	Butajira	1968-2004	431353	897207	2088	38	67	136	127	115	125	173	172	116	45	11	14	1138
7	Digelu	1967-1977	527676	858354	2689	31	50	71	91	91	108	175	179	84	52	24	21	976
8	Ejersalele	1967-2004	465763	912116	1779	16	36	58	76	66	79	196	162	86	24	5	4	807
9	Kater Guent	1987-2004	505853	863367	2149	4	20	45	71	88	94	138	124	104	39	3	5	736
10	Kersa	1968-1997	498222	822323	2760	26	47	78	104	95	78	113	122	106	57	21	11	858
11	Koshe	1974-2004	448183	884908	1873	22	48	78	91	90	100	171	170	109	51	5	5	941
12	Kulumsa	1966-2004	517632	887514	2153	22	44	81	80	83	91	127	136	105	41	10	10	831
13	Meki	1965-2004	481640	900802	1663	13	35	56	65	64	77	170	149	87	34	8	4	762
14	Meraro	1968-2004	526432	819553	2975	36	41	71	105	87	98	179	185	92	46	23	20	983
15	Sagure	1973-2004	517076	856788	2516	13	27	59	73	81	98	155	149	74	35	7	5	775
16	Torra	1974-2004	436647	868906	2012	25	43	83	116	95	87	133	124	117	49		6	885
17	Ziway	1970-2004	468771	876858	1646	17	30	56	75	72	83	145	122	86		2	4	732

Table 4.1 Point precipitation over meteorological stations in the catchment (Alemu Diribsa 2006)

Table 4.2 Arial mean depth of precipitation using Thiessen polygon (Alemu Diribsa 2006)

No	Station	Area enclosed by polygon	Weighted Area (%)	Mean annual Precipitation (mm)	Weighted Annual precipitation (mm)
1	Abura	419	5.65	617	35
2	Arata	87	1.17	781	9
3	Asela	147	1.98	1167	23
4	Bokoji	387	5.22	1014	53
5	Bui	574	7.74	992	77
6	Butajira	875	11.80	1138	134
7	Digelu	637	8.59	976	84
8	Ejersalele	324	4.37	807	35
9	Kater Gu	633	8.54	736	63
10	Kersa	383	5.17	858	44
11	Koshe	484	6.53	941	61
12	Kulumsa	331	4.46	831	37
13	Meki	467	6.30	762	48
14	Meraro	285	3.84	983	38
15	Sagure	471	6.35	775	49
16	Torra	276	3.72	885	33
17	Ziway	634	8.55	732	63
	Total	7414	100.00	-	887

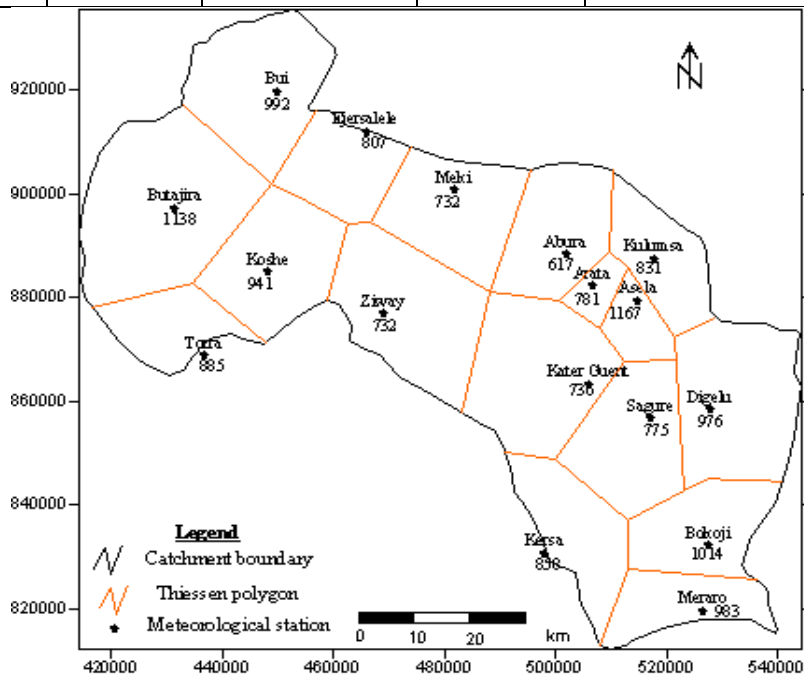


Figure 4.1 Thiessen polygon (station/annual precipitation, mm) (Alemu Diribsa 2006)

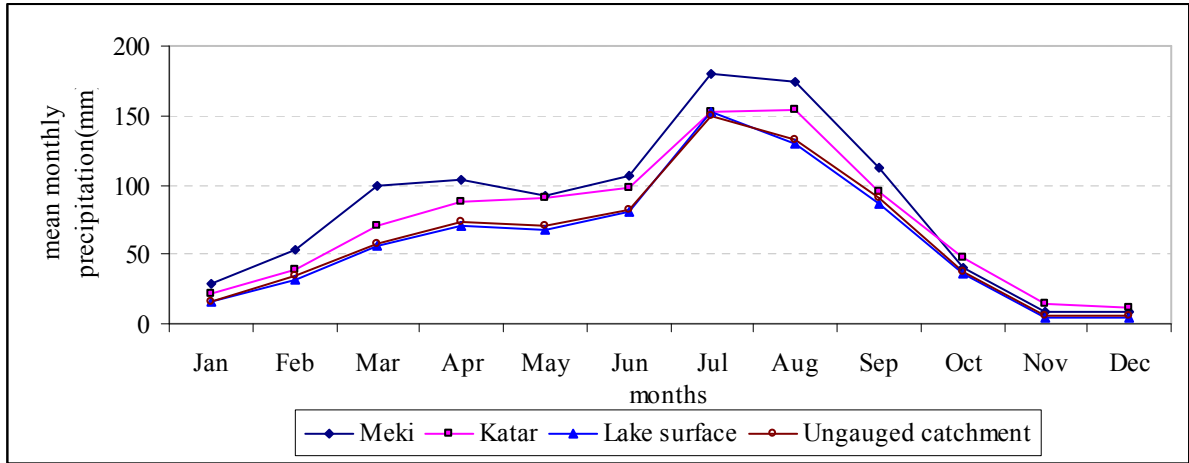


Figure 4.2 Mean monthly distribution of precipitation in River Catchments and on Lake Surface (Alemu Diribsa 2006)

Note that bi modal distribution of precipitation is more pronounced in Meki catchment than the Katar basin due differences in distribution of spring rain.

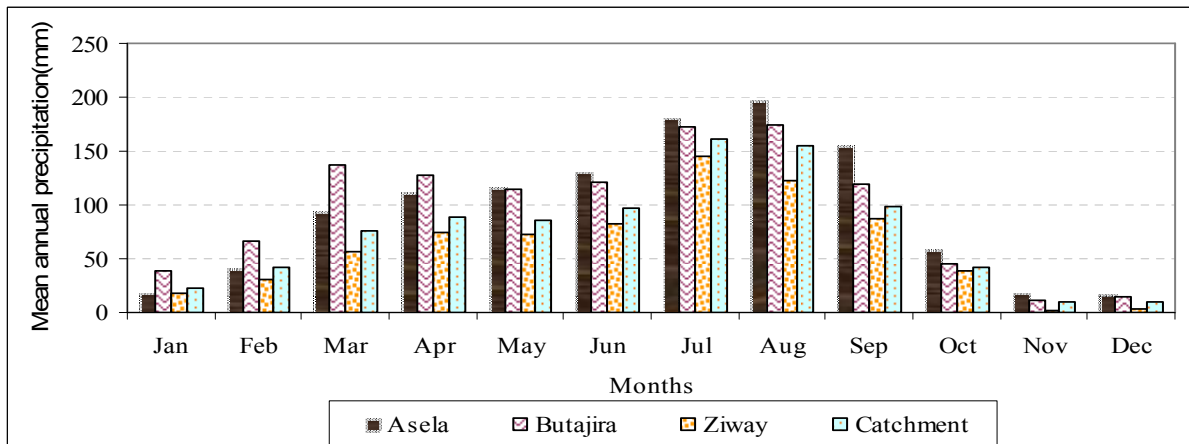


Figure 4.3 Mean monthly precipitations of selected stations and overall weighted catchment area. (Alemu Diribsa 2006)

### 4.3 Evapotranspiration

Evapotranspiration is the loss of water to the atmosphere through evaporation from all surfaces; including evaporation from free water surfaces, soil, and manmade surfaces and transpiration from plants (Houghton, 1985).

It is customary to divide evapotranspiration in to free water (or lake) evaporation and evapotranspiration from plants and soil. Although the deriving climatic forces behind the two processes are the same, evapotranspiration from soil and plants is more complex. This is due to the fact that the nature of evaporating surface of soil and plants is influenced by various physiological and aerodynamic factors as well as the availability of water.

### **4.3.1 Common hydrometeorologic factors affecting evapotranspiration**

#### **4.3.1.1 Temperature**

The higher the air temperature, the more vapor it can hold, and similarly if temperature of evaporating water is high, it can more readily vaporize (Shaw, 1994).

In the study area, there are seven stations recording maximum and minimum daily temperatures. Four of the stations: Asela, Sagure, Meraro and Bui are found at highlands while Kulumsa and Burajira, are situated at the escarpments; and Ziway at rift floor. Temperature varies with altitude; and there is correlation coefficient of -0.89 between them.

Table 4.5 Mean monthly temperature of the stations in the catchment (°C) (Alemu Diribsa 2006)

No	Station	Recording period	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Asela	1960-2004	14.3	15.6	15.9	16.4	16.5	15.8	14.9	14.7	15.9	14.9	14.1	14.0
2	Bui	1990-2004	16.6	17.3	18.4	18.6	19.5	17.5	16.2	16.3	16.7	16.4	15.8	15.7
3	Butajira	1972-2004	18.2	18.6	19.2	19.2	19.1	18.5	17.6	17.7	18.4	18.4	18.1	17.8
4	Kulumsa	1966-2004	15.7	16.7	17.8	18.2	18.1	17.2	16.1	15.8	16.0	16.6	15.9	15.4
5	Meraro	1986-2004	14.3	14.9	15.8	15.9	16.1	15.2	14.5	14.0	14.2	14.7	14.1	13.5
6	Sagure	1981-2004	14.0	15.1	15.9	15.8	15.7	14.9	14.3	14.3	14.3	14.1	13.6	13.5
7	Ziway	1970-2004	19.3	20.4	21.4	21.5	21.8	21.0	19.9	19.7	19.9	19.7	18.9	18.7

#### **4.3.1.2 Relative Humidity**

The relative humidity for an air mass is the percent ratio of the grams of water per cubic meter of air to the capacity of air to hold maximum amount of air, for the temperature of air mass (Fetter, 1994).

It expresses the degree of saturation of the air as a ratio of the actual ( $e_a$ ) to the saturation ( $e_s(T)$ ) vapor pressure at the same temperature (T):

$$RH = 100e_d/e_a \quad (4.1)$$

Where, RH: relative humidity

$e_d$  : actual vapor pressure

$e_s$ : saturation vapor pressure

Four stations in the study area (Meraro, Kulumsa, Ziway and Bui), have monthly records of mean relative humidity.

Table 4.6 Mean monthly relative humidity of the selected meteorological stations (%) (Alemu Diribsa 2006)

No	Station	Recording Period	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Bui	1990-2004	63	61	64	64	63	72	80	80	74	65	63	63
2	Kulumsa	1971-2004	58	54	58	61	61	68	78	81	78	62	54	58
3	Meraro	1971-2004	62	57	58	69	67	73	82	82	78	73	65	62
4	Ziway	1970-2004	67	66	66	68	68	69	76	77	74	66	64	66

#### 4.3.1.3 Wind Speed

Presence of atmospheric turbulence can greatly increase the rate of evaporation by removing vapor from evaporating surfaces and giving space for fresh air capable of holding additional vapor in the atmosphere.

Four stations located in the study area have records of wind speed at 2m above the ground surface.

Table 4.7 Monthly average wind speed at 2m above ground surface of meteorological stations in the basin (m/s) (Alemu Diribsa 2006)

No	Station	Recording period	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Bui	1991-2004	2.1	2.1	2.1	1.8	2.1	1.6	1.5	1.4	1.4	1.9	2.1	2.1
2	Kulumsa	1980-2004	2.6	2.5	2.2	2.1	2.2	1.9	2.1	1.7	1.3	2.7	3	2.8
3	Meraro	1991-2004	2.5	2.6	2.9	3	2.8	1.9	1.5	1.5	2	2.8	2.8	2.6
4	Ziway	1979-2004	1.4	1.4	1.3	1.3	1.5	1.9	1.8	1.6	1.1	1.2	1.5	1.5

#### 4.3.1.4 Sunshine hours

Since the evaporation requires continuous supply of energy which is derived mainly from solar radiation, the radiation will be a factor of considerable importance. Like the above variables the area consists of four sunshine hour recording stations.

Table 4.8 Average sunshine hours of meteorological stations in the catchment (hours/day) (Alemu Diribsa 2006)

No	Station	Recording period	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Ziway	1976-2004	9.5	9.4	8.3	8.4	9.2	8.4	6.4	6.6	7	9.1	10.2	10.1
2	Meraro	1989-2004	8.5	7.5	7.9	6.7	7.6	6.3	4.6	5.5	6.1	6.3	8.6	8.8
3	Bui	1990-2004	8.9	8.4	8.2	8.1	8.2	6.8	5	5	6.8	8.7	9.9	9
4	Kulumsa	1976-2004	8.1	7.8	7.3	6.7	7.2	7	5.3	5.3	5.6	7.5	8.7	8.7

#### 4.3.2 Estimation of Evapotranspiration

##### 4.3.2.1 Thornthwaite Method

Thornthwaite produced a formula for calculating PET based on temperature as index of energy available for evapotranspiration with an adjustment being made for the latitude, location and number of daylight hours (Dunne and Leopold, 1978)

First, Thornthwaite defined the heat index  $i_m$  for any month  $m$  as

$$i_m = (t_m/5)^{1.514} \quad (4.2)$$

$$m = 1,2,3 \dots 12$$

Where  $t_m$  is mean monthly temperature in  $^{\circ}\text{C}$ . The twelve monthly heat indexes are then added to obtain the annual heat index  $I$ .

$$I = \sum_{m=1}^{12} i_m \quad (4.3)$$

The monthly potential evapotranspiration for any month in cm/month is then calculated from the equation:

$$\text{PET} = 1.6b(10t_m/5)^a \quad (4.4)$$

$$a = 6.75 \times 10^{-7}I^3 - 7.71 \times 10^{-5}I^2 + 1.792 \times 10^{-2}I + 0.49239 \dots \quad (4.5)$$

$b$  is a factor to correct for unequal day length between months and expressed by:

$$b = \frac{\text{possible sunshine hours for the particular month}}{12 \times 30 (\text{or } 31)} \quad (4.6)$$

$$12 \times 30 (\text{or } 31)$$

Accordingly, the land surface annual potential evapotranspiration of Lake Zeway catchment based on Thornthwaite method is 1077 mm/year (table 4.10).

Table 4.10 Monthly mean precipitation and potential evapotranspiration of different Physiographic areas in the catchment (Alemu Diribsa 2006)

	Phys. area	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Precipitation (mm)	Highland	26	46	82	96	93	105	166	167	99	46	15	12	954
	Escarpment	20	42	77	91	88	97	157	148	105	42	7	7	882
	Rift floor	15	33	55	69	66	78	153	131	84	34	6	5	730
PET (mm) Thornthwaite mtd	Highland	73	91	89	95	94	91	84	78	83	78	74	68	998
	Escarpment	83	101	101	109	109	101	90	86	91	87	84	78	1121
	Rift floor	93	113	119	128	130	125	111	103	108	99	94	87	1310
<i>Weighted PET</i>		79	97	97	103	103	98	90	84	89	83	79	74	1077

### 4.3.3. Estimation of actual evapotranspiration (AE)

Actual evapotranspiration is the amount of evaporation that occurs under a given climatic and soil moisture conditions. It is less than or equal to potential evapotranspiration (PET).

When there is abundant moisture in the soil, the actual evapotranspiration rate is equal to potential evapotranspiration. On the other hand, if there is no rain to replenish the water supply, the soil moisture gradually becomes depleted by the demand of vegetation and produces soil moisture deficit. Therefore, the gap between potential and actual evapotranspiration is reflected by the amount of deficit.

The values of soil moisture deficit and actual evapotranspiration vary with soil type and vegetation (Shaw, 1994). Accordingly, the study area has been classified in to four major groups of soil (fine sand, fine sandy loam, silty loam, and clay) with four types of root depths of vegetation cover such as: mature forest woodland, deep rooted crops, moderately deep rooted crops and shallow rooted plants.

The actual evapotranspiration of the area is calculated using Thornthwaite and Mather standard soil water balance model. I chose this method because of its familiarity based on

the above soil and vegetation categories as well as precipitation and potential evapotranspiration.

In the model, accumulated potential water loss, which indicates the severity of water shortage, is obtained by cumulation of the negative values of the differences between monthly precipitation and evapotranspiration for dry season only; and the summation begins with the first month of dry season.

The soil moisture during the dry months is then obtained from the following formula:

$$S_m = W \exp\left[-\frac{(La_m)}{W}\right] \quad (4.7)$$

Where,  $S_m$ : Soil moisture during the month M (mm)

$La_m$ : Accumulated potential water loss at month M (mm).

$W$ : Available water capacity of the root zone (mm)

The soil moisture for each wet month is obtained by adding the excess of rain of the current month to the soil moisture of the month before. However, this sum may not exceed the water capacity and excess is booked as moisture surplus.

The monthly actual evapotranspiration,  $AET_m$ , is then found as:

$$AET = PET \text{ if } P_m > PET_m \quad (4.8)$$

Otherwise,

$$AET_m = P_m + S_{m-1} - S_m \quad (4.9)$$

Where,  $AET$  is actual evapotranspiration,  $PET$ , Potential evapotranspiration,  $P$  is aerial precipitation,  $S_{m-1}$  and  $S_m$  are soil moisture during the month m-1 and m respectively.

Accordingly, the monthly and annual actual evapotranspiration from the three physiographic areas as well as river catchments using inputs of Thornwaite potential evapotranspiration results are given in the following table:

Table 4.12. Actual evapotranspiration on the basis of catchment physiography (Alemu Diribsa 2006)

Methods	Phys. area	Actual evapotranspiration (mm)												Annual
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Thornwaite	Highland	41	57	83	95	94	91	84	78	83	74	52	35	869
	Escarpment	38	53	81	94	91	97	90	86	91	63	54	36	874
	Rift floor	20	36	56	70	66	78	109	101	95	63	22	14	730
<i>Weighted</i>		37	53	78	91	89	91	90	84	87	70	48	32	849

Note that AET of Rift floor is lower than that of Highland due to the fact that it cannot exceed the amount of precipitation even though the former has higher PET.

Table 4.13 Actual evapotranspiration on the basis of the physiography of the respective river Catchments (mm) (Alemu Diribsa 2006)

Method	Catchment	Actual Evapotranspiration(mm)												Annual
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Thornwaite	Katar	40	56	82	94	93	92	86	80	85	73	51	35	865
	Meki	32	48	71	84	82	86	95	88	88	70	39	26	808
	Ungauged Catchment	25	41	63	77	73	84	104	97	94	63	31	20	772

Note that Thornwaite method gives fairly close actual evapotranspiration values for a given physiographic area in the catchment. This shows that temperature and sunshine hours, which are inputs for this method, are the most important factors controlling the rate of actual evaporation in the area.

#### 4.4 Runoff and Lake Level

As previously described in chapter two, Ziway Lake is fed by Meki and Katar Rivers from its western and eastern sides respectively; and finally outflows to Bulbula River in southwest.

Meki River originates from the highlands of Guraghe Mountains; and travels a distance of about 100km from the highlands at altitude of 3600m a.s.l to about 1630m a.s.l before draining in to Ziway Lake. Based on discharge data of the past forty years (1965 -2004) recorded at Meki town, the mean annual discharge of the river is estimated to be around 295mcm. High

discharge occurs during the months of July and August; and often dries during extreme dry season.

Katar River originating from the highlands of Arsi, has drainage area of 3302km<sup>2</sup>. The average seasonal discharge of the river varies from 7mcm during the months of December to February; and 140mcm in August based on hydrologic data of 1970-2004 obtained from Ministry of Water Resources. The average annual discharge of the river is 409mcm (Table 3.14).

Bulbula River is the outflow of Lake Ziway at its southwest and drains in to the terminal lake Abiyata located 30 km in southwest direction. The river is gauged near Adami Tulu; and has mean annual discharge of 173mcm based on data of 1979 to 2004. Flow of Bulbula River varies with level of Ziway Lake and there is correlation coefficient of 0.96 between the two.

Ziway Lake level is estimated by a staff gauge located at Bochesa around the outflow of the lake to Bulbula River. Based on thirty years (1975 to 2004) data, lake level declines from November to June and then rises from July to October (Figure 3.6).

Table 4.14 Mean monthly Discharges of main rivers (mcm) (Source Alemu Driribsa)

No	River	Recording Period	Discharge (mcm)												
			Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1	Meki	1965-2004	2	5	14	18	19	17	53	83	52	24	9	2	295
2	Katar	1970-2004	7	7	10	16	15	16	48	140	86	44	13	7	409
3	Bulbula	1979-2004	12	6	4	3	3	3	5	14	35	38	30	20	173

Table 4.15 Mean monthly Ziway Lake level (Recording period: 1975-2005) (Source Alemu Driribsa)

Lake Level (m)											
Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1.09	0.98	0.88	0.82	0.79	0.76	0.85	1.20	1.51	1.52	1.42	1.25

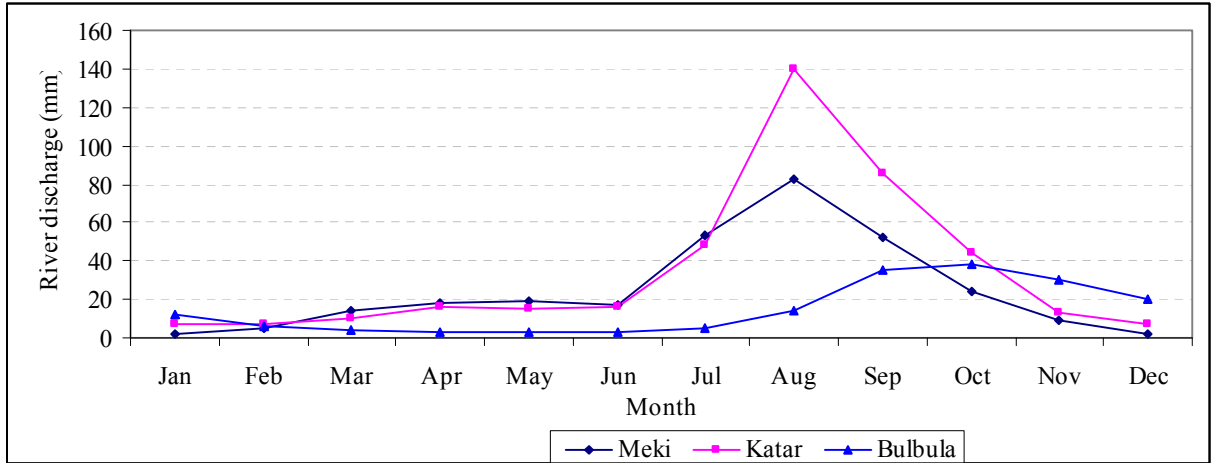


Figure 4.5 Long-term mean monthly discharges of main rivers in the catchment (Source Alemu Driribsa)

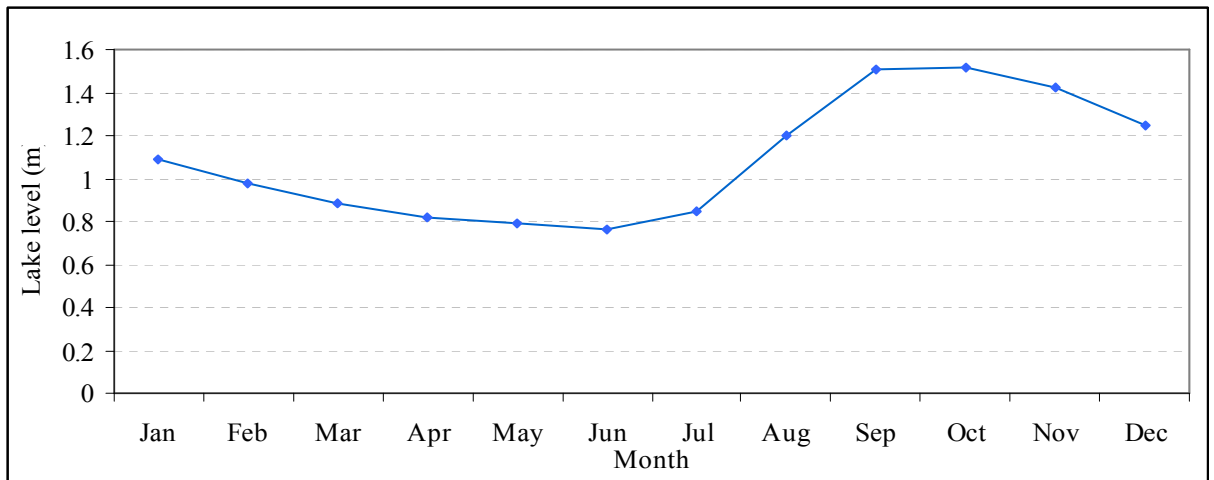
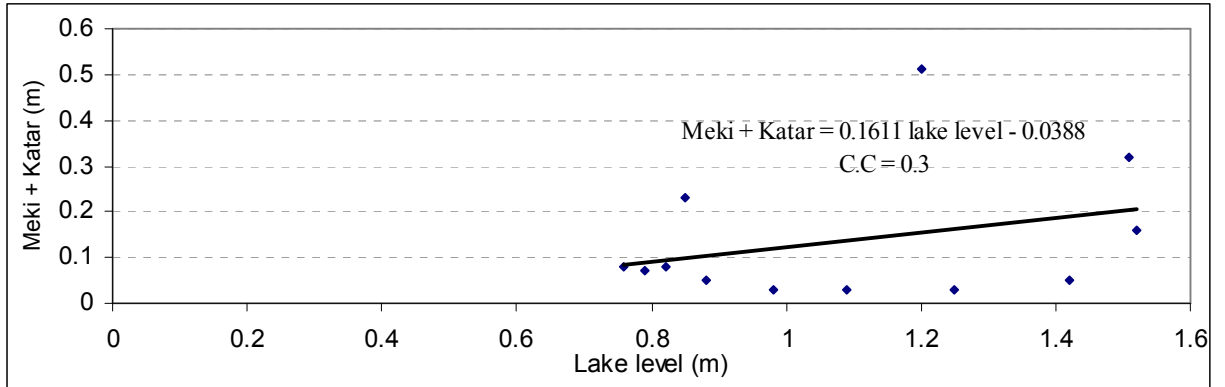


Figure 4.6 Mean monthly fluctuation of Lake Ziway level (Source Alemu Driribsa)

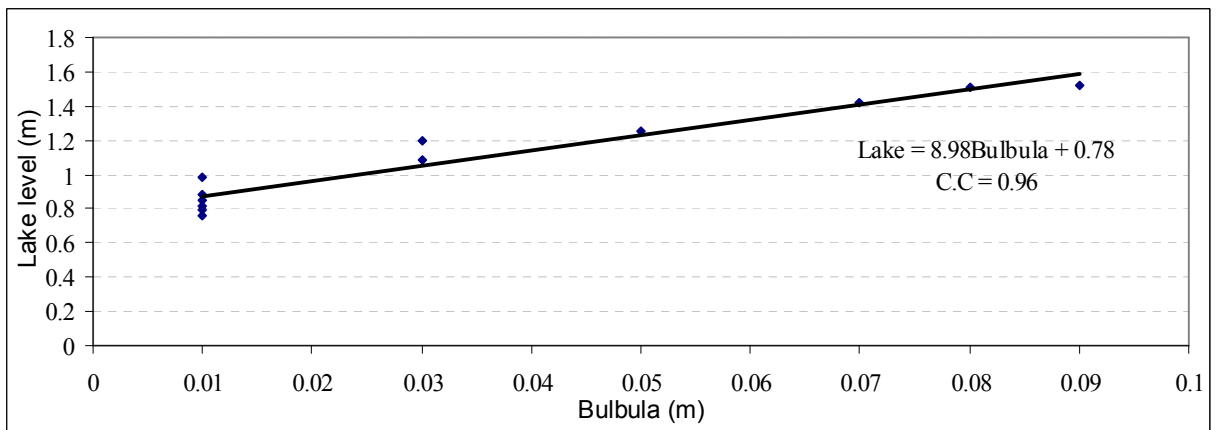
From the above graphs we can understand that peaks of lake level and Bulbula River flow do not coincide with peak discharges of rivers inflow (Meki and Katar) to the lake. There is about 45 days (one month and half) lag time between peak of inflow and that of lake level; and in turn about 15 days between the lake and peak of Bulbula River outflow.



CC: Correlation coefficient

Figure 4.7 Scatter plot between Ziway Lake level and sum of Meki and Katar Rivers Discharge (Alemu Diribsa 2006)

The above graph shows that significant lake level will not appear at gauging station if there is no flow from Meki and Katar Rivers. (i.e. at zero flow from Meki and Katar Rivers, the average lake level will only be about 0.24m above the bottom of the current staff gauge.) From this relationship it is apparent that the effect of groundwater and ungauged catchment on lake level is small.



CC: Correlation coefficient

Figure 4.8 Scatter plot between Ziway Lake level and Bulbula River discharge(Alemu Diribsa 2006)

From the equation of the above graph, we can understand that no flow of Bulbula River will be formed if lake level drops below 0.78m of the current staff gauge.

## CHAPTER FIVE

### ESTIMATION OF DIRECT GROUNDWATER RECHARGE

Groundwater recharge is a function of the volume of residual rainfall, surface infiltration, and geological percolation rates (Malin, 1989). Accordingly, part of the rainwater that falls on the ground is infiltrated in to the soil. A part of this infiltrated water is utilized in filling the soil moisture deficits, while the remaining portion percolates down to reach the water table forming groundwater recharge from rainfall.

The methods for estimation of rainfall recharge (direct groundwater recharge) involve the soil-water balance and groundwater balance.

#### 5.1 Soil water balance method

This method is essentially a book-keeping procedure which estimates the balance between the inflow and outflow of water. When applying this method to estimate the recharge for a catchment area, the calculation is repeated for areas with different precipitation, vegetation and soil type.

The soil water balance can be represented by

$$Gr = P - Ro - Ea \pm \Delta S \quad (5.1)$$

Where, Gr : recharge

P : precipitation

Ro : runoff

Ea: actual evapotranspiration

$\Delta S$ : change in soil water storage

According to this approach, water is held in a soil moisture store; precipitation adds to the store, evapotranspiration depletes it. When full, excess precipitation is routed to

groundwater as recharge. Therefore, the analysis of soil water balance for the determination of actual evapotranspiration in chapter four is further used to evaluate the residual moisture after evaporation loss. The surplus amount determined in this process after deduction of surface runoff represents direct groundwater recharge for a given soil and vegetation condition.

Using hydrograph separation of different rivers like Asebeka, Temala, Upper Katar, Lower Katar and Meki in to their respective surface runoff and baseflow components, the surface runoff of highland rivers is about 42% of total flow, while at escarpments it is about 35%. Accordingly, the weighted annual recharge of the area using soil moisture budgeting method is 57mm.

## CHAPTER SIX

### GROUNDWATER AND SURFACE WATER INTERACTION

#### 6.1 Introduction

Groundwater and surface water interaction is a natural phenomenon dictated by the fact that the two water media are critical components of one system intimately linked by hydrologic cycle (Winter, 1998).

Groundwater is discharged to the surface through natural springs, transpiration by plants, seepage under rivers and streams. On the other hand, groundwater is recharged by surface water from direct precipitation and indirectly from losing rivers and streams.

In this chapter, the hydrogeology of the catchment is discussed based on flow characteristics of major rivers with respect to geology, groundwater elevation contours, slopes and climate.

#### 6.2 The hydrologic characteristics of rivers in the catchment

In the study area, the rivers are gauged at six stations. Each catchment shows its distinct hydrogeological characteristics being controlled by geology, slope, soil and climate.

Table 6.1 Hydrological characteristics of gauged rivers in the catchment(Alemu Diribsa 2006)

No	Catchment name	Catchment area(km <sup>2</sup> )	Gauging station	Mean annual Precipitation(mm)	Slope %	Mean annual discharge (mm)
1	Upper Meki	2030	Dugda	995	3.6	143
2	Lower Meki	2256	Meki town	1005	2.5	131
3	Upper Katar	2023	Fite	881	3.6	174
4	Lower Katar	3302	Abura	925	4.1	123
5	Chufa	510	Arata	906	5.2	149
6	Ashebeka	265	Near Sagure-	963	5	196

In the forgoing analysis, records of Lower Meki, Upper Katar, Lower Katar, and Chufa stations are used thoroughly while the remaining ones are used in some comparisons due to their limitation in necessary data.

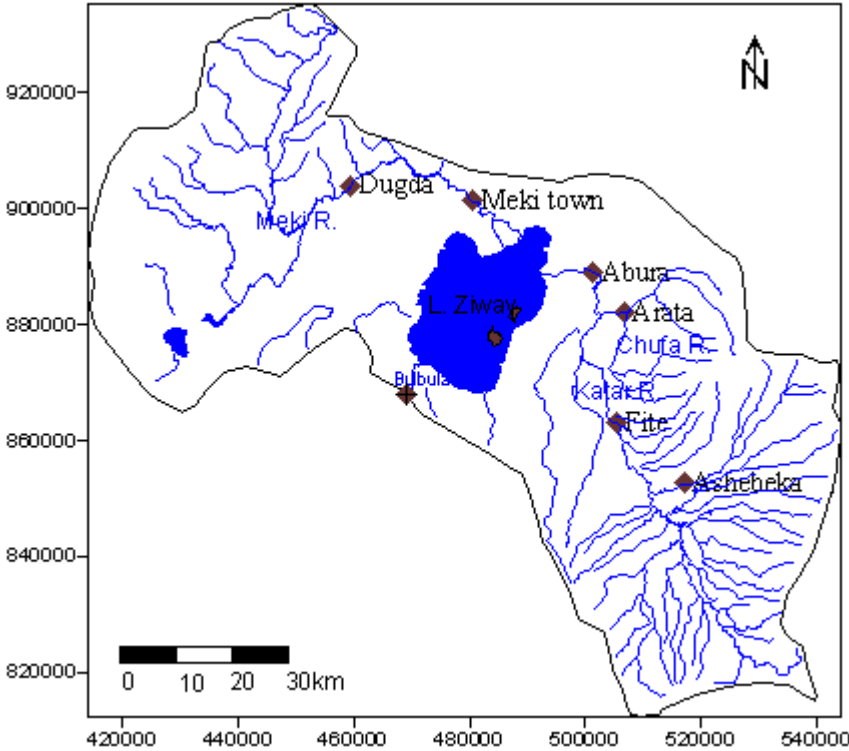


Figure 6.1 Location of river gauging stations(Alemu Diribsa 2006)

**6.3 Permeability distribution in the catchment**

The rocks in the study area possess different permeabilities due to variation in lithology, primary and secondary structure, fragment size of pyroclastic sediments, and weathering grades. Because of the lack of extensive research and time constraint, the catchment is classified in to five ranges of permeability by referring the research of Dr. Tenalem (1998) Ayalew (Figure 5.2).

### 6.3.1 High to very high permeability zone (K: 10 - 20m/day)

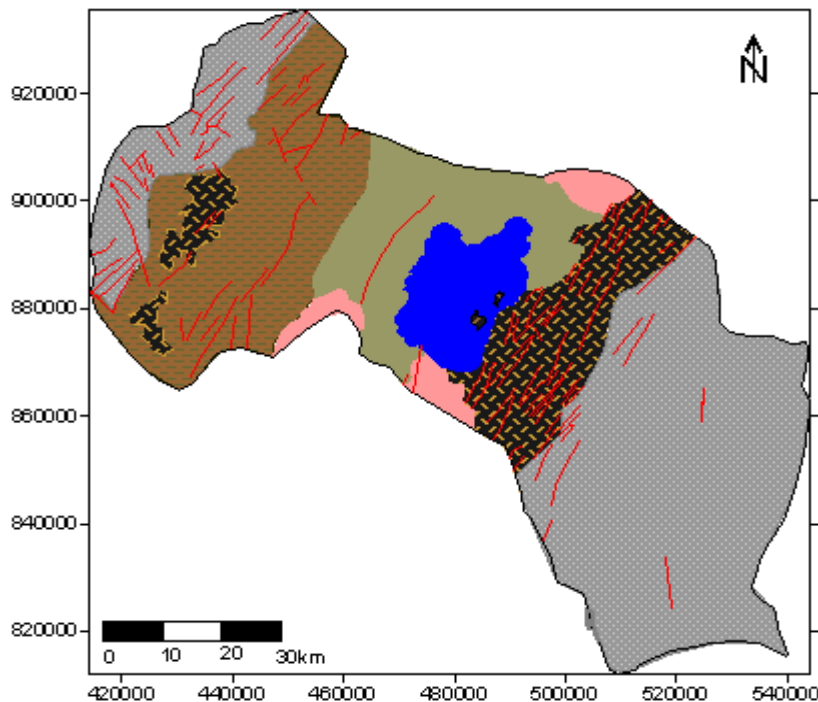
This zone consists of recent basalts and highly fractured ignimbrites in the eastern fault escarpment; and scoria cones along the major fault east of Butajira. Permeabilities in these areas are largely related to joints, faults, vesicles and fragment size of scoria.

### 6.3.2 Medium to high permeability zone (K: 5 - 10m/day)

These are less welded ignimbrites intercalated with pumice fragments, less fractured basalts, alluvial and colluvial deposits located at the foot of volcanic mountains. Based on the characteristics of ignimbrite, fracturing and weathering grade, the units possess medium to high permeability.

### 6.3.3 Medium permeability zone (K: 1 - 5m/day)

This permeability zone covers large area around the lake. The lithologic groups found in this area are ignimbrites overlain by lacustrine sediments such as: clay, diatomite, shale beds and reworked pumice. The group also includes rhyolite, pumice, tuff and ignimbrite with low secondary permeability; and covered dominantly with silty soil, black cotton soils and occasionally lacustrine sediment.



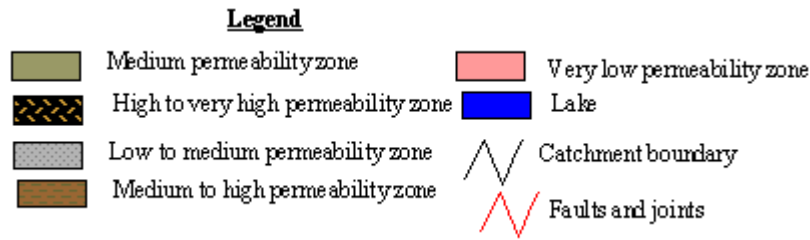


Figure 6.2 Permeability distributions in the study area (Taken from Tenalem Ayenew, 1998)

#### **6.3.4 Low to medium permeability zone (K: 0.1 - 1m/day)**

It is the most extensive zone covering large part of eastern highland mountainous regions of Chilallo, Kakka, Galama and western highlands of Guraghe Mountain. The rocks comprising this zone are highly welded ignimbrites, tuff, rhyolite and trachyte without visible large faults. The upper weathered rock and soils are permeable; however, the underlying volcanic sequences are massive.

#### **6.3.5 Very low permeability Zone (K: 0.01-0.1m/day)**

The group consists of acidic volcanic plugs and caldera rims dominated by silicic pyroclastic like pumice flow and ash with subordinate obsidian lava flows.

### **6.4 Identification of effluent and influent reaches on the main rivers using Ground water table elevation contour map**

By constructing groundwater table contour, it is possible to find centers of recharge and discharge along river reaches. Stream is influent (losing water to subsurface system) as it traverses recharge area; and effluent (gaining water from the subsurface system) as it crosses the discharge area (Freez and Cherry, 1979).

In this section, the relationship between the positions of groundwater table elevation with respect to elevation of river bed derived from DEM (digital elevation model) is analyzed to conceptualize effluent and influent behavior of river at a point

As can be observed from figure 5.3 and table 5.2: in the eastern highland, western highland and escarpment; and lower reaches of Katar and chufa rivers groundwater table lies above river bed (point CR1, CR2, CR13 and CR14, figure below) showing that the rivers are gaining from

subsurface system. However, Meki river bed in volcano lacustrine sediment, and Katar river bed in middle and upper part of escarpment zone are lying above the groundwater table contour reflecting losing reaches or recharge areas (CR5, CR9 – CR12).

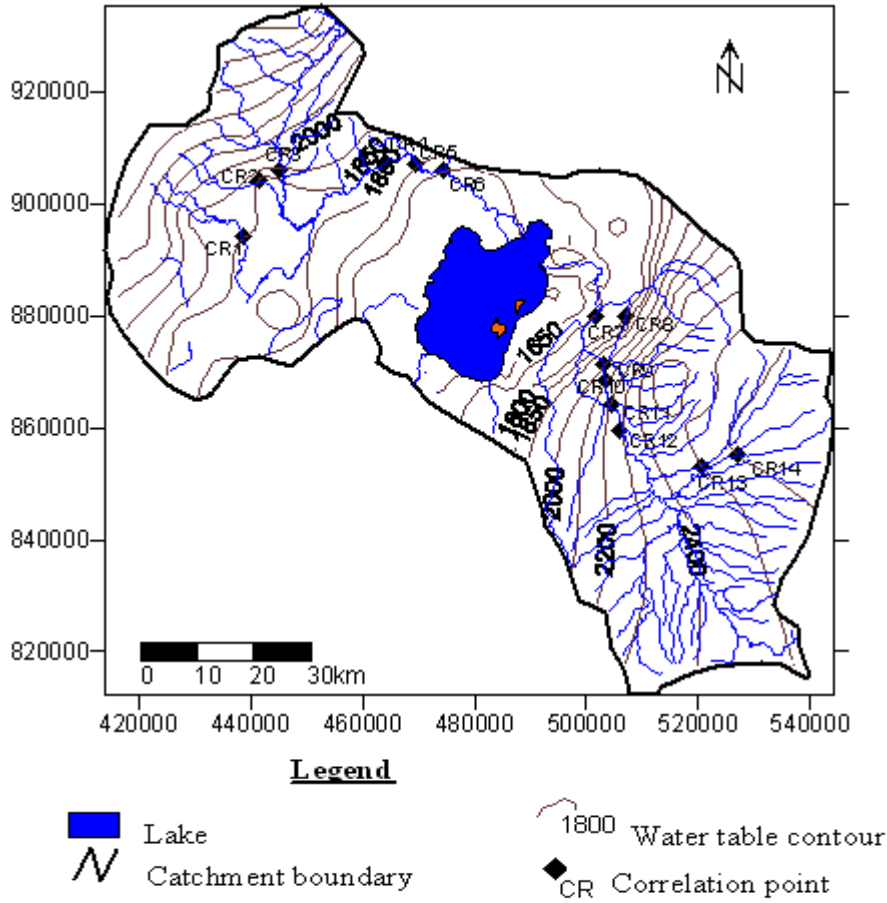


Figure 6.3 The relationship between groundwater table elevation contour and rivers(Alemu Diribsa 2006)

Table 6.2 The relationship between river bed elevation taken from DEM and groundwater table elevation at that point (Source Alemu Diribsa, 2006)

Label	XUTM(m)	YUTM(m)	Groundwater elevation (m.a.s.l)	River/Stream bed Elevation (m.a.s.l)	Characteristics of river/stream
CR1	438730	893730	1850	1848	gaining
CR2	441374	903779	1850	1842	gaining
CR3	445473	904969	1900	1894	gaining
CR4	464909	907437	1800	1795	gaining
CR5	463212	906666	1800	1809	loosing
CR6	474781	905277	1650	1670	loosing

CR7	501249	879729	1700	1692	gaining
CR8	56849	879742	1800	1795	gaining
CR9	502255	872550	1900	1910	loosing
CR10	503191	867237	2100	2198	loosing
CR11	504552	863360	2200	2287	loosing
CR12	506648	859663	2300	2337	loosing
CR13	520440	853294	2500	2494	gaining
CR14	527073	855145	2600	2596	gaining

## CHAPTER SEVEN

### LAKE WATER BALANCE

#### 7.1 The water balance equation

Water balance is the application of the principle of conservation of mass in hydrology (UNESCO, 1974). According to the law of conservation of matter, there is equilibrium between inflow component, out flow component and the change of water volume for each interface of time. Therefore, this equilibrium is described by the following equation:

$$\Delta V = P + S_i + G_i - E - S_o - G_o - A \quad (7.1)$$

Where,  $\Delta V$ : net change in lake volume

P : precipitation on the surface of lake

$S_i$ : surface inflow in to the lake

$G_i$ : groundwater inflow

E : evaporation from the lake surface

$S_o$ : surface out flow from the lake

$G_o$ : groundwater out flow from the lake

A : abstraction (irrigation, municipal water supply etc)

#### 7.2 Estimation of water balance variables

Mean monthly change in volume was calculated from 1975 – 2004 records of lake level obtained from Ministry of Water Resources. Due to difficulty of estimating changes in lake level resulting from siltation, the total change is assumed to be formed from inflow and outflow of water.

Monthly precipitation over Lake Surface was computed using Thiessen Polygon method from 30 years monthly data of Meki, Ziway, Abura and Ejersalele stations.

Surface inflow consists of three sources: Meki, Katar and ungauged tributaries around the lake. As evidenced from observation during field trips and information from the area, the ungauged tributaries contribute surface water only during wet seasons from months of June to September.

Therefore, the flow in these months was calculated based on mean rainfall- runoff coefficients for each month using adjacent gauged rivers.

Due to difficulty of estimating groundwater inflow and outflow, they are treated as net flux (Gi-Go) and estimated as residual of other water balance components.

Evaporation from the lake surface was estimated by Thornthwaite method using Ziway station climatic data of 1979- 2004.

Monthly mean surface outflow of Bulbula River from the lake was calculated using the records of Kerkersitu station data (1979-2004), collected from Ministry of Water Resources.

Finally, lake water abstraction was estimated based on the data obtained from JICA & OIDA 2004 joint report, OWRB 2004 report, OIDA & OWRB , 2005 joint report, as well as Dugda Bora, Adami Tulu, and Ziway Dugda District Agriculture and Rural Development Offices. The conversion of irrigable area to volume of water consumption was computed using average crop-water relationship presented by FAO in 1979.

### 7.3 Lake water balance estimation

Monthly water balance of the lake is summarized in the following table:

Table 7.1 Monthly water balance of the lake (Alemu Diribsa 2006)

Month	Inflow (mm)				Outflow (mm)			change in Lake Storage (mm)	Net GW flux (mm)
	Lake surface P	Meki Q	Katar Q	Ungauged Catchment Q	Lake surface E	Bulbula Q	Abstraction		
Jan	16	5	16	0	146	27	19	-70	85
Feb	32	11	16	0	147	14	12	-48	66
Mar	56	32	23	0	165	9	16	-44	35
Apr	71	41	36	0	154	7	5	-26	-8

May	68	43	34	0	163	7	8	-13	20
Jun	80	39	36	5	143	7	5	-13	-18
Jul	152	120	109	22	123	11	2	40	-227
Aug	130	182	318	28	133	32	1	154	-338
Sep	86	118	195	20	133	80	7	136	-63
Oct	36	55	100	0	147	86	8	4	54
Nov	5	20	30	0	149	68	12	-44	130
Dec	4	5	16	0	146	45	17	-75	108

P,Q and E stand for precipitation, river discharge and evaporation respectively

In addition, annual water balance of the lake is presented as follows:

Table 7.2 Lake water balance on annual basis

Inflow (mcm)			Outflow (mcm)			Change in storage (mcm)	Net GW flux (mcm)	
Lake surface P	Meki Q	Katar Q	Ungauged Q	Lake surface E	Bulbula Q			Abstr- action
324	295	409	33	770	173	49	0	-69

Negative net groundwater (Gi-Go) flux shows that there is more groundwater outflow than inflow based on the following relationship; derived from equation 7.1

$$\text{Change in storage} + \text{Surface outflow} - \text{Surface inflow} = \text{Groundwater inflow} - \text{Groundwater outflow}$$

Accordingly, when the result of the left hand side equation is negative, it shows that there is more groundwater outflow than inflow and vice versa.

#### 7.4 Discussion

From table 7.1 and figure 7.1 we can observe that more groundwater outflow than inflow occurs in April as well as between mid May and Mid September; and reach maximum in August. Less groundwater outflow (more groundwater inflow) takes place in other months; and attain its maximum in mid October (i.e. few months after precipitation ceases).

If we observe figure 7.1, the recession in groundwater inflow over outflow continues up to the month of August. This could be due to the time lag between the beginning of surface moisture (i.e. beginning of precipitation and increase in magnitude of surface water) and percolation to groundwater table that ultimately reach the lake. Similarly, the shift in maximum value of

groundwater inflow over outflow from the end of precipitation for a month shows the time gap between the two, being affected by aquifer characteristics in the area.

The possibility of more groundwater outflow over inflow with the rise of lake level is the other relevant explanation for the groundwater inflow deficit that has been observed in August.

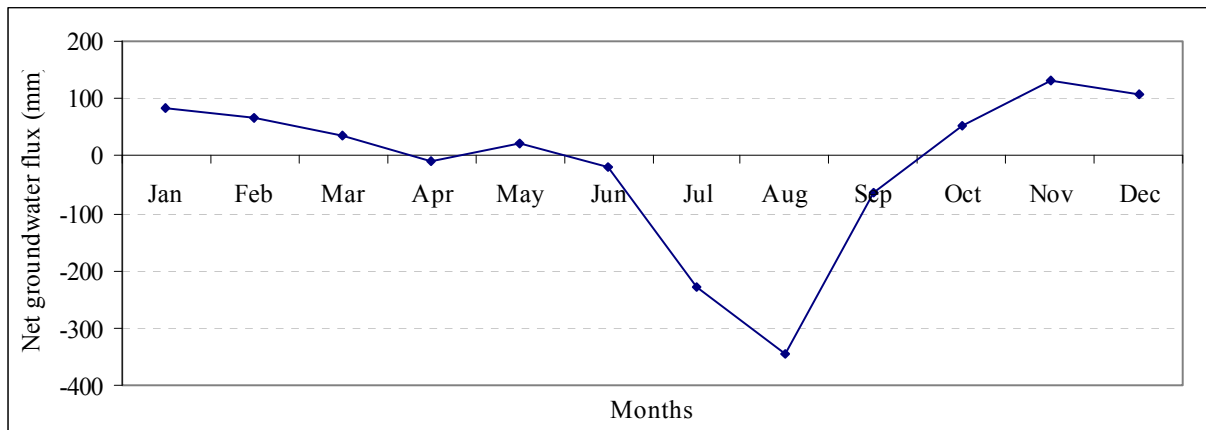


Figure 7.1 Monthly distribution of groundwater flux (GW inflow – GW outflow) (Alemu Diribsa 2006)

The occurrence of more groundwater outflow over inflow in April resulted from the spring rain, during which there are less evaporation and abstraction; and more precipitation and inflow than its preceding months as well as in May. Therefore, more groundwater outflow is needed to keep the system at equilibrium.

## **CHAPTER EIGHT**

### **CONCLUSION AND RECOMMENDATION**

#### **8.1 Conclusion**

It is a common observation that, management of water resources has focused on surface water or groundwater as if they were different entities. Groundwater and surface water are interdependent that is why as development of land and water resource increases, it is apparent that development of either of these resources affects the quality and quantity of the other. Nearly all surface water features (streams, lakes, reservoirs, wetlands and estuaries) interact with ground water. These interactions take many forms. In many situations, surface water bodies gain water and solute ground water systems and in others the surface water body is the source of ground water recharge and causes in ground water quality. As a result, withdrawal of water from streams can deplete ground water or conversely, pumpage of ground water can deplete water in streams, lakes, or wetlands. . thus, effective land and water management requires a clear understanding of the linkage between ground water and surface water as it applies to any given hydrologic setting.

#### **8.2 Recommendation**

- Heat tracing methods should be employed in future works for analysis of groundwater and surface water interaction in the catchment because it is by far the latest method to actually locate the presence and location of ground water flow in to a river stream.
- Detail fracture mapping has to be done in order to determine the specific points of losses on Katar River along the Wonji Fault Belt.
- Detail hydraulic properties like hydraulic conductivity, transmissivity, storage coefficient and aquifer geometry of the rocks in the carchment should be determined in future works using additional borehole data.
- In order to decrease losses during irrigation, efficient irrigation techniques like drip irrigation should be employed especially by investors irrigating large area to minimize the excess water lost due to evaporation. Such technique can help to develop more area using the same amount of water.

- Water harvesting has to be practiced especially in the lowland areas where there is high evaporation that depletes available moisture in the areas so as to reduce abstraction from other sources
- Groundwater development is needed for communities living in the downstream of the lake who are facing water supply problem when the flow of Bulbula River diminishes.
- Efficient irrigation using groundwater is important especially at high resource areas like eastern fault escarpment where Katar River losses to supplement existing schemes and reduce direct abstraction from surface resources.
- Soil and water conservation should be practiced in the area; by: tree plantation, fallowing, and contour farming to increase groundwater recharge and reduce land degradation which can potentially bring losses of available moisture; including lake.
- In order to avoid over abstraction from the lake especially during the years of less precipitation in the catchment, the lake level should be monitored before irrigation activities in the area.
- Community awareness and training about the effect of their activities on the hydrologic environment as well as efficient and sustainable use of their water resources.
- Focusing on high value crops, using limited area and water, can reduce the amount of abstracted water, increase productivity and hence the achievement of equitable water resource distribution.

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Station	Abura	Areta	Asela	Bokoji	Bui	Butaira	Diga-lu	Ejer-salele	Katarguent	Kersa	Koshe	Kulumsa	Meki	Meraro	Sagure	Tora	Ziway
Abura	1.00	0.93	0.88	0.84	0.97	0.76	0.84	1.00	0.88	0.87	0.96	0.90	1.00	0.85	0.88	0.91	0.94
Areta	0.93	1.00	0.96	0.83	0.90	0.69	0.86	0.93	0.93	0.86	0.95	0.89	0.93	0.84	0.93	0.90	0.93
Asela	0.88	0.96	1.00	0.84	0.85	0.64	0.87	0.88	0.88	0.87	0.90	0.90	0.88	0.85	0.88	0.85	0.88
Bokoji	0.84	0.83	0.84	1.00	0.81	0.75	0.99	0.84	0.78	0.83	0.86	0.80	0.84	0.93	0.90	0.81	0.84
Bui	0.97	0.90	0.85	0.81	1.00	0.79	0.81	0.97	0.85	0.84	0.93	0.87	0.97	0.82	0.85	0.88	0.91
Butaj-ira	0.76	0.69	0.64	0.75	0.79	1.00	0.72	0.76	0.70	0.72	0.75	0.75	0.76	0.79	0.70	0.73	0.76
Diga-lu	0.84	0.86	0.87	0.99	0.81	0.72	1.00	0.84	0.81	0.83	0.86	0.83	0.84	0.93	0.93	0.81	0.84
Ejer-salele	1.00	0.93	0.88	0.84	0.97	0.76	0.84	1.00	0.88	0.87	0.96	0.90	1.00	0.85	0.88	0.91	0.94
Katarguent	0.88	0.93	0.88	0.78	0.85	0.70	0.81	0.88	1.00	0.81	0.93	0.87	0.88	0.79	0.88	0.85	0.94
Kersa	0.87	0.86	0.87	0.83	0.84	0.72	0.83	0.87	0.81	1.00	0.89	0.83	0.87	0.90	0.81	0.96	0.87
Koshe	0.96	0.95	0.90	0.86	0.93	0.75	0.86	0.96	0.93	0.89	1.00	0.88	0.96	0.87	0.90	0.93	0.99
Kulumsa	0.90	0.89	0.90	0.80	0.87	0.75	0.83	0.90	0.87	0.83	0.88	1.00	0.90	0.81	0.84	0.81	0.87
Meki	1.00	0.93	0.88	0.84	0.97	0.76	0.84	1.00	0.88	0.87	0.96	0.90	1.00	0.85	0.88	0.91	0.94
Mera-ro	0.85	0.84	0.85	0.93	0.82	0.79	0.93	0.85	0.79	0.90	0.87	0.81	0.85	1.00	0.85	0.88	0.85
Sagure	0.88	0.93	0.88	0.90	0.85	0.70	0.93	0.88	0.88	0.81	0.90	0.84	0.88	0.85	1.00	0.85	0.88
Tora	0.91	0.90	0.85	0.81	0.88	0.73	0.81	0.91	0.85	0.96	0.93	0.81	0.91	0.88	0.85	1.00	0.91
Ziway	0.94	0.93	0.88	0.84	0.91	0.76	0.84	0.94	0.94	0.87	0.99	0.87	0.94	0.85	0.88	0.91	1.00

Annex 1. Correlation matrix between precipitations in different stations (Alemu Diribsa 2006)

Annex 2. Integrated vegetation and available water holding capacity of different soil types(Alemu Diribsa 2006)

Vegetation group	Soil texture	Rooting depth	Available water Capacity(mm)	Area( %)		
				H	E	R
Shallow rooted plants(spinach, peas beans etc.)	Fine sand	0.50	50	21	-	-
	fine sandy loaam	0.50	75	-	-	29
	Silty loam	0.62	125	14	100	71
	Clay	0.25	75	65	-	-
Moderately deep deep rooted plants(corn,cereals, etc.)	Fine sand	0.75	100	20	-	-
	fine sandy loaam	1.00	150	-	-	69
	Silty loam	1.00	250	14	100	31
	Clay	0.50	200	66	-	-
Deep rooted crops(alfalfa,grasses, bushes and shrubs)	Fine sand	1.00	100	66	-	-
	fine sandy loaam	1.00	150	-	-	25
	Silty loam	1.25	250	-	100	75
	Clay	0.67	200	34	-	-
Mature forest woodland	Fine sand	2.50	250	35	-	-
	fine sandy loaam	2.00	300	-	-	-
	Silty loam	2.00	400	-	-	100
	Clay	1.17	350	65	-	-

H: Highland    E: Escarpment    R: Rift floor

Annex 3 Monthly mean Class A pan evaporation(Alemu Diribsa 2006)

No	Statiom	Month											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Meraro	149	174	156	137	149	90	67	69	90	116	140	144
2	Kulumsa	153	188	167	160	168	118	91	78	87	165	177	162
3	Ziway	169	207	185	180	186	165	122	110	116	181	196	188
4	Bui	176	196	196	186	183	118	90	86	110	170	185	175

Annex 4 Approximate Range of Seasonal ET crop in mm (Alemu Diribsa 2006)

Seasonal ET crop	mm	Seasonal ET crop	mm
Alfalfa	600-1500	Onions	350 - 600
Avocado	650- 1000	Orange	600 - 950
Bananas	700 - 1700	Potatoes	350 - 625
Beans	250 - 500	Rice	500 - 950
Cocoa	800 - 1200	Sisal	550 - 800
Coffee	800 - 1200	Sorghum	300 -650
Cotton	550 - 950	Soybeans	450 -825
Dates	900- 1300	Sugarbeets	450 - 850
Deciduous trees	700- 1050	Sugarcane	1000 - 1500
Flax	450- 900	Sweet potatoes	400 - 675
Grains (small)	300- 450	Tobacco	300 - 500
Grapefruit	650 - 1000	Tomato	300 - 600
Maize	400 - 750	Vegetables	250 - 500
Oil seeds	300 - 600	Vineyards	450 - 900
		Walnuts	700 - 1000

Annex 5 Groundwater table elevation (m) (Alemu Diribsa 2006)

No	Location	XUTM	YUTM	GWL altitude	No	Location	XUTM	YUTM	GWL
1	Meki nueplity	479988	900609	1610	39	Doya	497823	884832	1608
2	Ate Meti	474664	902456	1615	40	Golbe	496185	890206	1774
3	Laluna Dero	469030	901999	1640	41	Hallo	501517	887144	1669
4	Dugda	460343	901488	1829	42	Horde	505307	895726	1669
5	Choroke	471543	898467	1622	43	Kararu	494143	883539	1607
6	Korke Adi	476314	897861	1630	44	Kiyansho	494534	874497	1676
7	Abonn	471774	892430	1635	45	Kobota	491921	870986	1724
8	Chefe	484943	896277	1636	46	Korbeyyi 3	504121	891438	1672
9	Welinbula	461393	887564	1625	47	Lammaffo	500706	897575	1782
10	Abosa	469237	886519	1623	48	Oda Dima	497883	898267	1644
11	Beda Gosa	469806	890976	162 6	49	Ogolcho	501573	888485	1639
12	Negallign	468657	886623	1645	50	Sango Lakke	497443	892522	1552
13	Edo Kontola	469071	882855	1627	51	Shanan	496332	896999	1662
14	Gubiba	457350	887119	1661	52	Sheled Goto	500226	884570	1711
15	Galo Fechasa	462131	883354	1619	53	Tirratti	497648	896992	1649
16	Hesbawi Batele	468296	879413	1643	54	Toya Leman	509634	892212	1764

17	Ziway prison	467438	877282	1611
18	Koshe	448573	884180	1830
19	Faka	447136	880164	1891
20	W. Gerbi	465881	875514	1625
21	Boromo	460735	874769	1604
22	Woleyie	463164	870844	1617
23	Shisho Tabo	462052	866226	1614
24	Adami Tulu	467301	869468	1609
25	Garbi	468448	871433	1624
26	Waji	514202	870371	2528
27	Abura	500220	889567	1675
28	Gonde	521570	887113	2265
29	Burkitu	510611	883617	2120
30	Abargeda	499840	889943	1699
31	Adulala	495776	886600	1636
32	Andode	505428	890015	1740
33	Arba	508715	897993	1694
34	Baddara	498435	882864	1613
35	Bowenni	501266	889596	1595
36	Burka	497049	892945	1641
37	Ch.e Burkitu	489704	867598	1793
38	Choba	495299	884905	1644

55	Udada	495014	884350	1643
56	Hellanna	513788	870666	2557
57	Mulqiicha	495969	863601	1898
58	Shola Chabetti	514055	866034	2566
59	Wanji Gora	516954	884109	2278
60	Totoke	473605	827856	1623
61	Kurteta	480132	824147	1811
62	Buku	476682	829321	1621
63	Gubeta	477268	830389	1622
64	Digalu	510579	859046	2409
65	Doddoba	496886	878152	1675
66	Mereko Woreda	429307	897130	1871
67	Meskan oreda	449039	891512	1825
68	Meskan Woreda	440217	886397	1833
69	Meskan Woreda	439248	896637	1873
70	Meskan Woreda	428001	877580	1824
71	Meskan Woreda	441911	891294	1817
72	Meskan Woreda	442504	904859	1832
73	Meskan Woreda	424189	892802	2179
74	Soddo Woreda	434853	907907	2054
75	Soddo Woreda	440353	918436	2702
76	Soddo Woreda	449186	933018	2651

Annex 6 Annual discharges of main rivers in the catchment (Alemu Diribsa 2006)

Year	Katar at Abura	Katar at Fite	Meki at Dugda	Meki at Meki town	Arata at Chufa	Ashebeka near Sagure	Temala near Sagure	Bulbula near Adami Tulu
1970	610		348	334				
1971	384		333	321				
1972	327		359	350				
1973	322		248	211				
1974	288		275	240				
1975	575		384	317				
1976	324		230	176				
1977	529			406				
1978	421			228				
1979	418			361				232
1980	276			170				39
1981	574			319				144
1982	345			237		45	24	79
1983	827	571		334		98	56	395
1984	250	180		135		35	11	103
1985	296	274		172	36	39	11	21
1986	431	302		181	39	63	20	43
1987	288	208		216	53	39	11	63
1988	528	486		230	45	74	56	112
1989	288	243		220	52	34	19	127
1990	310	372		331	42	46	25	139
1991	333	267		271	119	45	18	159
1992	466	346		412	121		34	228
1993	460	434		456	115		23	353
1994	446			391	99		30	209
1995	411	405		261	125		31	135
1996	421	401		535				344
1997	208	150		185			10	212
1998	508	574		499			52	321
1999	364			281			18	271
2000	365			299				192
2001	521			437				290
2002	202			196				113
2003	329			365				28
2004	322			294				16

Annex 7 Annual level of Ziway Lake (Alemu Diribsa 2006)

Year	Lake level			Year	Lake level		
	Average	Max.	Min.		Average	Max.	Min.
1975	0.78	1.64	0.13	1990	1.26	1.74	0.88
1976	0.90	1.23	0.60	1991	1.11	1.65	0.69
1977	0.97	1.68	0.51	1992	1.13	1.75	0.66
1978	1.34	1.74	0.86	1993	1.36	1.80	0.95
1979	1.32	1.72	1.06	1994	1.17	1.76	0.71
1980	0.91	1.83	0.52	1995	1.11	1.47	0.90
1981	0.80	1.31	0.38	1996	1.36	2.24	0.72
1982	0.99	1.31	0.66	1997	1.30	1.53	1.11
1983	1.39	2.18	0.81	1998	1.31	2.13	0.79
1984	1.06	1.44	0.77	1999	1.31	1.81	0.82
1985	0.62	1.07	0.26	2000	1.15	1.58	0.74
1986	0.68	1.18	0.36	2001	1.45	2.25	0.94
1987	0.94	1.21	0.69	2002	1.14	1.57	0.80
1988	0.68	1.39	0.18	2003	0.69	1.19	0.23
1989	0.97	1.36	0.70	2004	0.71	1.11	0.37

Annex 8 monthly percentage of abstraction as total annual from lake (Alemu Diribsa 2006)

Month	%
Jan	17
Feb	11
Mar	14
Apr	4.5
May	7.3
Jun	4.6
Jul	2.2
Aug	0.5
Sep	5.9
Oct	7
Nov	11
Dec	15

Annex 9. Annual precipitation, pan evaporation, estimated lake evaporation and baseflow (Alemu Diribsa 2006)

Year	Precipitation					Catch-ent Pan Evapora- tion	Lake surface E (Penman)	Base flow (mcm)	
	Catchment	Meki Cat. P	Katar Cat.P	Asela	Butaji ra			Meki	Katar
1970	886	1207	844	1420	1484				
1971	860	1026	852	1283	1044				
1972	918	1200	813	1256	1415				
1973	737	692	776	919	702				
1974	797	845	728	917	893				
1975	845	924	814	1159	1034				
1976	807	912	818	1446	1072				
1977	1062	1068	1052	1356	1114				
1978	922	838	961	1179	712				
1979	1076	1176	1044	1423	1272		1506		
1980	721	771	737	1117	908		1461		
1981	966	973	992	1197	1077		1500		
1982	1003	1092	1038	1566	1419		1443		
1983	1138	1336	1046	1428	1419		1553		
1984	816	779	900	1195	787		1631		
1985	806	854	809	1086	889		1571		
1986	946	947	1041	1387	1061		1605		
1987	879	1029	863	903	1251		1736		
1988	885	931	943	908	1113		1731		
1989	942	1051	891	1020	1289		1673		
1990	964	1151	924	960	1467		1727	219	317
1991	840	968	832	804	1158		1692	249	239
1992	924	1021	893	1096	1149		1647	250	311
1993	1033	1256	933	1023	1449		1646	264	331
1994	789	873	824	1100	1025		1709	234	315
1995	872	1086	872	1080	1151	1625	1753	153	264
1996	1011	1288	873	1132	1471	1522	1671	303	293
1997	884	979	831	1184	1237	1713	1709	103	155
1998	945	1136	889	1088	1354	1638	1721	284	313
1999	763	866	750	828	987	1712	1649	118	342
2000	803	852	810	1062	865	1893	1689	67	246
2001	962	1143	943	1444	1291	1721	1739	110	361
2002	708	866	704	780	1158	1999	1794	115	218
2003	827	959	751	977	1167	1927	1727	155	236
2004	782	824	813	1061	894	1883	1760	145	239

P : Precipitation