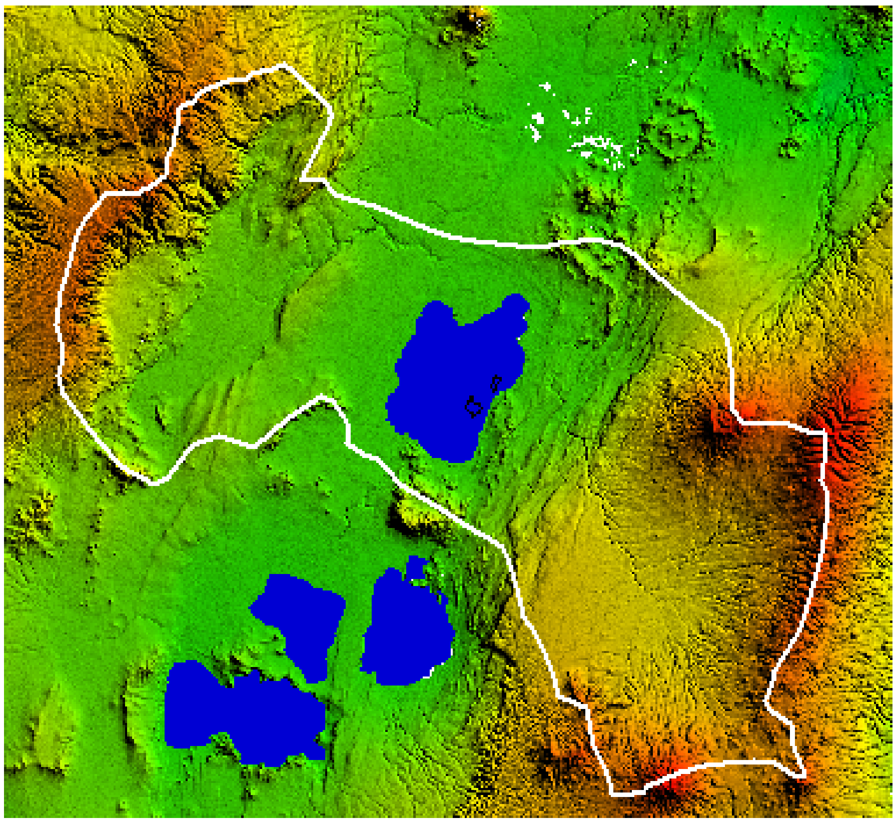
ADDIS ABABA UNIVERSITY

SCHOOL OF GRADUATE STUDIES

DEPARTMENT OF EARTH SCIENCES

GROUNDWATER–SURFACE WATER INTERACTION AND ANALYSIS OF RECENT CHANGES IN HYDROLOGIC ENVIRONMENT OF LAKE ZIWAY CATCHMENT



A THESIS SUBMITTED TO THE SCHOOL OF GRADUATE STUDIES OF ADDIS ABABA UNIVERSITY IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTERS IN HYDROGEOLOGY

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ANNEXES

ABSTRACT

The study area is 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. 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 loosing 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.

CHAPTER ONE

INTRODUCTION

1.1 Background

Of all the substances that are necessary to life on the earth, water is by far the most important to sustain life. Water is abundant, yet frequently scarce and characterized by uneven spatial and temporal distribution.

Water is finite resource and must be managed in sustainable way to meet human as well as environmental needs. The sustainable use of water is becoming increasingly important in legislative agenda of the country. The overall goal of the National Water Resource Policy is to enhance and promote all national efforts toward the efficient, equitable and optimum utilization of the available water resources of the country for significant socio-economic development on sustainable basis.

Rift valley and its environment are important area in the country in connection with their water resources. It is where lakes useful for agricultural production, industrial and recreation are present. Highlands adjacent to the lake are important agricultural areas using both rain-fed and irrigation from closely spaced rivers and tributaries draining high altitude areas that get large annual precipitation.

Recently, the cumulative effect of increase in population and climate change that enhance over abstraction of water to meet fast growing demand are threatening the area. The impact is more pronounced in the down stream areas where there is poor groundwater development and the people have been using surface water for home consumption and their livestock.

In order to manage equitable distribution of water in the area, determination of total available resources is critically important. 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. Identification of factors accountable for depletion of water resources is useful for policy makers to manage the problem with respect to the rising demand.

The research is therefore, an important input for water resource management of the area to provide sustainable and equitable supplies for communities in and around the catchment.

1.2 Previous Work

A number of studies have been carried out in Central Ethiopian Rift Valley that includes the study area. These studies have been focusing on 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:

Di Pola (1972), 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 7^0 00’ to 8^0 40’N latitudes.

Wenner(1972), 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.

Tesfaye Chernet (1982), Presented a regional geological and hydrogeological map of Ziway – Shala basin. The report includes regional classification of rocks in to different permeability groups.

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

Haile Gashew(1998), Studied Hydrogeology and Hydrology of lake Ziway area and its surroundings. In this work lake water balance and hydrogeology of part of the current study area were investigated.

Tenalem Ayenew, (1998), In his Ph.D thesis entitled 'The hydrogeological system of lakes district basin, Central Ethiopian rift', he analyzed general hydrology and hydrogeology of Ziway–Shala basin. The study includes evaluation of groundwater and surface water interaction, water balance and recharge estimation of subcatchments.

JICA and OIDA (2001), 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.

Dainelli et al (2001), Prepared Geological Map of the Ziway-Shala Lakes Basin.

Dagnachew Legesse (2002), presented in his 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.

In all studies conducted so far, there is limited consideration of the role of geological structure and geological units in affecting the hydrogeological dynamics of the catchment under consideration. Moreover, the current study considers these factors to critically estimate direct groundwater recharge. Monthly basis lake water balance calculation after incorporating recent data to the existing ones and assessment of recent changes in hydrology and hydrogeology of the area are new works that supplement the existing ones to provide useful information for Policy makers and general public to manage the resource on sustainable basis.

1.3 Research Objectives

The general objective of the research is to analyze groundwater-surface water interaction and assess recent changes in hydrological environment of Lake Zeway catchment

The specific objectives are the following:

1. To estimate direct groundwater recharge of Lake Zeway basin

2. To evaluate groundwater - surface water interaction and indirect groundwater recharge in the catchment

3. To perform monthly and annual lake water balance

4. To assess changes in hydrology and hydrogeology of the catchment and evaluate the sensitivity of lake level to climatic factors and human interfaces.

1.4 Methodology

- River discharge and meteorological data were collected from Ministry of Water Resources and National Meteorologic Service Agency respectively; and used for the analysis in many parts of this work.
- River discharge measurements were conducted using current meter along river reaches to determine the river losses or gains between the points; and characterize hydrogeologic dynamics of the area.
- Static water level and spring locations have been collected from Oromia and South Nations and Nationality States Water Resource Bureaus; and previous works. These data were used to construct groundwater table contour for determination of the relationship between river bed and contour elevation at a point.
- 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.
- Most of the work has been analyzed using important soft wares like Microsoft Excel, ARCVIEW3.3, SURFER 8, Global Mapper5, Time plot, Water balance, SPSS etc.

CHAPTER TWO

GENERAL OVERVIEW OF THE STUDY AREA

2.1 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^2 and bounded between latitude of 7^{0}20'54" to 8^{0}25'56" and longitude of 38^{0}13'02" to 39^{0}24'01".

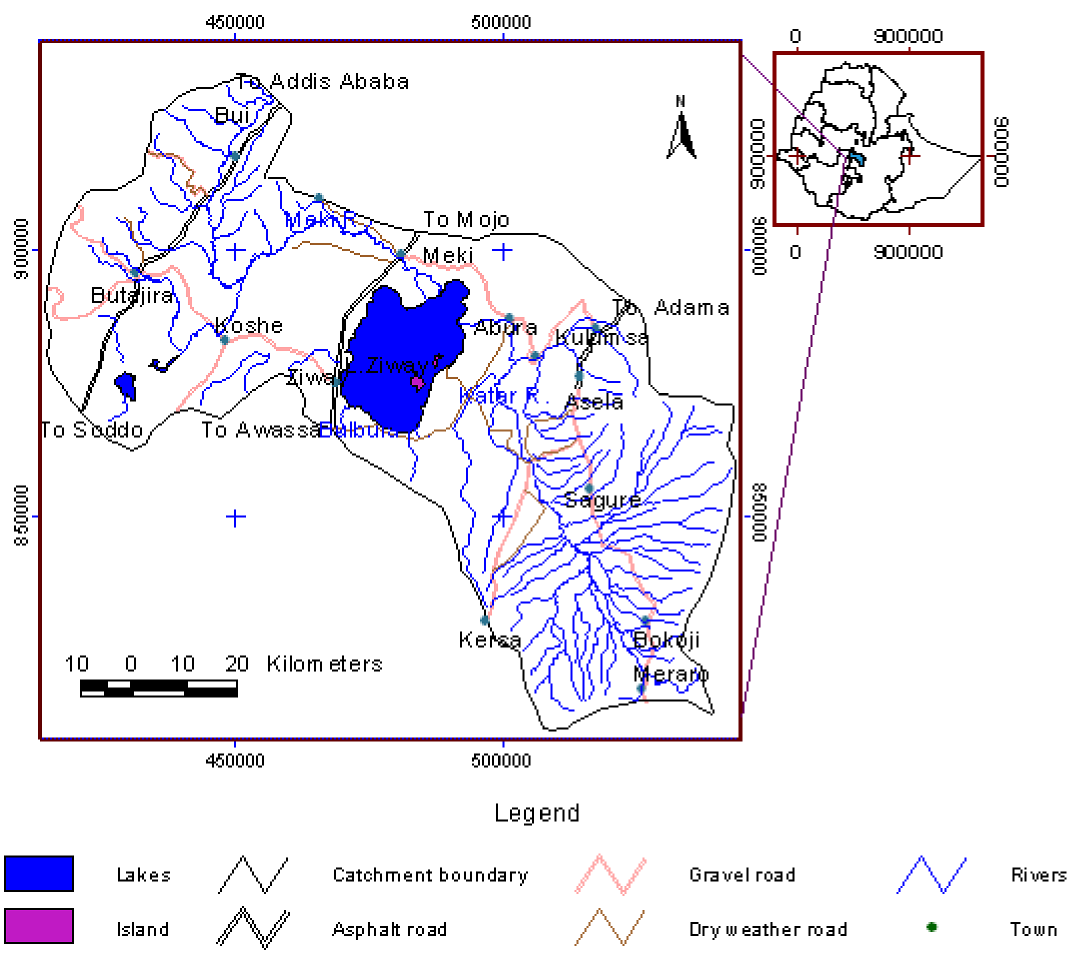


Figure 2.1 Location map of Lake Ziway Catchment

In this work, all maps are referenced by Zone 37, UTM and Adindan.

The catchment is accessed by Addis Ababa-Mojo-Ziway, Addis Ababa-Alem Gena-Butajira or Addis Ababa-Asela asphalt road. Intra catchment areas are accessed by numerous gravel and dry weather road.

2.2 Population

2.2.1 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.

2.2.2 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.

2.3 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 13.5^0C and 21.8^0C in different physiographic areas.

2.4 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 in to 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 1.1). 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 differences in rock permeability, climate and slope.

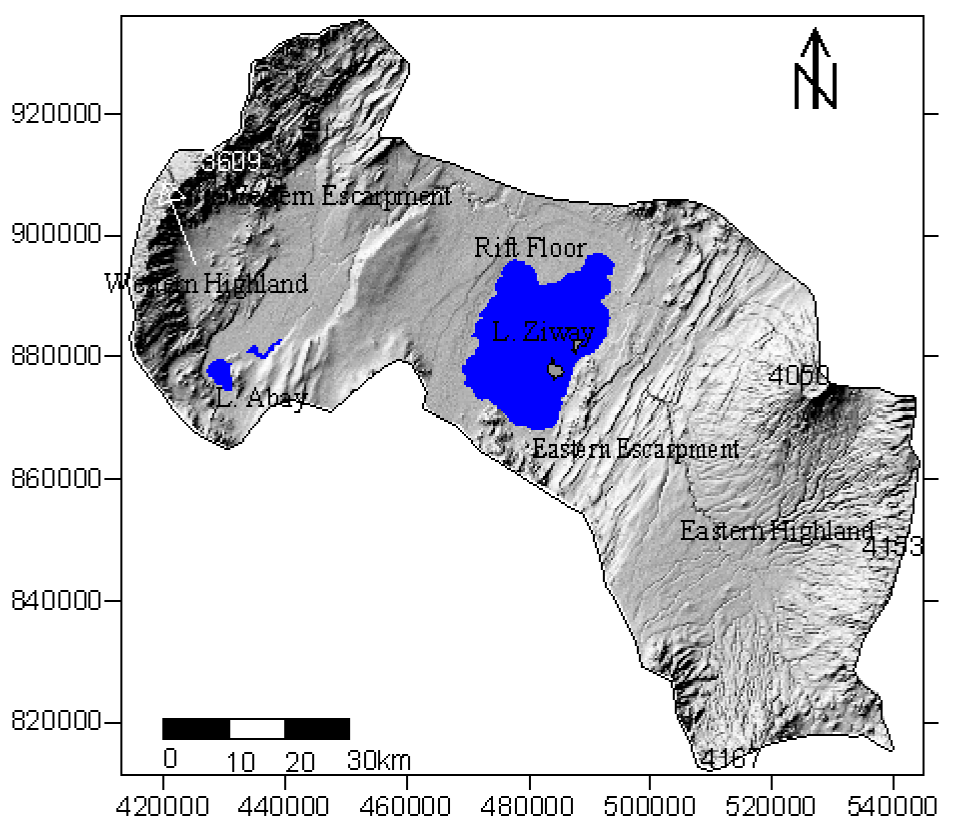


Figure 2.2 Topography of the catchment derived from digital elevation model

2.5 Soil, land use and land cover

2.5.1 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)

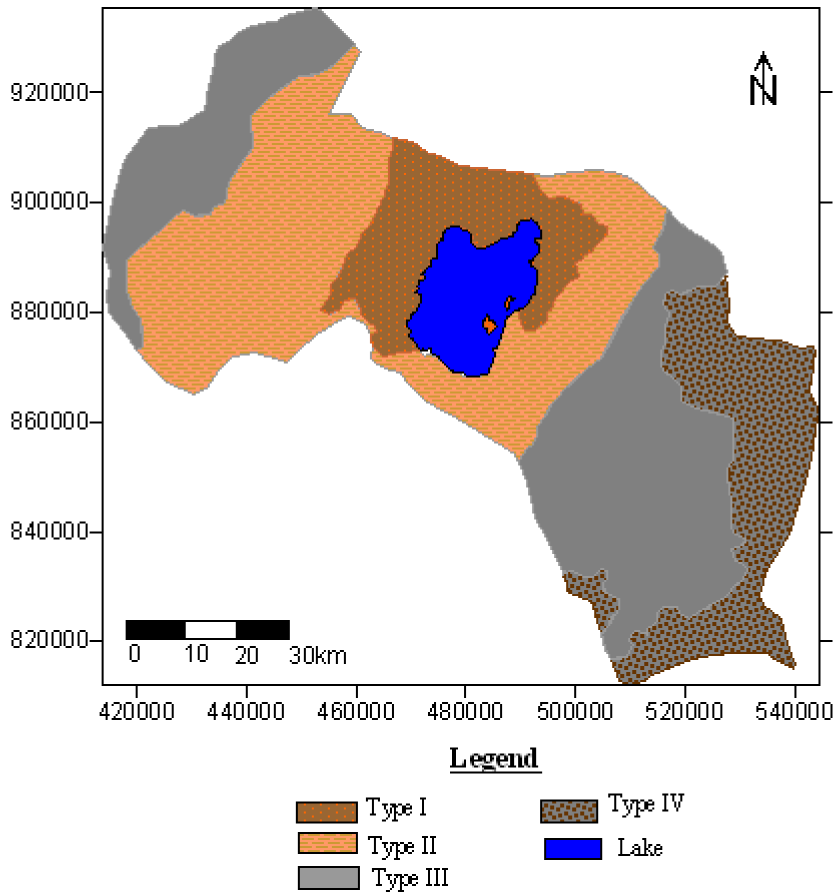


Figure 2.3 Generalized soil map of Lake Ziway catchment (from Makin et al, 976)

2.5.2 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 2.1 Arial distributions of land cover units

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

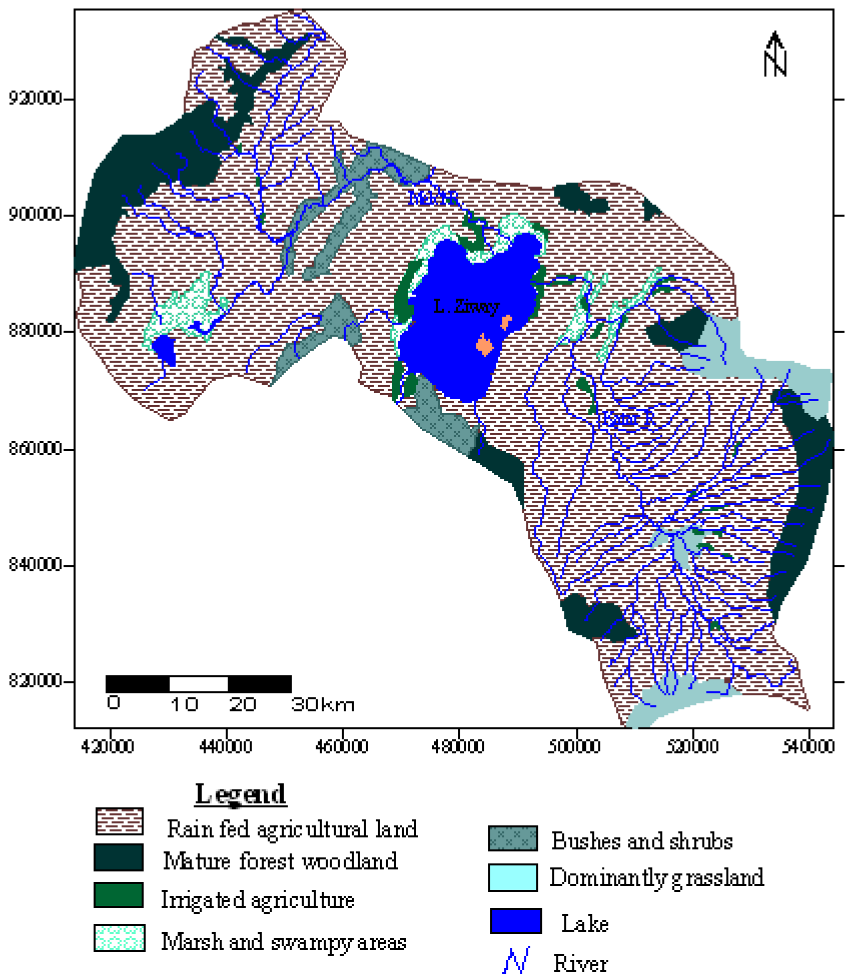


Figure 2.4 Land use/land cover map

CHAPTER THREE

GEOLOGY

3.1 Introduction

The geologic and geomorphic features observed in the region are the results of Cenozoic volcano-tectonic and sedimentary processes (Tenalem Ayenew, 1998). During this era there was extensive magmatism and faulting which modified the face of east Africa. The great Afro-Arabian rift system including the Ethiopian rift was formed following the Arabo-Swell which was followed by extensive episodic tectonic activity. The initial down faulting was accompanied by the extensive basaltic and sialic volcanism restricted to separate centers aligned with the rift axis.

At the commencement of Tertiary, extensive alkaline basalt extrusion occurred reaching up to 3000m in southern Ethiopia. The basalts are thought to have extruded through fissures indicating a zone of major crustal weakness related to regional doming. The basalt extrusions were inter-spread with large accumulations of rhyolite, trachyte and ignimbrite forming trap series.

During rift development, rapid subsidence of rift floor was accompanied by the formation of shield volcanoes in part of the main Ethiopian rift on both sides of the rift shoulders. The abortive phase of crustal extension to the east of the proto-rift gave rise to the extinct Pliocene trachytic shield volcanoes of the eastern highland which rest on trap basalts (Kunz et al., 1975 in Tenalem Ayenew, 1998). The volcanoes include Chilalo, Galama, Hunkulo, Kakka, Chike and Kubsa.

In the rift, recent continental type volcanism has developed, giving rise to large sialic rocks from the predominantly central type eruptions accompanied by partly fissural basic lava flows. The basalts are now concealed by cover of silicic stratoid volcanoes. Subsquent volcanic activities have been largely confined to the active Wonji Fault Belt running parallel to the rift axis (Mohr, 1967).

3.2 Stratigraphy

3.2.1 Nazreth Group and Dino Formation Undifferentiated

These groups are part of the trap series unconformably overlying Precambrian and Mesozoic rocks.

The Nazreth Group includes alkaline and alkaline stratoid, silicics, ignimbrites, unwelded tuffs, ash, rhyolites, trachytes. The rocks are intruded by dolorite sills, acidic dykes and gabbro- diabases. Individual basalt flows vary in thickness from one or two meter up to tens of meters. This group range in age from 9 to 12 million years B.P.

Dino formation is a sequence of contemporaneous and post-Nazareth volcanics. The formation extends from the highland boundaries through much of the valley slopes and escarpments, and in to floor of the rift valley. The sequence is acidic consisting predominantly of ignimbrite, tuff, layered pumice and reworked pyroclastics.

In the rift the Nazreth and Dino formation attain a thickness of up to 250m, while on the plateau it reaches only up to 30m.

3.2.2 Chilallo Volcanics

The group includes Chilello and Galama forming two elliptical shield volcanoes on the eastern rift shoulder formed in the upper Pliocene. This stratigraphic group consists of rhyolites, trachytes, trachybasalt and alkali basalt, and are widely observed between Asela and Bokoji in the eastern highland. These rocks are intruded by enormous radial dikes.

3.2.3 Basalts and associated flows of the rift floor

The formation of this group is from Pleistocene to Holocene and includes basaltic hyaloclastites and recent basalts outcropping in the rift floor.

The hyaloclastics consist of fine glassy material, generally yellowish to brown in color containing small boulders of basaltic lava.

The recent basalts are uninterrupted lava fields elongated parallel to the main tectonic trend of the rift (NNE-SSW) and were produced by fissure eruption. This basaltic group comprises of Wonji and Silte volcanics. The Wonji lava field is located close to the eastern escarpment, just east of Lake Ziway and reaches a thickness of about 100m. The other lava field, Silte is located close to the western escarpment just along the main fault which limits the rift in the Butajra Silte area.

3.2.4 The Central Rift volcanic complexes

The study area portion of the main Ethiopian rift valley consists of several individual volcaneous and volcanic complexes. The groups are characterized by rhyolytic lava flows and domes associated with the rift floor ignimbrites. The ignimbrites and pumice are the result of gas rich silicics magma. The alkaline and peralkaline silicics are the last volcanic products and are located in the slopes of Bericho, Bora, Aluto, Gadamotta and Chobbi Volcanoes. The pyroclastics are unwelded pumice and tuff, obsidian, pitchstone and rhyolitic lava flows.

The group is divided in to three units with respect to the study area and described as follows:

i. *Aluto volcanics*: These volcanics are of late Pleistocene-Holocene age, and represented by multiple flows. The rock forms are silicic pyroclastics such as pumice falls and ashes with subordinate lava flows, mostly obsidian. The lava flows descended the slope of the volcano in every direction frequently show a flowage folding. Both old and very recent obsidians are porphyritic, sometimes very rich in crystals.

ii. *Bora-Bericho*: The volcanics are formed in late Pleistocene - Holocene and consist of two large volcanic centers (Bora and Bericho) associated with a great number of smaller volcanic foci and with sub historical limited fissure eruptions. Most of the products found in this area are silicic pyroclastics. Bora volcano is located on the northeast of the study area and it consists of alternances of pumice and ash layers *iii.* poorly welded or completely unwelded. Baricho volcanics is located just northeast of Bora and comprises completely of unwelded pumice flows.

iv. *Gadamotta rhyolite*: This rhyolitic lava is of early Pleistocene alkaline and peralkaline lava and beded tuff covering small area in southwest of the study area.

3.2.5 Volcano-sedimentary rocks and lacustrine sediments

These sediments predominantly comprise volcanoclastic sediments, tuff and associated lacustrine sediments.

The lacustrine sediments include silts, clays, diatomite and materials of ash and tuff associated with rock fragments derived from wide varity of volcanic rocks.

The sediments must have been deposited during a wide time interval from the end of Pliocene until recent which is suggested by their considerable thickness and by the fact that in many places they underlie young volcanic products and are often rather deeply affected by regional faults. Besides volcano-sedimentary and lacustrine deposits alluvium is widely observed in valleys.

Eight lithostratigraphic units were identified in the study area:

i. *Pelite dominated lacustrine deposits*: deposits of pelite and peat (200 BP-Present)

ii. *Colluvium*: gravels, sands, silts and volcanic pyroclastics (mid Pleistocene-Recent)

iii. *Alluvial deposit*: mainly terrace gravel, sand and silt associated locally with clay (Holocene - Present).

iv. *Deltaic and fluvio-deltaic deposits*: deposits of sand, silt, and clay (Holocene).

v. *Meki and Kater deltaic deposits*: sand, silt and clay (Holocene).

vi. *Tufa fluvo-lacustrine deposits*: mainly gravel, sand, pelite, and peat (Holocene).

vii. *Ziway terrace and volcano-lacustrine deposits*: pyroclastics derived from ash and tuff. Also included are pelite, diatomite, silt, and clay with occasional shore sand and shell beds (Holocene).

vii. *Bulbula deposits*: volcano-lacustrine deposits, mainly pyroclastics derived from ash and tuff, and subordinate shell beds and sand.

3.3 Structure

The Ethiopian rift valley is a graben with average width of 80km in the study area. Tensional movements are responsible for formation of the rift which produced a number of normal faults (Di Pola, 1972). These faults run in NNE - SSW direction or in few cases in NE - SW and more rarely in N - S direction. A large number of these faults run for long stretches even hundreds of kilometers and show displacements greater than 300m.

Some differences exist in the tectonic lineaments between the eastern and western escarpments. The eastern escarpment is characterized for all its length by step faults with an important through compared to the distance from one block to the other. On the other hand the western escarpment shows in its N - E sector an abrupt displacement, some times exceeding 1500m while in its S - W sector the main faults have a small down throw and progressively die out.

The different tectonic styles of the two rift margins make the rift valley asymmetric in the study area. The main reasons for this asymmetry are the difference in faulting characteristics on the two rift margins and the effect of young faults of Wonji Fault Belt which shattered the rift floor in to several relatively small horst and graben.

The most depressed areas are occupied by lakes or swamps. The numerous faults forming the youngest tectonic lines close to the eastern escarpment and running parallel to each other in NNE - SSW form an ec-echlon fault set as a result of the rift margin due to transcrent faulting across the fault Mohr (1968).

The tectontc movements are still active in Ethiopian rift valley as confirmed by young faults often affecting recent formations and high seismicity of the whole region (De pola 1972).

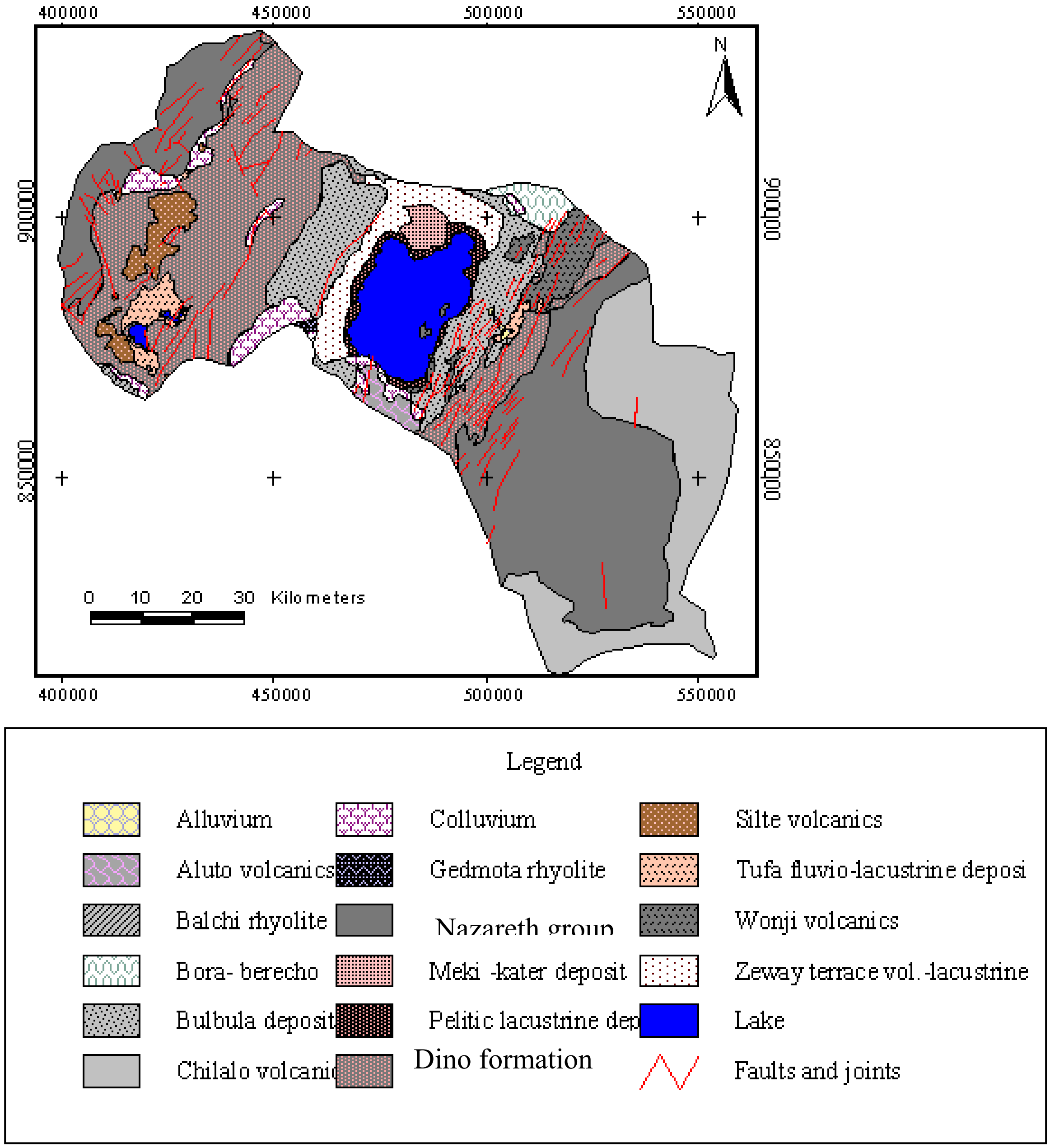


Figure 3.1 Geologic Map (taken from Tenalem Ayenew,1998)

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 Garaghe 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 and Ishyetal methods.

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

The Isohyetal method makes use of joining points of equal rainfall values and then measures their inter isohyetal area. The mean annual precipitation of the catchment using this method is 896mm.

Table 4.2 Arial mean depth of precipitation using Theissen polygon

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

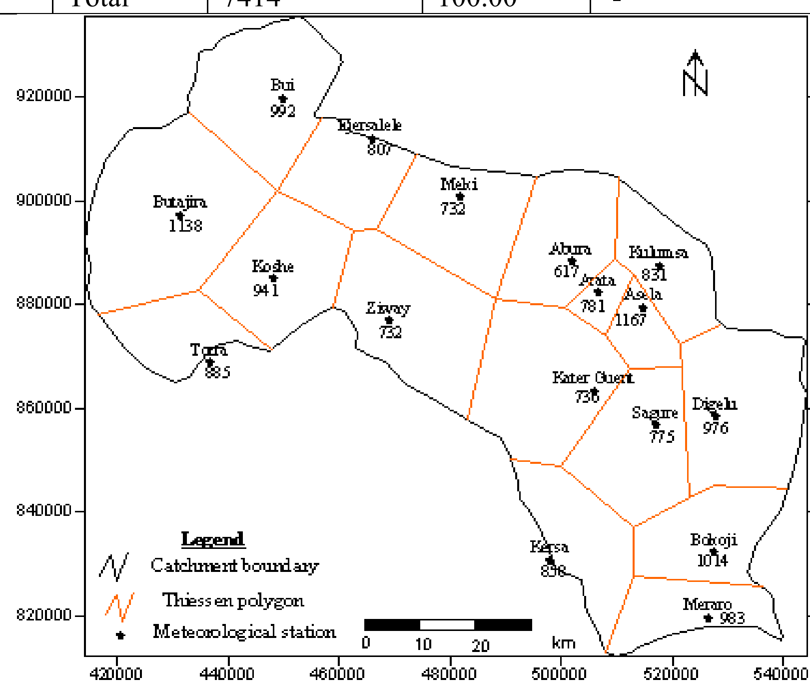


Figure 4.1 Thiessen polygon (station/annual precipitation, mm)

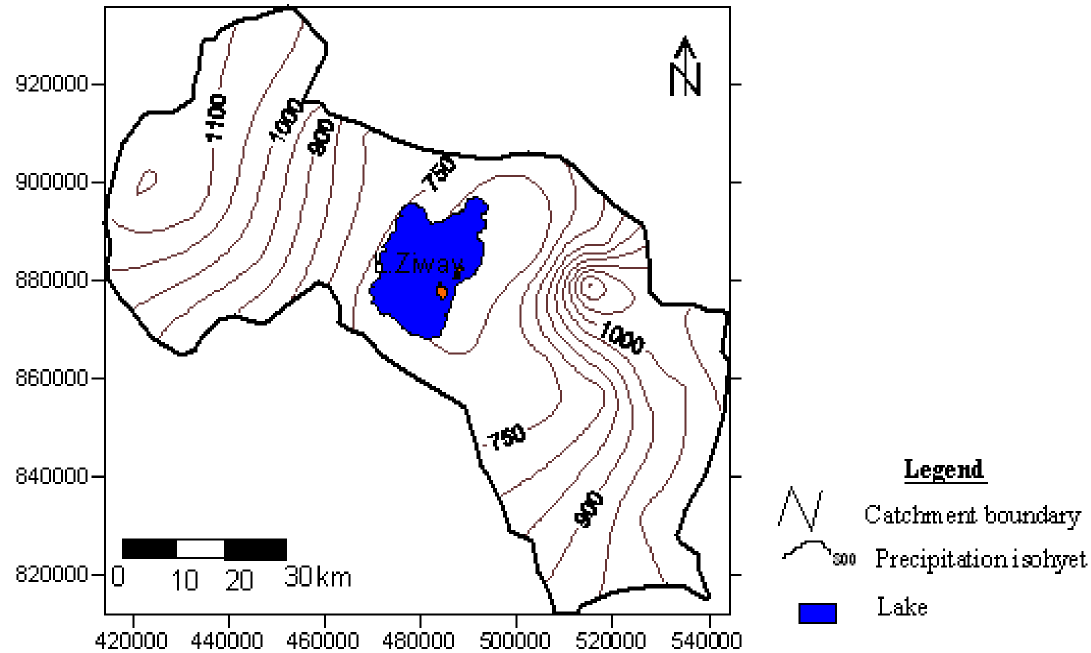


Figure 4.2 Isohyetal map (mean annual precipitation isohyets, mm)

Table 4.3 Arial mean depth of precipitation using Isohyetal method

Position of Isohyet	Isohytal range	Area between Isohyets (km^2)	Weighted area (%)	Average value of isohyets	Weighted precipitation(mm)
Western part	750-800	355	4.79	775	37
	800-850	210	2.83	825	23
	850-900	228	3.08	875	27
	900-950	290	3.91	925	36
	950-1000	591	7.97	975	78
	1000-1050	416	5.61	1025	58
	1050-1100	299	4.03	1075	43
	1100-1150	492	6.64	1125	75
	>1150	14	0.19	1150	2
Central part	<700	567	7.64	700	53
	700-750	1156	15.59	725	116
Eastern part	750-800	410	5.53	775	43
	800-850	323	4.36	825	36
	850-900	338	4.56	875	40
	900-950	451	6.08	925	56
	950-1000	481	6.49	975	63
	1000-1050	646	8.7	1025	89
	1050-1100	124	1.7	1075	18
	>1100	23	0.31	1100	3
	Total annual precipitation				896mm

Table 4.4 Mean monthly precipitation in river catchments using data of Thiessen polygon(mm)

Catchment	Area (km2)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann-ual
Meki	2256	29	53	99	103	92	107	180	172	112	41	8	9	1005
Kater	3302	21	39	70	88	90	98	153	154	95	47	14	12	881
Lake surface	440	16	32	56	71	68	80	152	130	86	36	5	4	736
Ungauge catchment	1416	16	35	58	73	71	82	150	133	90	37	6	6	757

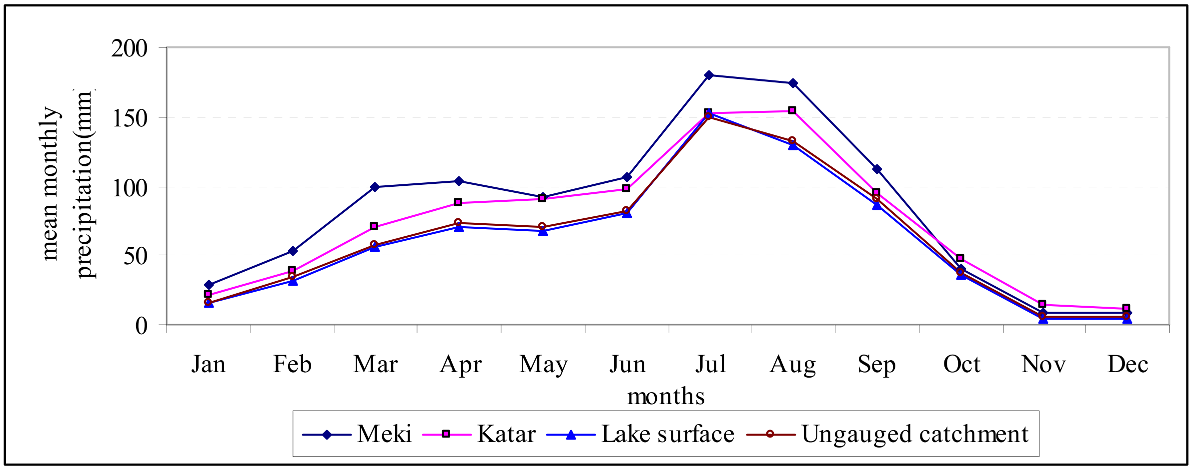


Figure 4.3 Mean monthly distribution of precipitation in River Catchments and on Lake Surface

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

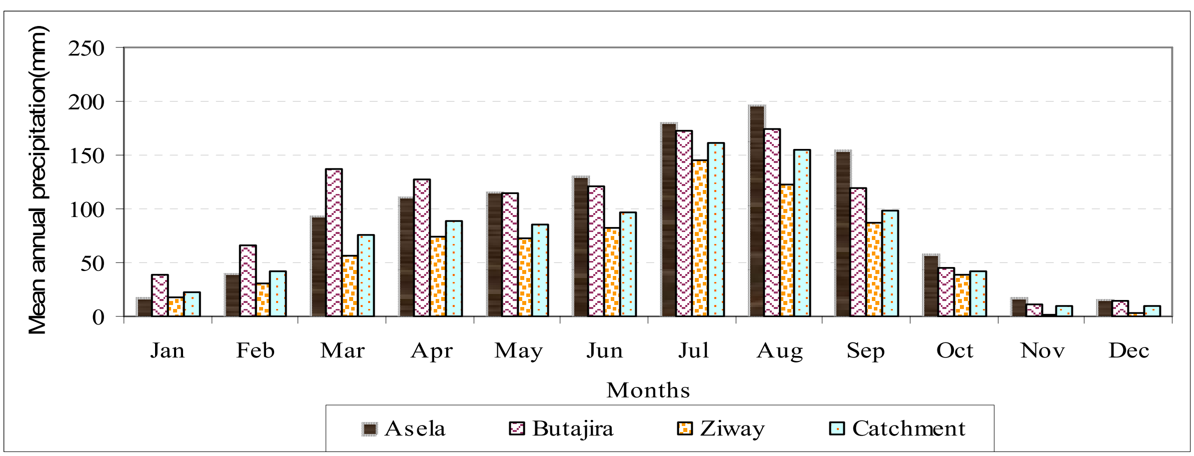


Figure 4.4 Mean monthly precipitations of selected stations and overall weighted catchment area

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 (o_C)

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):

$$RH = 100ed/ea \quad (4.1)$$

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 (%)

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)

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 continues 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)

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

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

$$m = 1,2,3\ldots12$$

Where t_m is mean monthly temperature in 0_C. The twelve monthly heat indexes are then added to obtain the annual heat index I.

$$I = tm\sum_{m=1}^{12} im \qquad (4.3)$$

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

$$PET = 1.6b(10t_m/5)^a \qquad (4.4)$$

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

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

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

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

4.3.2.2 Penman aerodynamic and energy budget combined method

Penman combined the energy balance with the mass transfer methods of evaporation estimates; and derived an equation to compute the evaporation from an open water surface using standard climatological records of sunshine, temperature, humidity and wind speed. Later on the equation was modified (MAFF, 1967 in Shaw,1994) to allow for the condition under which evaporation plus transpiration takes place from a vegetated surface.

i. Lake Water Evaporation

The basic Penman formula for open water evaporation is:

$$Eo = \frac{\frac{\Delta}{\gamma} H + Ea}{\frac{\Delta}{\gamma} + 1} \qquad (4.7)$$

Where:

E_0 : evaporation rate (mm /day)

Ea : energy for evaporation (mm/day)

Δ : slope of the curve of saturated vaprer pressure plotted against temprature and

γ : hygrometric constant taken as 0.27 mmHg/^{o} F.

The equation is derived from a simplified energy balance formula:

$$H = Eo + Q \quad (4.8)$$

Where;

H : available heat.

Eo : rate of for evaporation

Q : energy for heating air.

The value of E_0 and Q can be defined by aerodynamic equation as

$$E_o = f(u)(e_s - e_d) \quad (4.9)$$

and:

$$Q = \gamma f_1(u)(T_s - Ta) \quad (4.10)$$

The slope of the curve of saturated vapor pressure plotted against temperature, Δ is represented by the formula:

$$\Delta = \frac{ea - ed}{Ta - Td} \quad (4.11)$$

then, $Q = \gamma f(u)\left[\left(\frac{es - ed}{\Delta}\right) - \left(\frac{ea - ed}{\Delta}\right)\right]$

$$Q = \gamma\, Eo/\Delta + \gamma\, Ea/\Delta \quad (4.12)$$

Where, ed : actual vapor pressure at dew point temperature (Td)

ea : saturated vapor pressure at air temperature (Ta)

$ea - ed$: the saturation deficit

es : saturation vapor pressure of the air at the water surface (mm of mercury)

$f(u)$: a function of wind speed

Ta is easily measured and ea is also obtained from table or graph against Ta

ed is calculated from equation 4.1.

More often, H is calculated from incoming radiation (RI) and out going radiation (Ro) determined from the sunshine records, temperature and humidity using the relation:

$$H = RI(1-r) - Ro \tag{4.13}$$

Where, r : the albedo and equals 0.05 for water.

RI : a function of the solar radiation (Ra) which is fixed by altitude and season modulated by a function , n/N ,

n : measured sunshine hours in a day and

N : possible sunshine hours,

for r =0.05,

$$RI(1-r) = 0.95 Rafa(n/N) \tag{4.14}$$

Penman used *fa(n/N)= (0.16+0.62n/N)* for latitude south of $54^{1/2}$

$$Ro = \sigma T_a^4 \left(0.56 - 0.09\sqrt{ea}\right)\left(.0.1 + 0.90\, n/N\right) \tag{4.15}$$

Where, σT_a^4: the theoretical black body radiation at Ta

Ra : solar radiation

N and Ra are expressed in mm/day and taken from standard meteorological tables. For this Work, N and Ra is taken from Shaw, (1994) at 8^o north latitude.

Then H in equation 4.7 is obtained from value found in equation 4.14 and 4.15 inserted into equation 4.13.

$$Ea = 0.35(0.5 + u_2/100)(ea - ed) \tag{4.16}$$

Where u_2 is mean wind speed at 2m above the ground surface.

Using the above approach, the mean annual evaporation of the lake is 1749mm.

In addition evaporation from lake was estimated using US class A pan situated at Ziway station; and found to be 2047mm. Since evaporation from pan exceeds that of the nearby lake due to differences in heat storage capacity, air turbulence, heat exchange, advective energy, etc, pan coefficient of 0.83 was used (Tenalem Ayenew, 1998, HALCROW, 1992). Accordingly, the mean annual evaporation from the lake is 1699mm.

Table 4.9 Mean monthly Lake water evaporation using Pan and Penman methods (mm)

Method	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Penman	146	147	165	154	163	143	123	133	133	147	149	146	1749
Pan (1995-2004)	182	209	185	179	184	163	125	114	120	186	205	196	2047

ii. Evapotranspiration from land surface

The Penman-Monteith form of the combination equation for the calculation of potential evaporation and transpiration from vegetated surface is given by the equation:

$$PET = \frac{\frac{\Delta}{\gamma} Ht + Eat}{\frac{\Delta}{\gamma} + 1} \qquad (4.17)$$

Where, subscript t signifies inclusion of transpiration effects.

$Ht = RI(1 - r) - Ro$

Where: r is the reflective coefficient for incident radiation or albedo of the vegetation covers of the catchment that depends on the nature of the surface. As described in section 2.5 the dominant land cover of the study area are mature forest, bushes and shrubs, grasses and cultivated crops; and therefore albedo of 0.24 is taken for the catchment.

$$Ht = 0.76RI - R0 \qquad (4.18)$$

Eat is very similar to Ea in equation 4.16 except the coefficient 0.5 is being replaced by 1 to allow for the extra roughness in wind speed function (Shaw, 1988).

$$Eat = 0.35(1 + u_2/100)(ea - ed) \qquad (4.19)$$

$$RI(1 - r) = o.76Rafa(n/N) \qquad (4.20)$$

$fa(n/N) = (0.16 + 0.62\,n/N)$ for latitude south of $54^{1/2}$ (4.21)

$$Ro = \sigma T_a^4 \left(0.47 - 0.075\sqrt{ea}\right)\left(.0.17 + 0.83\, n/N\right) \tag{4.22}$$

The climatic data input for computation of potential evapotranspiration at different physiographic areas of the catchment consist of Asela, Meraro, Sagure and Bui for highlands; Kulumsa and Butajira for escarpments; and Ziway station for rift floor.

Accordingly, potential evapotranspiration (PET) computed using the above equations for different physiographic areas and river catchments are presented in table 4.10. and 4.11.

Table 4.10 Monthly mean precipitation and potential evapotranspiration of different Physiographic areas in the catchment

	Phys. area	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Precipita-Tion (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) Thornthwa-ite 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
Weighted PET		79	97	97	103	103	98	90	84	89	83	79	74	1077
PET (mm) Penman method	Highland	112	113	132	110	117	87	67	77	87	99	109	110	1217
	Escarpment	120	121	130	119	124	98	79	81	90	123	125	118	1329
	Rift floor	121	126	132	127	135	121	101	104	106	120	124	121	1438
Weighted PET		115	117	131	115	121	95	75	82	91	108	115	114	1279

4.11. Potential evapotranspiration on the basis of the physiography of the respective river Catchments (mm)

Method	Catchment	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Thornthwaite	Katar	75	93	92	98	97	93	86	80	85	80	76	70	949
	Meki	82	96	95	102	102	96	88	82	87	83	79	73	983
	Ungauged Catchment	78	110	114	122	124	118	105	98	103	96	91	84	1165
Penman	Katar	113	114	132	112	118	89	70	78	88	103	112	112	1239
	Meki	116	116	131	114	120	93	73	80	89	110	116	114	1272
	Ungauged Catchment	121	124	131	125	132	114	94	98	102	121	125	120	1406

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. Therefore, it is always 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 (annex 2).

The actual evapotranspiration of the area is calculated using Thornthwaite and Mather standard soil water balance model 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 moths is then obtained from the following formula:

$$S_m = W \exp\left[-\frac{(La_m)}{W}\right] \qquad (4.23)$$

Where, Sm: 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:

$$AET = PET \text{ if } P_m > PET_m \quad (4.24)$$

Otherwise,

$$AET_m = P_m + S_{m-1} - S_m \quad (4.25)$$

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 both Penman and Thornwaite potential evapotranspiration results are given in the following table:

Table 4.12. Actual evapotranspiration on the basis of catchment physiography

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
	Weighted	37	53	78	91	89	91	90	84	87	70	48	32	849
Penman	Highland	40	54	87	97	95	87	67	77	87	88	65	38	883
	Escarpment	33	49	80	92	90	97	79	81	90	86	60	34	871
	Rift floor	19	35	55	69	66	78	101	104	95	63	25	14	727
	Weighted	35	50	80	92	89	88	75	82	89	84	58	33	856

Note that AET of Rift floor is lower than that of Highland due to the fact that it can not 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)

Method	Catchment	Actual Evapotranspiration(mm)												
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Penman	Katar	38	53	85	96	93	88	70	79	88	87	63	37	876
	Meki	31	46	73	85	82	83	82	89	91	77	47	27	814
	Ungauged Catchment	23	39	63	76	73	84	95	97	94	70	35	20	769
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 both Penman and Thornwaite methods give fairly close actual evapotranspiration values for a given physiographic area in the catchment. This shows that temperature and sunshine hours, which are inputs for both methods 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 Garaghe 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 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^2. 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 4.14).

Bulbula Rver 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 4.6).

Table 4.14 Mean monthly Discharges of main rivers (mcm)

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)

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

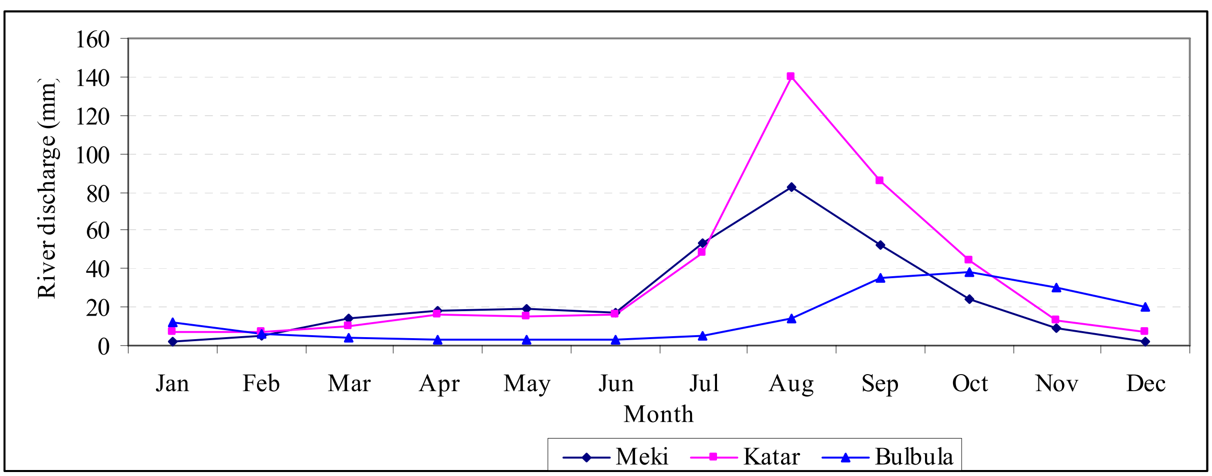


Figure 4.5 Long-term mean monthly discharges of main rivers in the catchment

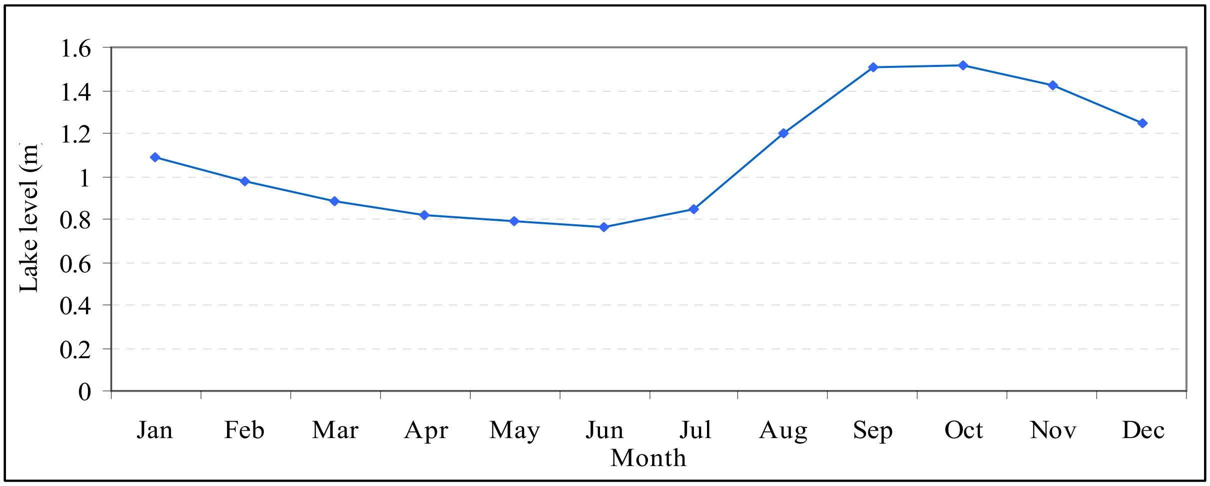
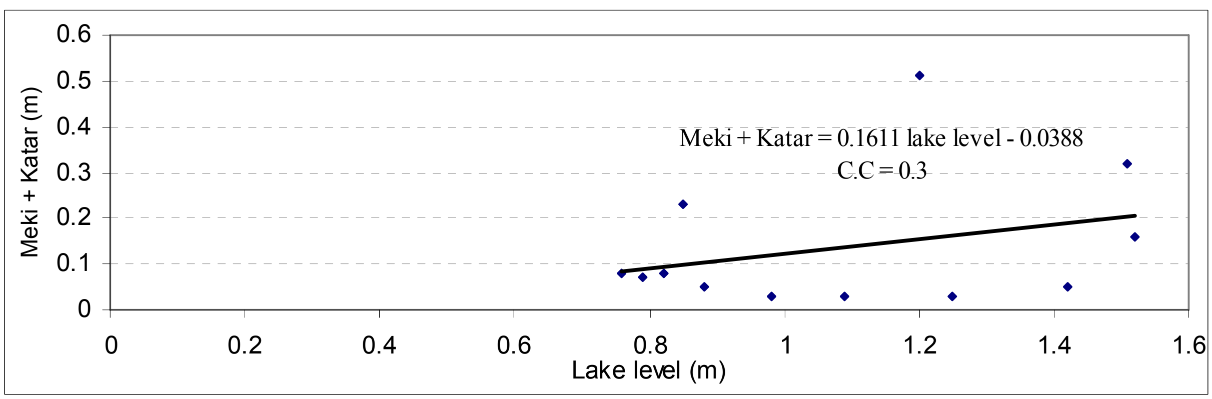


Figure 4.6 Mean monthly fluctuation of Lake Ziway level

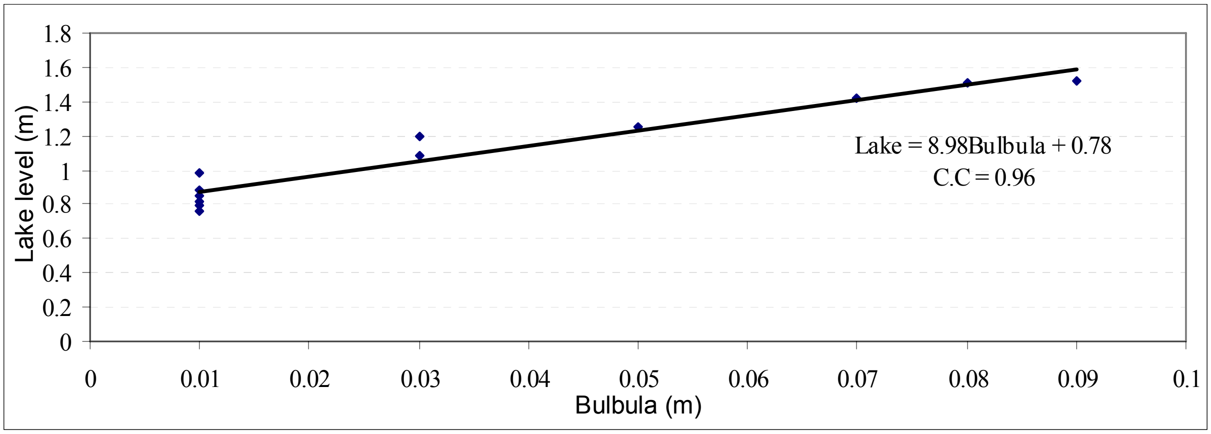
From the above graphs we can understand that peaks of lake level and Bulbula River flow do not coincide with peak discharges of rivers inflow (Meki and Katar) to the lake. There is about 45days (one month and half) lag time between peak of inflow and that of lake level; and in turn about 15 days between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

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, he 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

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

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

Where, Gr : recharge

P : precipitation

Ro : runoff

Ea: actual evapotranspiration

ΔS: 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% (chapter six). Accordingly, the weighted annual recharge of the area using soil moisture budgeting method is 57mm.

5.2 Groundwater balance method

Groundwater recharge can be estimated by water balance as follows:

$$Gr = D+A+E+L \pm \Delta S \quad (5.2)$$

Where, Gr : Groundwater recharge

D : Groundwater discharge (Base flow and spring discharge)

A : Groundwater abstraction

E : Evaporation

L : Channel losses (influent seepage)

ΔS: Change in groundwater storage

When we consider on annual basis, the change in storage is assumed to be zero; and if evaporation and groundwater abstraction are further assumed to be negligible, the remaining equation will become:

$$Gr = D+L \quad (5.3)$$

The discharge (D) in this equation is represented by baseflow while influent seepage (L) is the water which is part of baseflow contributed to groundwater from rivers and does not appear at the gauging station.

The uncertainty in estimating actual amount of upstream abstraction forced to use the river discharge data before commencement of significant irrigation projects.

In order to determine recharge of Lake Ziway catchment using this method, mean daily discharge records of Katar River gauged on Abura from 1970 – 1985(i.e data before the commencement of Irrigation Projects in the upstream) and Meki River from 1970 – 2000 were used.

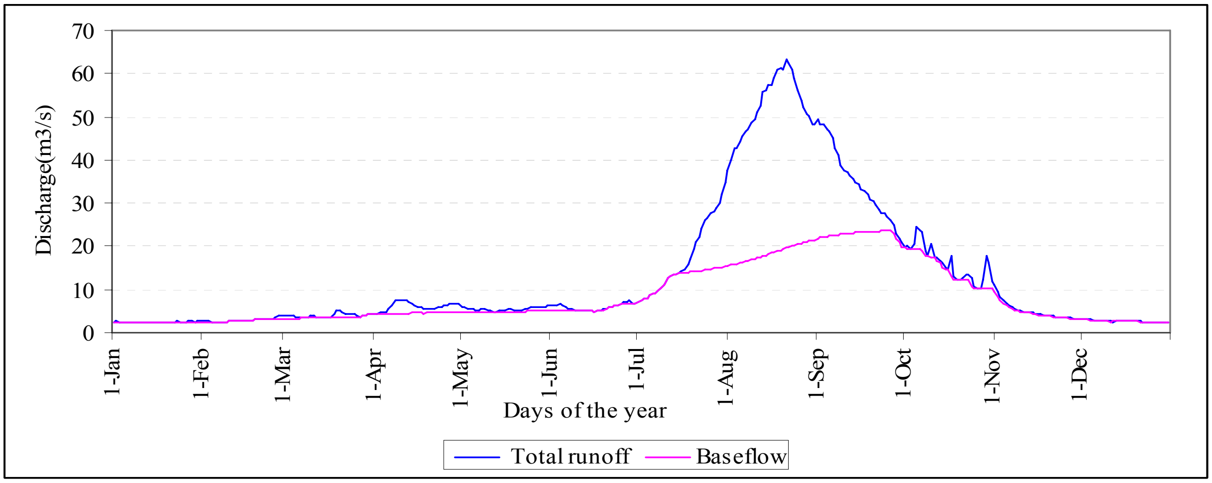


Figure 5.1 Base flow separation of Katar River discharge gauged at Abura station

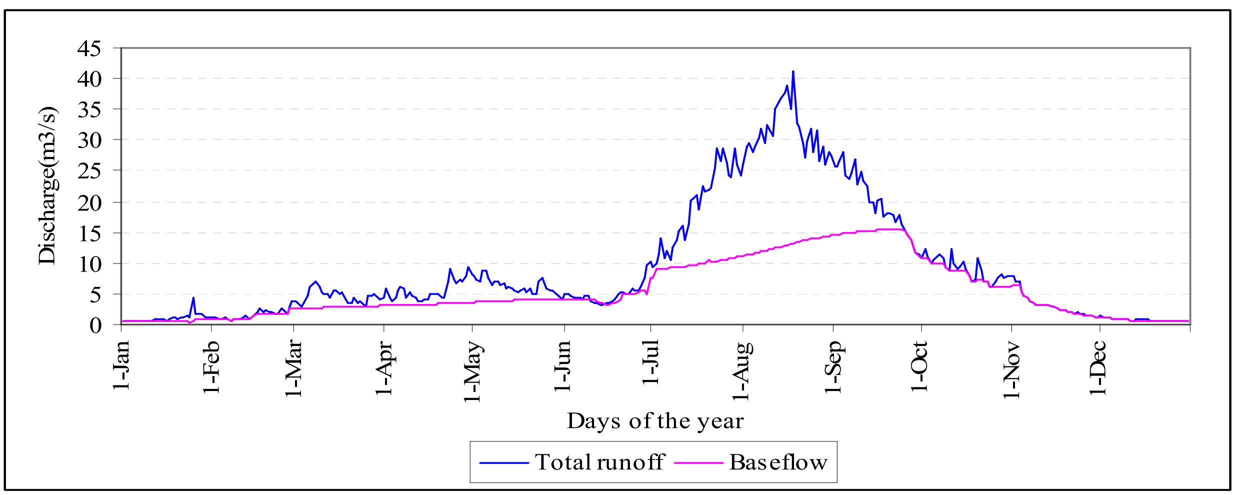


Figure 5.2 Base flow separation of Meki River disharge gauged at Meki town

Table 5.1 Monthly baseflow, surface runoff and total flow of Katar and Meki Rivers at respective gauging stations for the considered period

Catch-ment	Gauging station	Area Km2		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Tot-al
Meki	Meki town	2256	BF	1.7	3.3	7.7	8.6	10.6	11.4	27.4	33.9	38.6	21.9	7.7	1.9	175
			SR	1.1	0.7	4.6	5.9	6.2	1.5	25.2	49.8	12.9	2.3	0.3	0.1	111
			T	2.8	3.9	12.2	14.6	16.7	12.9	51.5	83.7	51.2	24.2	8.0	2.0	286
Katar	Abura	3302	BF	6.3	6.8	9.5	11.8	13.1	14.4	33.5	49.5	59.0	39.6	12.3	7.0	263
			SR	0.2	0.2	1.1	4.1	1.6	0.9	13.0	90.6	30.8	4.3	0.7	0.1	147
			T	6.5	7.0	10.6	15.8	14.7	15.4	46.5	140.1	89.8	43.5	12.9	7.1	410

BF: Baseflow (mcm) SR: Surface runoff (mcm) T: Total monthly flow (mcm)

Accordingly, the annual baseflow components (groundwater discharges) of Karar and Meki catchments are 263mcm (80mm) and 175mcm (78mm) respectively.

Based on groundwater table contour, field baseflow measurements and channel water balance, channel loss is observed on Meki River in rift floor sediment; and on Katar River at medium and upper part of fault escarpment (Chapter six). Accordingly, Meki River recharges the groundwater by about 43mcm annually; where as loss from Katar River is about 87mcm. Losses above the considered areas of river reach are negligible as has been evidenced by discharge measurements and water table contour map.

Using the method, groundwater recharges of Katar and Meki catchment are 105mm and 97mm respectively. The ungauged portion of the catchment is the area surrounding the lake where mean annual actual evapotranspiration (757mm) is almost close to amount of precipitation (770). If baseflow percentage of the surplus (13mm) is assumed to be similar to Chufa (i.e the nearest gauged river with baseflow 74% of total annual discharge), the baseflow of this catchment is about 10mm. Therefore, the weighted direct groundwater recharge of the study area is about 83mm annually.

When we compare the above methods, the soil-water balance method suffers from its less validity in arid and semi arid zones, as it was developed for humid climate (Lerner et al, 1990). Moreover, storage of moisture in the unsaturated zone and the possibility of infiltration along the various possible routes to the aquifer form important and uncertain factors in this method. Therefore, groundwater balance appears to be better approximation method after considering the hydrogeological dynamics of the catchment (Chapter Six). Therefore, it is fair to take 83mm as annual direct groundwater recharge of the studied catchment.

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 loosing rivers and streams.

In this chapter, the hydrogeology of the catchment is discussed based on flow characterstics 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

No	Catchmnt name	Catchment area(km^2)	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.

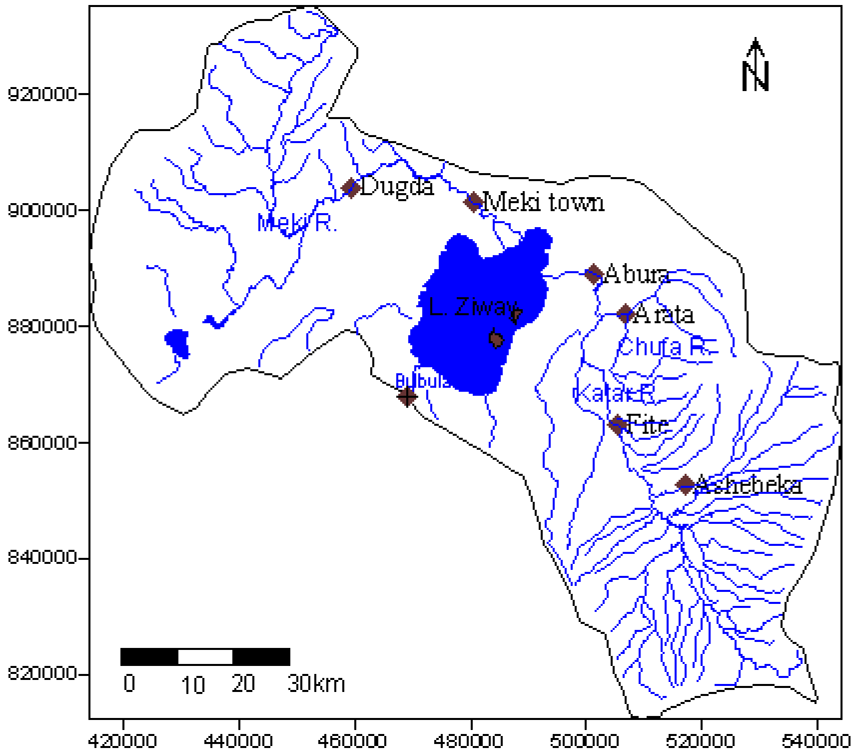


Figure 6.1 Location of river gauging stations

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. Accordingly, the catchment is classified in to five ranges of permeability (Figure 6.2).

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

This zone consists of recent basalts and highly fractured ignambrites 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.

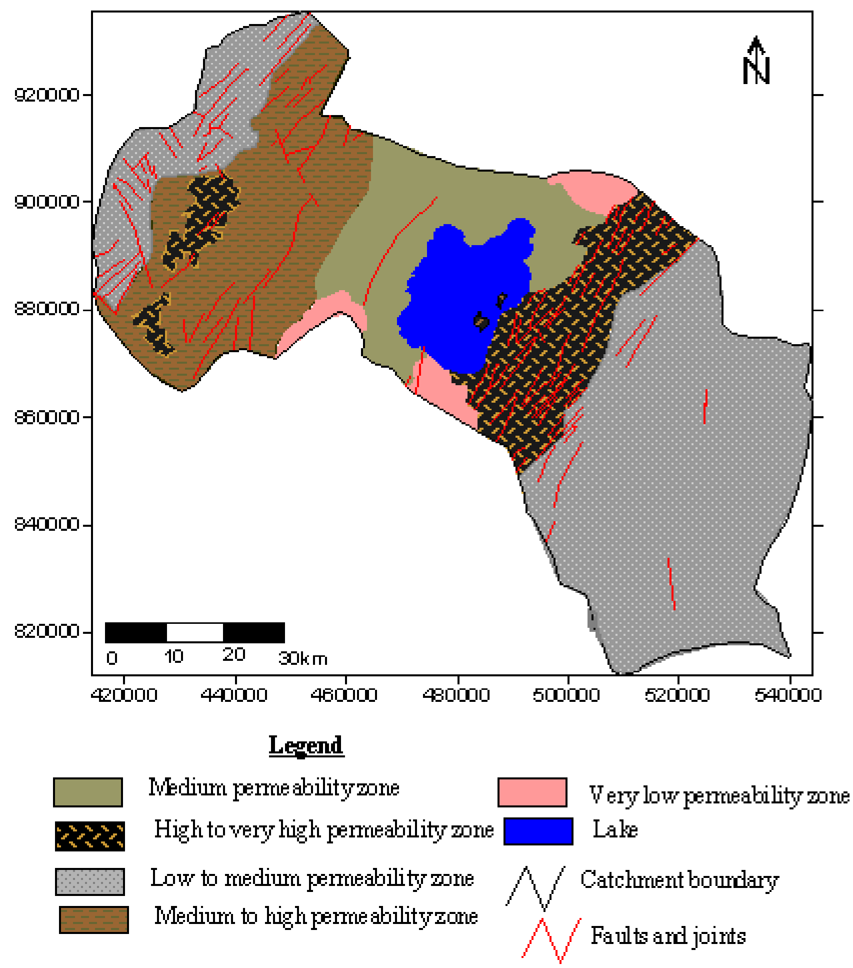


Figure 6.2 Permeability distributions in the study area (Taken from Tenalem Ayenew, 1998)

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 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).

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 6.3 and table 6.2: 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 loosing reaches or recharge areas (CR5, CR9 – CR12).

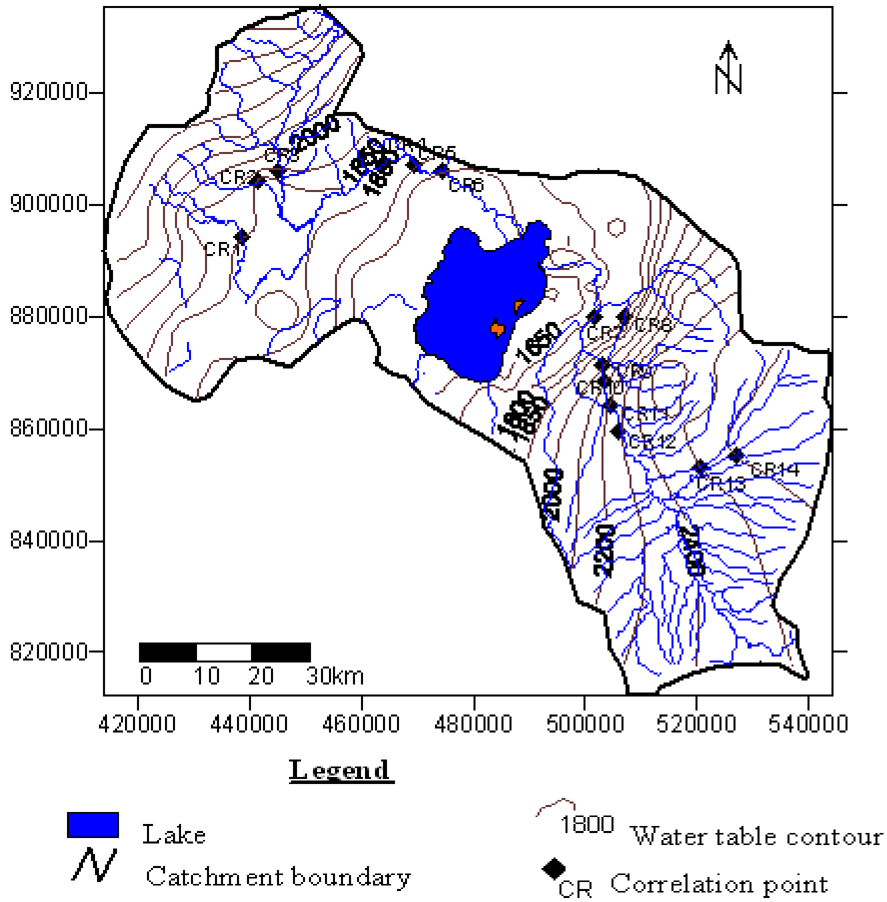


Figure 6.3 The relationship between groundwater table elevation contour and rivers

Table 6.2 The relationship between river bed elevation taken from DEM and groundwater table elevation at that point

Label	XUTM(m)	YUTM(m)	Groundwater elevation (m.a.s.l)	River/Stream bed Elevation (m.a.s.l.)	Characterstics 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

6.5 Assessment of groundwater and surface water interaction using field base river discharge measurements and spring survey

In order to analyze the hydrogeological dynamics in the catchment, rive discharge measurements were made at different reaches in the area. The measurements were conducted in the months of November, December and February during which the river flow was entirely the groundwater component (Table 6.3).

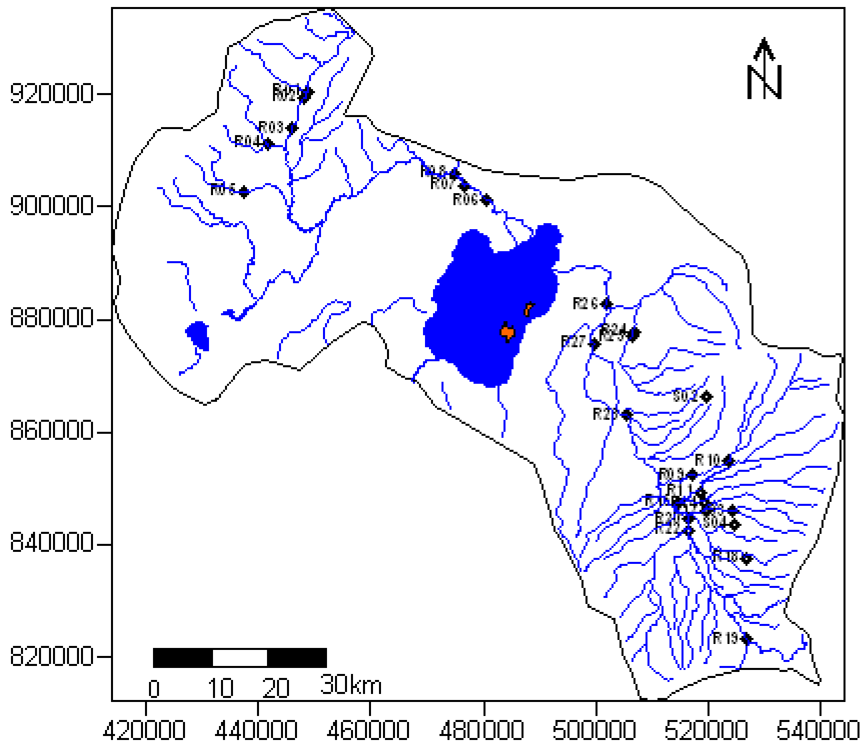


Figure 6.4 Location Map of field base river discharge measurements.

Note that only representative measurement sites are indicated on the map for clarity; and additional data are available in the following table:

Table 6.3 Location and amount of discharge using field base measurements

No	Date	Label	XUTM (easting)	YUTM (Northing)	Q(l/S)	Site name
1	27/11/05	R02	448284	919070	157	Meki after Junction with Weldia
2	27/11/05	R03	445971	913906	209	Meki Near bridge between Kela and Bui
3	27/11/05	R04	441668	911350	263	Lebu above diversion wear
4	27/11/05	R05	437252	902365	220	Akemuja near bridge on the way to Butajira
5	27/11/05	R06	480510	900742	612	Meki at Meki town
6	28/11/05	R07	476559	904115	640	Meki at Chirecha before Meki Town
7	28/11/05	R08	474659	905540	706	Meki Wakelle on the way to Dugda
8	02/12/05	R09	517074	852165	796	Ashebeka near bridge
9	02/12/05	R10	523507	854533	577	Ashebeka near the lower intake
10	02/12/05	R11	518488	849381	164	Temala near bridge
11	02/12/05	R12	520028	846699	111	Weshe
12	02/12/05	R14	519190	847507	61	Gusha
13	02/12/05	R13	514546	846735	229	Temala after junction with Gushe
14	02/12/05	R15	514524	845500	846	Katar
15	24/02/06	R16	519661	846200	161	Weshe around Sida spring
16	24/02/06	R17	519560	845982	336	Weshe after junction with Sida
17	24/02/06	R18	526763	837570	85	Dima
18	24/02/06	R19	526909	822580	17	Katar between Bokoji and Meraro
19	24/02/06	R20	516513	844623	149	Katar before junction with Sida and Sirba
20	24/02/06	R21	516656	844791	495	Katar ater junction with Sida and sirba
21	24/02/06	R22	516448	842639	148	Katar after junction with werga
22	2402/06	R23	505443	863015	2128	Katar near Fite Gauging station
23	25/02/06	R24	506808	877798	280	Bosha near Balwald spring
24	25/02/06	R25	506360	877000	150	Bosha at Doro
25	25/02/06	R26	499254	875675	2559	Katar above Sheled irregation
26	26/02/06	R27	499737	875658	1159	Katar at Onshiti
27	02/12/05	S01	520028	846699	10	Sida 1 spring
28	23/02/06	S02	519559	866324	15	Sida 2 spring
29	23/02/06	S03	524458	845685	20	Debela spring
30	23/02/06	S04	524628	843701	5.5	Limu ariya spring
31	25/02/06	S05	506994	877916	30	Balewold spring
32	26/02/06	S06	499722	875658	25	Gura spring

The analysis in this section consists of comparison between the discharges in the upper and lower reaches on respective river stretches based on the measurements taken in short time intervals along the rivers.

The discharge measurements in the western highland indicate that, Meki River and its tributaries are gaining reaches. The measurements taken on the river between R02 and R03 in the figure above show the contribution of groundwater to surface water flow. In addition, rivers in this area have average discharge-area correlation coefficient of 0.85.

Channel loss on Meki River was observed in rift floor sediment between Dugda and meki towns. Decline in baseflow between measuring points of R06, R07 and R08 in the above figure is suggestive of losses in the sediment. Hence, discharge-area correlation coefficient also reduces to 0.61.

In the lower part of eastern escarpment, both Katar and Chufa are gaining baseflow from underlying aquifers. This is evidenced by availability of several springs (S05, S06), in the area and the increase in river discharge as one goes downstream (R24, R25, R26 and R27) along Katar and Chufa Rivers. However, in the middle and upper part of eastern escarpment, Katar River losses water in faults and other fractures as observed from lowering in discharge between R23 and R27.

Moreover, the discharge measurement and spring survey in eastern highland indicates that all the rivers and streams are gaining reaches. From observation of change in river discharges between R09 & R10; R11, R14 and R15; R20 & R23; and availability of springs with large discharge, such as S01, S02, S03 and S04 (figure 6.3 and table 6.3), one can clearly observe the gaining behavior of rivers favored by climate, topography and geology (i.e shallow circulation of groundwater due to underlying impermeable pyroclastic and acidic rocks). In this area, river discharges and their contributing areas are highly correlated (0.94).

6.6 Channel water balance and estimation of indirect groundwater recharge on selected river stretches

Channel water balance is one of the assessment methods for the interaction between groundwater and surface water in a given river stretch.

Using groundwater elevation and field base river discharge measurements in preceding sections, it is apparent that there is channel loss on Meki River in rift floor sediment, and on Katar River in central and upper Wonji Fault Belt. In order to quantify the losses in these areas channel water budgeting model was conducted using data of gauging stations in respective areas and estimation of some parameters.

In channel water balance model, the discharge at the down stream end of a given river is expressed by the following formula:

$$Q_d = Q_u + Q_i + Q_t - Q_o - E \pm \Delta S_{rb} \qquad (6.1)$$

Where, Q_d : Discharge at the down stream section

Q_u : Discharge at the up stream section

Q_i : The net lose or gain along the reach (the unknown quantity)

Q_t : Discharge of tributaries

Q_o : Discharge diverted from the river

E : Rate of evaporation from river water surface and flood plain

ΔS_{rb} : Change in bank storage

6.6.1 Losses on Meki River between Dugda and Maki town stations

Considering the above equation, discharges of down stream and upstream (i.e Qd and Qu of the above equation) are Dugda and Meki town stations respectively (figure 6.1). In this analysis, river discharge records of 1970 – 1976 for both stations were used because of the limited records of Dugda station and the relative importance of using data of the same years.

Between these stations, the river gets surface runoff from area of 227 km^2 during the wet season (from months of June to October). This contribution was estimated based on mean rainfall-runoff relationships of adjacent catchments for each month under consideration. During the years considered in water balance, there was no significant abstraction. Annual evaporation from river channel and change in bank storage are assumed to be negligible in relation to other parameters in this work.

Using the above relationship, the difference between inflow (records of Dugda station and ungauged tributaries), and outflow at Meki town station shows annual channel loss of about 43mcm in the river stretch of 34.2km.

Table 6.4 Channel water balance on Meki River between Dugda and Meki town stations

Stations	Discharge (mcm)												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ann-ual
Meki town (Q_d)	2.23	2.58	11.02	7.72	9.59	12.43	58.29	78.62	61.09	17.51	4.71	1.07	267
Dugda (Q_u)	2.41	3.69	12.64	9.95	11.71	14.88	58.73	81.79	65.01	19.94	6.7	2.15	290
Ungauged Tributaries(Q_t)	0	0	0	0	0	1.18	5.86	7.59	5.35	0.8	0	0	20
Gain/loss(Q_i)	0.19	1.11	1.62	2.22	2.12	3.63	6.29	10.74	9.36	3.24	1.99	1.08	43

6.6.2 Losses on Katar River between Abura and Fite gauging stations

In order to quantify net loss of river to groundwater in the stretch of 36.2km between Fite and Abura stations, the inflow from Fite, Chufa (gauged tributary of Katar River) and ungauged tributaries as well as outflow at Abura station were used (figure 6.1).

Abura, Fite and Chufa have monthly discharge records of 1970-2004, 1982-2000 and 1981-1999 respectively. Due to establishment of irrigation projects since 1986 in this stretch and absence of well established abstraction data, mean monthly pre irrigation records of each station was considered in the analysis. Ungauged tributaries between the stations have flows only during wet season from June to October. The monthly contribution from these tributaries ($769km^2$) to the river was estimated based on rainfall-runoff relationship for each month of adjacent gauged rivers. Annual channel evaporation loss is less than one million cubic meters and the possibility of change in bank storage could also be very small in annual base; and both are assumed to be negligible in this analysis. Accordingly, the net loss due to the occurrence of fault belt is found to be 86mcm annually.

Table 6.5 Channel water balance between Fite and Abura station on Katar River

Stations	Discharge(mcm)												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Abura (Qd)	7.2	6.9	10.2	16.8	16.2	15.7	47.7	139.8	87.8	43.5	14.6	7.7	414
Fite (Qu)	4.5	5.8	7.6	12.4	11.0	11.8	41.0	138.5	63.7	31.1	8.3	6.3	342
Chufa (Qt1)	2.8	2.7	3.4	4.9	4.6	4.9	9.8	15.9	14.5	7.2	3.2	3.1	77
Ungauged Tributaries(Qt2)	0	0	0	0	0	4.9	12.6	30.6	23.9	9.6	0	0	81
Net loss/gain(Qi)	0.1	1.6	0.8	0.5	-0.4	5.9	15.7	45.2	14.3	4.4	-3.1	1.7	86

The negative signs in two months could be due to the contribution of ungauged streams during high storms before and after rainy season that have not been considered in the analysis.

6.7 Hydrograph analysis

In addition to the assessment techniques used in the preceding sections, the interaction of groundwater and surface water can be analyzed using hydrographs.

In this analysis, river gauging data of Meki at Meki town, Lower Katar at Abura, Upper Katar at Fite and Arata at Chufa are used for comparative assessment of hydrogeological characteristics in the catchment. The discharges used in the analysis are daily averages of pre irrigation data (i.e 1970-1985, 1970-2000, 1982-1990 and 1985-1996 for Lower Katar, Meki, Upper Katar and Chufa Rivers respectively)

6.7.1 Hydrograph shape

The shape of hydrograph depends on climate, topography, geology, soil etc. of the catchment. The shape of rising limb depends mainly on the duration and intensity distribution of rainfall; and the peak discharge in the crest segment represents the highest concentration of runoff from the basin while the recession limb represents withdrawal of water from storage within the channel system (Jayarami, 1996).

All the four river systems in the catchment have their own shape based on variation in climate, topography, geology, soil etc.

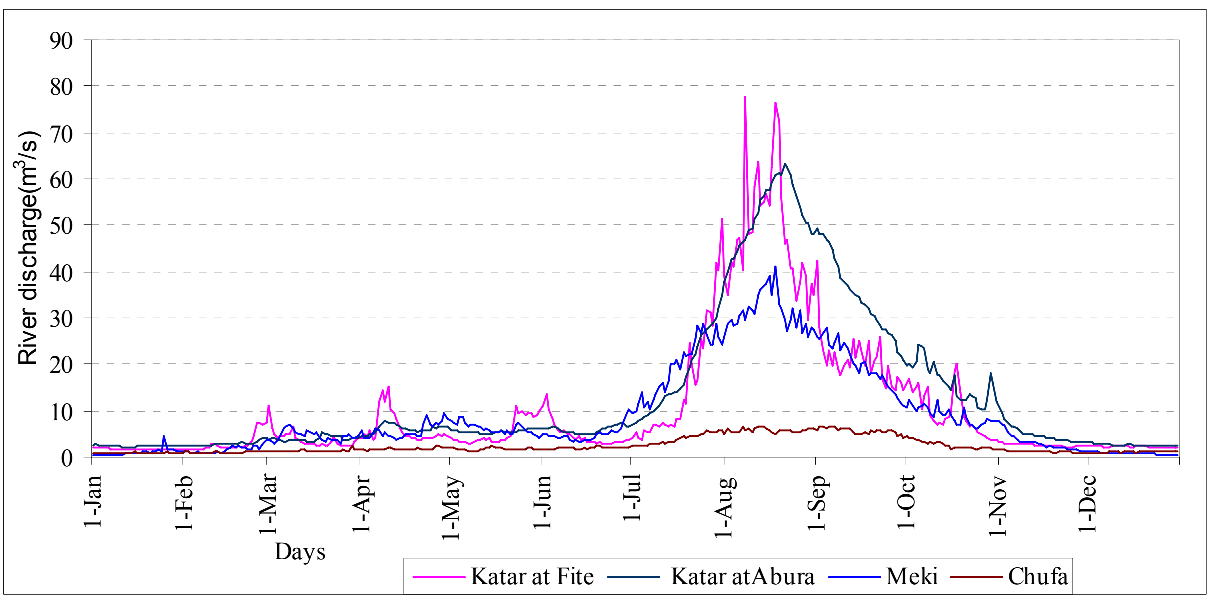


Figure 6.5 Hydrographs of different River systems showing distinct shapes

As can be observed in the above hydrographs, Katar River at Fite gauging station shows high irregularities reflecting fast response to rainfall because of high relief , low permeability rocks (section 6.3) and soils; causing high potential for flood runoff as response to daily precipitation.

Meki River hydrograph as of Meki town station has moderate irregularities and fast rising limb as compared to Katar at Fite. This can be explained by the effect of early commencement of precipitation in this region favored by Orographic effect of Garahge Mountains. Due to less topographic gradient and more permeable rocks in the catchment, the hydrograph shows less variation.

The shape of Katar River hydrograph gauged at Abura is smooth; slow rising limb and slow recession than the above mentioned rivers. As the gauging station is at the foot of eastern escarpment, all highland flows and the non defined channel flows during the rainy season in the catchment are regulated by the geological structure (i.e Wonji Fault Belt). The effect of the highly permeable structure is reflected by less response of flow to daily precipitation.

Most part of Chufa catchment lies in fault zone as a result of which the flow affected by high permeability of the structure and recent basalt making the hydrograph less responsive to daily rainfall as compared to the other river catchments.

6.7.2 Monthly flows of rivers as percentage of their respective total annual discharge

The actual pattern of flow during the year depends on precipitation, evapotranspiration, soil and geological characteristics of the catchment. The greater the infiltration in the storage capacity of a given catchment, the high flow is sustained through the dry seasons, and peak flows after period of highest precipitation (Malin, 1989).

Depending on geology, topography, climate and other factors each catchment in the study area is characterized by its distinct percentage of monthly flow.

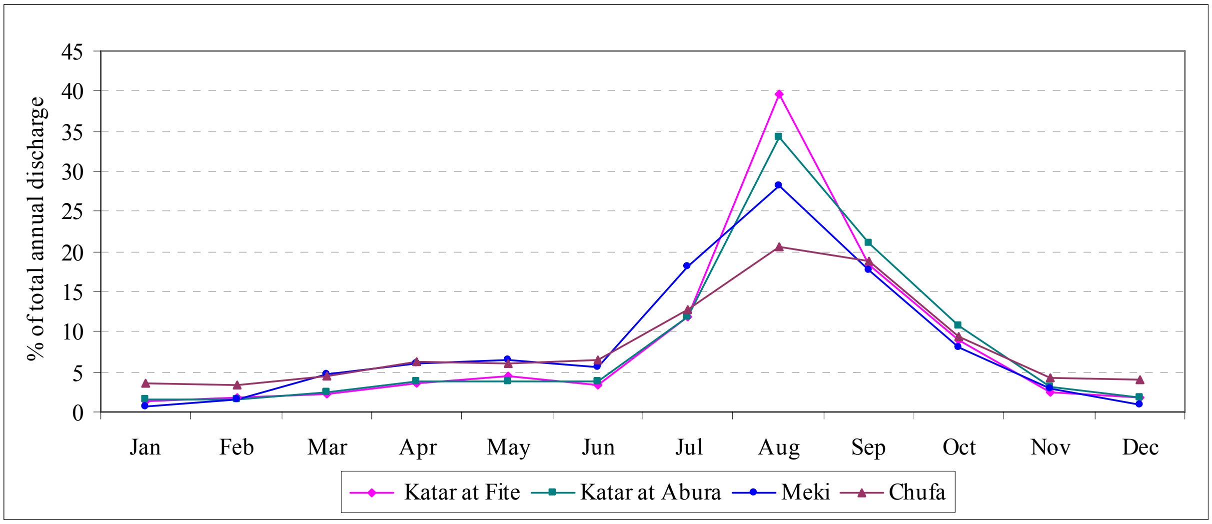


Figure 6.6 Monthly percent rivers discharge as their respective total annual flow

The variation in monthly percentage of rivers flow reflects the differences in hydrology and hydrogeology of the catchments.

Due to less permeability of eastern highland rocks such as: ignimbrite, tuff, trachyte and rhyolite and higher slope, Upper Katar gauged at Fite has the highest percentage of flow during rainy season in comparison to other catchments. Its lower proportion of flow during dry season is attributed to less storage of the rocks.

Katar River catchment gauged at Abura has similar behavior with Fite station except its higher proportion of flow after rainy season. As discussed above, this is due to the existence of geological structures at lower reach of the river favoring hydraulic conductivity and storage of groundwater.

Meki River has higher proportion of flow during early wet season due to commencement of precipitation, while its fast decline during extreme dry season is related to less storage of rocks and channel loss.

Chufa River has relatively less deviation of flow throughout the year. The hydrogeological position of this catchment (i.e discharge zone of the regional catchment) and favorable hydrogeological characteristics of rocks in the sub-catchment facilitate sustainable flow of the river.

6.7.3 Hydrograph separation

Hydrograph is an aggregate of surface runoff, interflow, channel precipitation and base flow. However, for practical application it is customary to divide the hydrograph in to surface runoff and base flow.

There are different methods to separate base flow; such as graphical, statistical, depletion curve analysis and using TIMEPLOT software. In this study, the software was used after independent check of the result with other methods of separation. Many years' daily average discharges have been used to construct hydrographs before separating baseflow.

Accordingly, the annual baseflow components of Meki, Katar gauged at Fite, Katar gauged at Abura and Chufa at Arata are 62%, 56%, 64% and 74% of their total annual flows respectively. From the above values, we can understand that about three fourth of Chufa river annual flow is its baseflow because of higher contribution by faults, joints and basaltic rock of high permeability in the catchment.

Baseflow recession is represented by the following generally used equation:

$$Q_t = Q_o e^{-\alpha(t-to)} \qquad (6.2)$$

Where, Qt : Baseflow at time t

Qo: Baseflow at tome t_o

α : recession constant

Table 6.6 Hydrograph components and recession constants of river systems in the catchment

No	Catchment name	Gauging station	Mean annual runoff(mcm)	Surface runoff(mcm)	Base flow (mcm)	Percentage of base flow	Recession Constant(α)
1	Meki	Meki	283	108	175	62	0.85
2	Upper Kater	Fite	328	143	185	56	0.67
3	Lower Kater	Abura	409	146	263	64	0.71
4	Chufa	Arata	76	20	56	74	0.37

Note from the above table that the recession constant of Lower Katar is higher than its tributaries due to the susceptibility of the river to rate of channel losses in its upstream. Lower recession constant of Chufa River shows its less variation in base flow during recession.

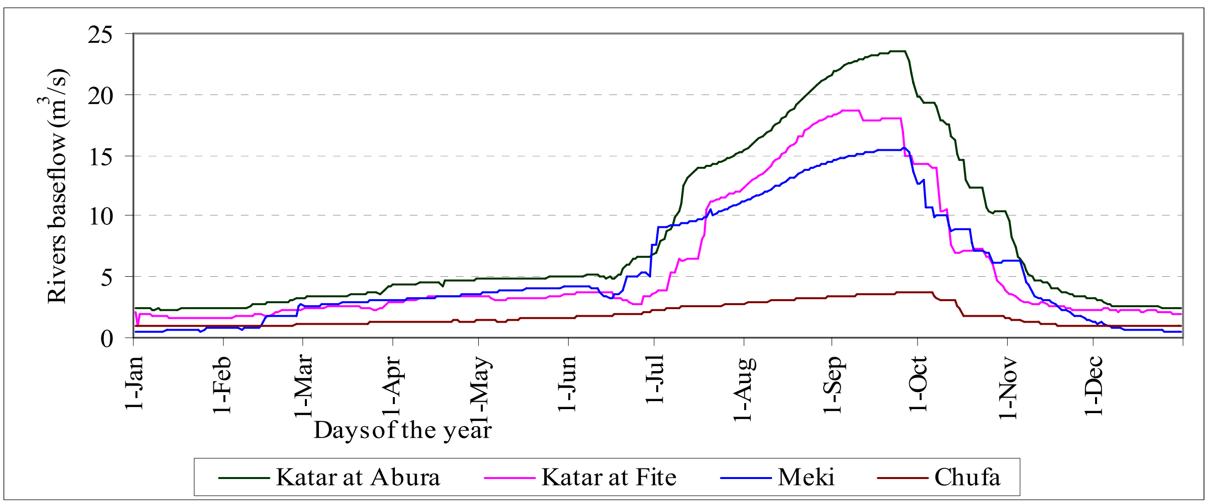


Figure 6.7 Baseflow components of major rivers in the catchment

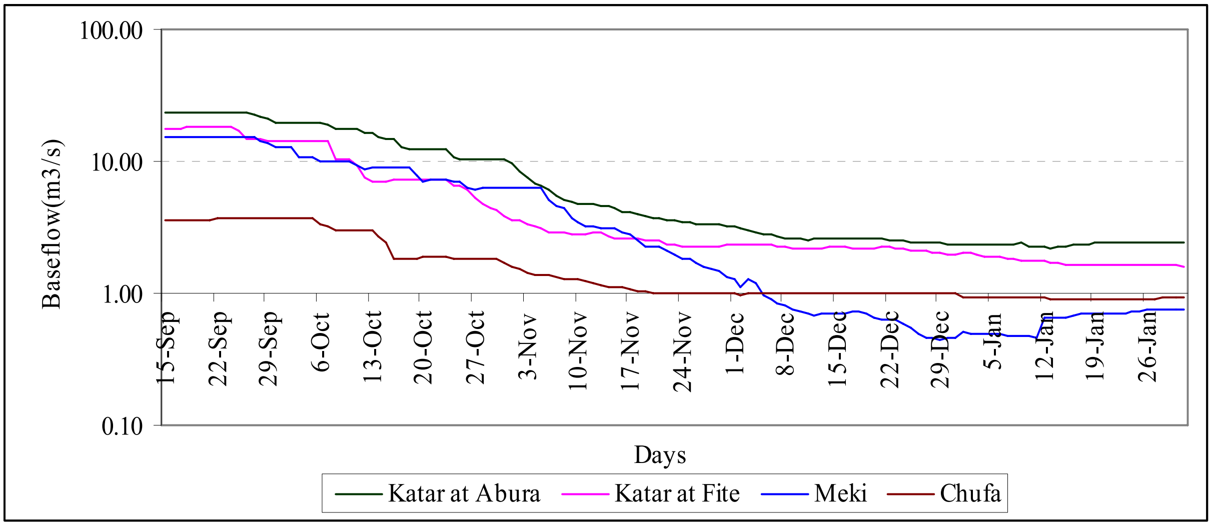


Figure 6.8 Baseflow recession curves of major rivers

Baseflow components of Upper Katar and Chufa Rivers show the storage characterstics of their catchment. However, baseflows of Lower Katar and Meki Rivers are part of the total groundwater components escaped from losses in their upstream. Therefore, they do not reflect the storage characterstics of their catchment.

The shape and slope of Lower Katar and Meki River recession graphs dictate the rate of channel losses. For instance, the graphs of these rivers become steeper after months of October while the other two have gentle slopes (figure 6.8).

Table 6.7 Monthly baseflow components of river systems (mcm)

No	Catchment	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1	Meki	1.7	3.3	7.7	8.7	10.6	11.4	26.4	33.4	38.6	23.0	8.6	2.0	195
2	Lower Katar	6.3	6.8	9.5	11.8	13.2	14.4	33.5	49.5	59.2	39.2	12.3	7.0	263
3	Upper Katar	4.6	4.8	6.8	8.5	8.8	8.9	21.8	41.1	45.5	23.2	7.0	5.9	187
4	Chufa	2.5	2.3	3.0	3.5	4.1	4.8	6.9	8.3	9.2	6.7	3.0	2.7	57

6.8 Baseflow and rainfall relationship

As explained in previous section, baseflow is part of precipitation representing water which has percolated through the soil and the vados zone to the groundwater table but which subsequently discharges to rivers.

In order to determine the relationship, regression analysis was made between baseflow and corresponding precipitations of gauged rivers in the catchment. The slope of the regression line represents baseflow as proportion of rainfall; and the intercept of the regression line with rainfall axis at the point where baseflow is zero gives the minimum critical rainfall to the baseflow to have occured.

Table 6.8 Mean annual precipitation and baseflow of the river catchments (mm)

No		Meki	Lower Katar(Abura)	Upper Katar (Fite)	Chufa
1	Mean annual precipitation	1005	881	925	906
2	Mean annual baseflow	78	80	91	109
3	Baseflow as % of precipitation	7.8	9.1	9.8	12
4	Minimum precipitation to generate baseflow	756	664	830	552

From the above table we can understand that rivers gauged at high altitude for example, Upper Katar need higher rainfall to produce baseflow. This is due to the fact that they have greater chance of producing higher surface runoff than baselow during high intensity precipitation because of the catchment relief and other hydrogeologic settings.

Lower Katar and Meki have low percentage of baseflow to precipitation due to the fact that as we go downstream to rift floor, there is decrease in precipitation, increase in evapotranspiration and more importantly channel loss above the gauging stations.

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 in flow component, out flow component and the change of water volume for each interface of time. Therefore, this equilibrium is described by the following equation:

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

Where, ΔV: 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 Penman aerodynamic and energy budget combined 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

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	Abstr action		
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 torage (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

Change in storage + Surface outflow - Surface inflow = Groundwater inflow - 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.

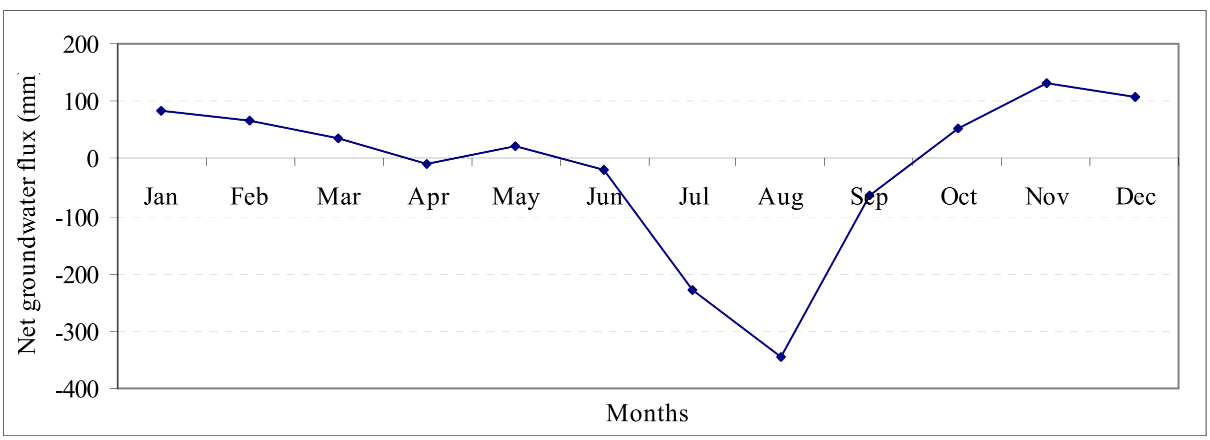


Figure 7.1 Monthly distribution of groundwater flux (GW inflow – GW outflow)

The occurrence of more groundwater outflow over inflow in April is 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

ASSESSMENT OF RECENT CHANGES IN HYDROLOGIC ENVIRONMENT OF THE CATCHMENT

8.1 Introduction

It is believed that the increase in atmospheric concentration of greenhouse gases due to human activities has brought climatic changes over the world. The gases alter heat balances of the earth and impact the regional hydrologic cycle with subsequent effect on quantity and quality of water resources. According to Yohannis G. Eyesus et al (2001), there are evidences that could be associated with climate changes in the country. The report shows that there is an increase of annual minimum temperature by 0.2^{o}C every decade in the last 50 years. Moreover, the country has experienced frequent and extensive draughts in recent decades.

In addition, there is an increase in population pressure continuously in the country which could greatly influence the hydrologic environment. This impact can be in the form of land improvements that affect the balance between evapotranspiration, surface runoff and groundwater recharge; and abstraction of water resulting in reduction of outflow and storage components of water balance.

This chapter focuses on the effect of climate change and human activities on hydrology and hydrogeology of the study area.

8.2 The response of water balance components to recent climatic change

8. 2.1. Precipitation

In this analysis, monthly records of Butajira, Asela and weighted average of all 17 stations from 1970 onwards were used. Monthly missing data of the stations were filled by averaging results obtained by linear regression of three stations having higher correlation coefficient with the station in question (Annex 1).

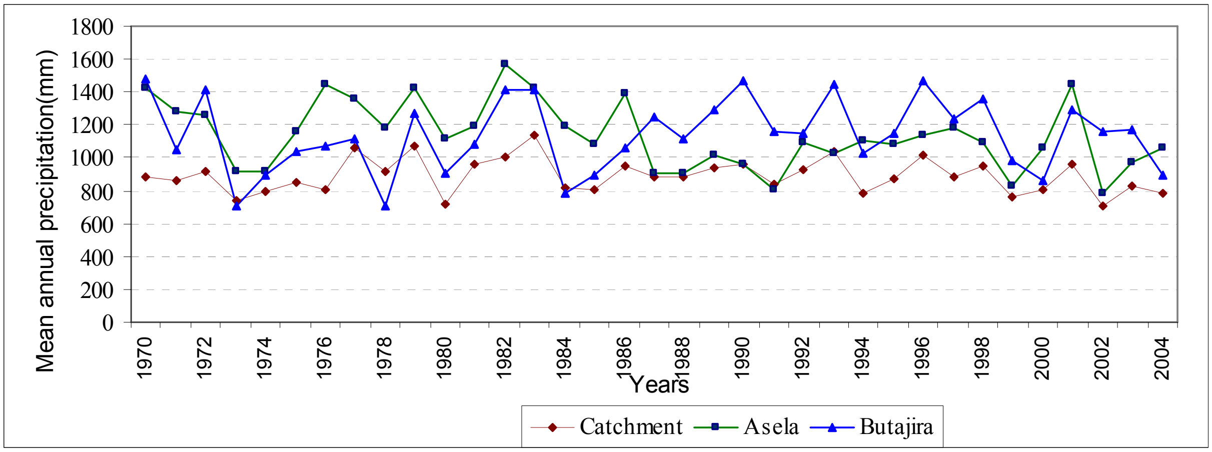


Figure 8.1 Long term precipitation of Asela, Butajira and the weighted catchment area

The above graph shows that there is decreasing pattern in mean annual precipitation over the considered stations and the catchment. From trend analysis of annual rainfall over the catchment (figure 8.2), it can be observed that precipitation is continuously declining. Long term average trends of precipitation for the above stations are presented I figure 8.7 and 8.9 along with their effect on river discharges.

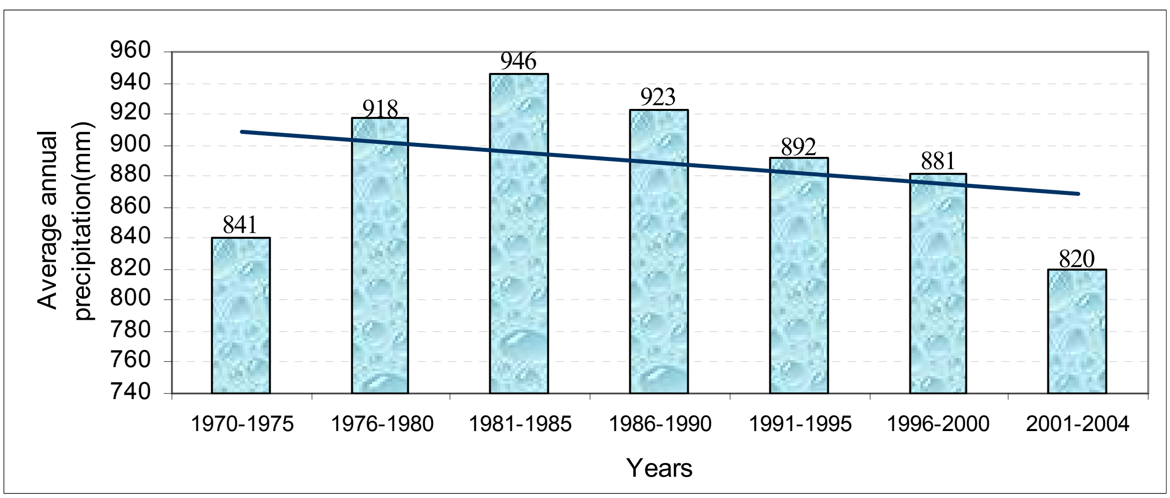


Figure 8.2 Trend in five years moving average precipitations over the catchment

8.2.2 Evaporation

The primary meteorological controls on evaporation from well-wetted surface are the amount of energy available, the moisture content of air, and the rate of movement of air across the surface. Accordingly, change in climate of a given area will greatly affect the rate of evaporation from the surface and in turn brings hydrological inbalance.

Change in evaporation of the study area was assessed using pan evaporation established at Bui, Ziway, Kulumsa and Meraro stations. The distribution of the station can represent all the three physiographic areas of the catchment (i.e highland, escarpment and rift floor). The assessment was done by considering Ziway and Meraro stations data as well as by weighing all stations data physiographic area wise after gap filling using regression and correlation analysis.

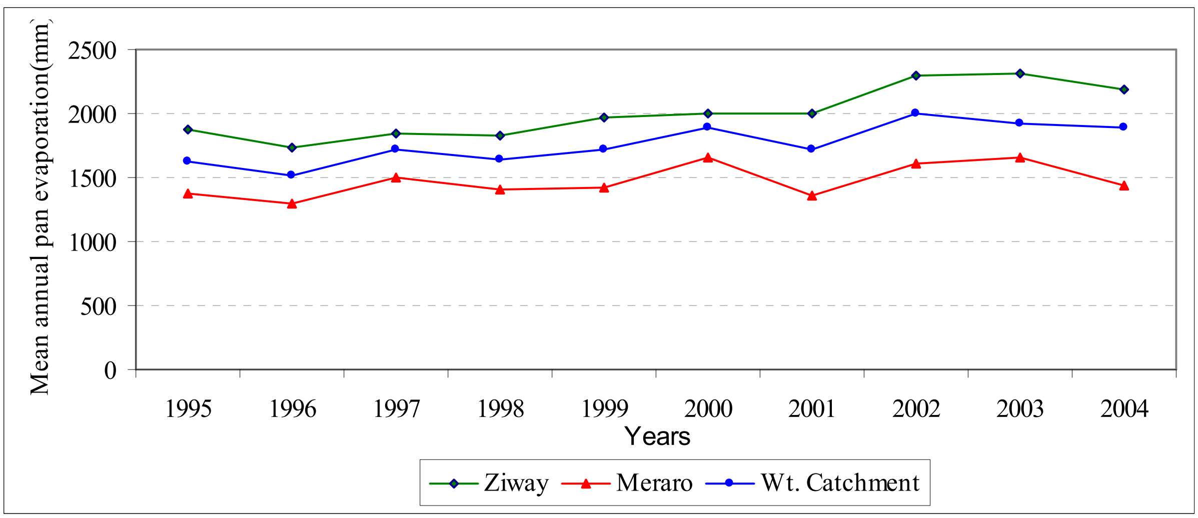


Figure 8.3 Pan Evaporation of Ziway, Meraro stations and weighted catchment area

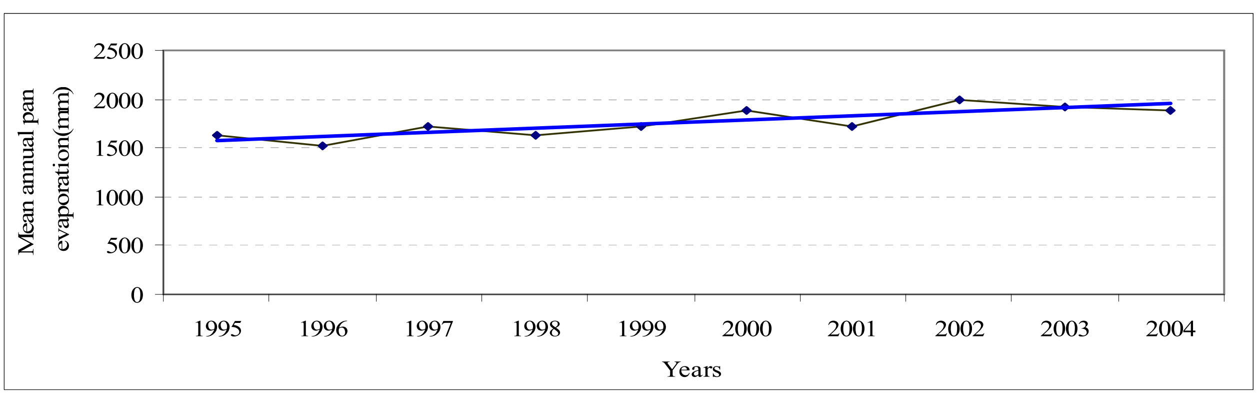


Figure 8.4 Trends in weighted pan evaporation of the catchment

In addition, trend in evaporation of the lake surface was analyzed using Penman computational method of water body evaporation (Chapter three).

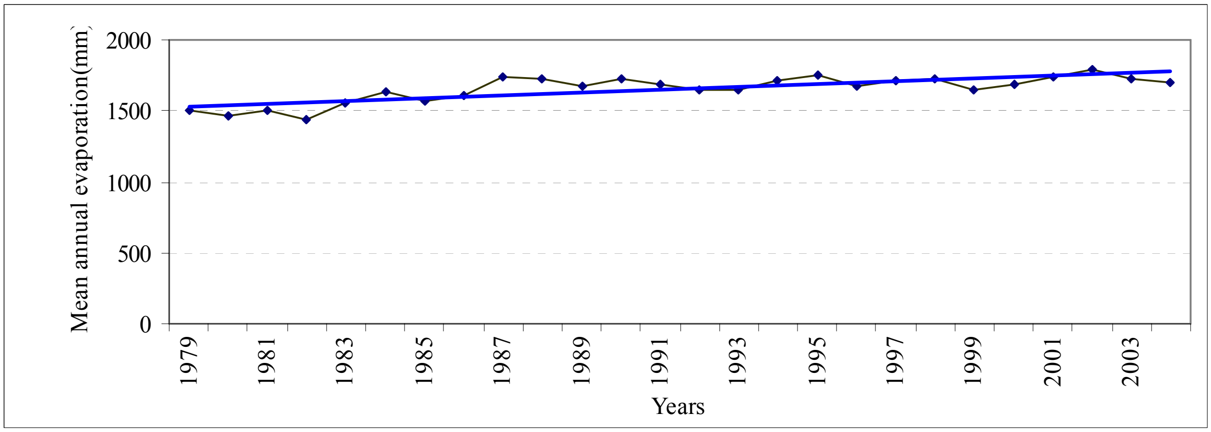


Figure 8.5 Trends in lake surface evaporation

As can be seen from Figure 8.3, 8.4 and 8.5 above, there is significant increase in evapotrenspiration over the area.

8.3 Changes in water use

In line with Government's Poverty Alleviation Program, there are numerous irrigation development activities using abstraction of water from the Lake and rivers in the catchment.

8.3.1 Lake water abstraction

Due to its accessibility, favorable location in relation to Addis Ababa and fresh water quality, Lake Ziway has been considered the most important water exploitation area in the rift valley (HALCROW, 1992).

Currently, plenty of variable capacity pumps are abstracting fresh water from the lake by state, investors and private commercial farms throughout the year. Even during the rainy seasons water demand of the crops is supplemented by irrigation due to high evapotranspiration and less precipitation to satisfy soil moisture.

A land total of about 3712ha (37.12km^2) is irrigated using the lake and rivers enclosed between gauging stations around the lake as of Feb. 2005. (Source: Dugda Bora, Adami Tulu and Ziway Dugda District Agriculture and Rural Development Offices).

Onion, tomato, cabbage, pepper, sorghum, and maize are the major crops grown in the area. Assuming 600mm average water requirement (FAO Irrigation, Drainage and Salinity Paper, 1973) for single season; and if two phases of irrigation are considered annually, the total annual abstraction of lake water will be 44.5mcm.

In addition, a total of 4.5mcm water is annually taken for Ziway town domestic water supply from the lake since April 2003 (Source OWRB, 2004).

8.3.2 Abstraction from Katar River

Large scale irrigation was started in Katar catchment in mid 1980's by Katar irrigation Project. Since then, irrigation demand has been increasing by using the river and its tributaries.

In the highland area potato is the most dominant vegetable while tomato, cabbage, onion and papaya are produced additionally in lowland areas. Assuming 60% of the irrigable areas to be developed twice a year and 600mm average water requirement during single growing season (annex 4), the total water abstracted currently to satisfy the demand of 2115ha vegetable will be 20.3mcm.(Data source: Arsi Zone Agriculture and Rural Development Department, Feb. 2006)

8.3.3 Abstraction from Meki River

Based on data collected during field work from Dugda Bora, Soddo, Meskan and Merako District Agriculture and Rural Development offices, about 462ha.of land is currently under cultivation using Meki River and its tributaries up stream of Meki town.

According to the reports, potato, tomato, onion and pepper are the major vegetables grown twice a year in the area. Using similar computational methods as above and annex 4 for crop-water requirement, the total annual abstraction from the river and its tributaries is 6mcm.

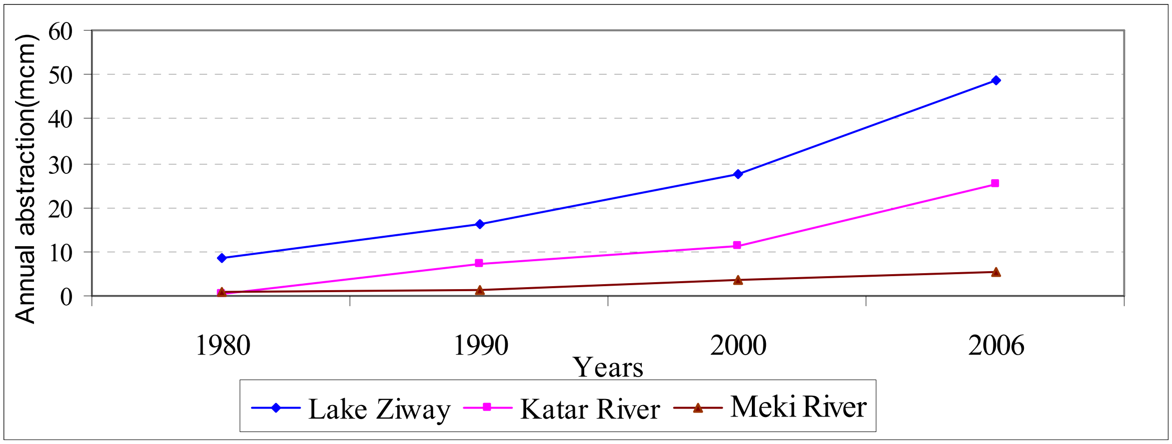


Figure 8.6 Trends in catchment water use from lake and rivers

Table 8.1 Estimated abstraction of water from Lake Ziway, Katar and Meki Rivers (mcm)

Year	Sources of abstraction		
	Lake	Katar	Meki
1980	8.79	0.24	0.85
1990	16.23	7.14	1.21
2000	27.68	11.27	3.43
2006	48.5	25.38	5.54

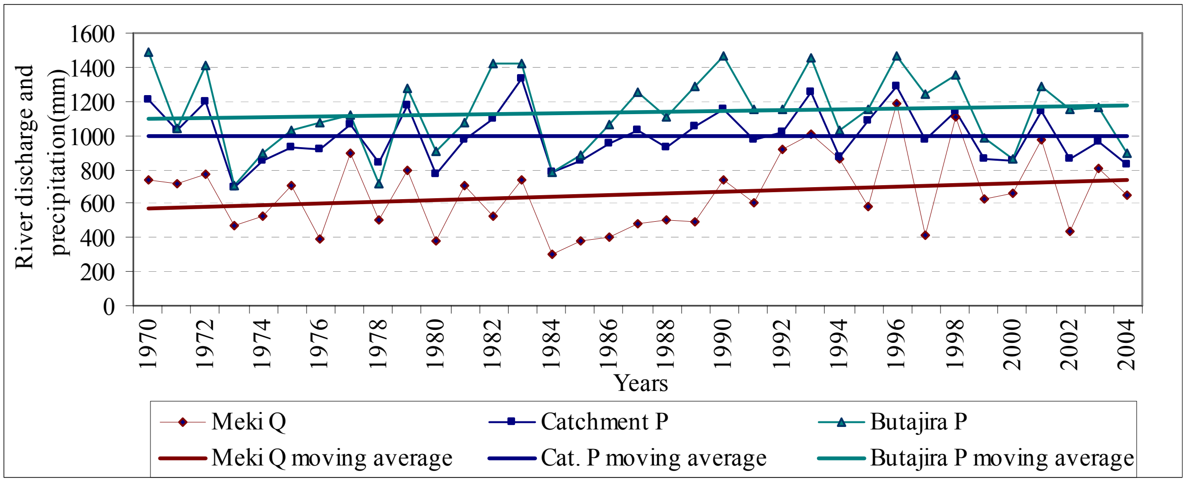
8.4 Changes in water balance components due to combined effects of climate and human interference

8.4.1 Rivers inflow to lake

As previously described Meki and Katar are the main rivers feeding Lake Ziway. In this section, changes in annual river flow in relation to precipitation of different stations and catchment; and the inconsistency between them are analyzed.

From Figure 8.7 it can be observed that the graph of Meki River discharge over the past 35 years shows rising trend. This rise in trend is attributed to low flows during mid 1980s' draught in the country. However, during the past 15 years the river flow has been declining resulting from change in climate and abstraction of water for irrigation purposes.

Meki river discharge is highly sensitive to Butajira rainfall than weighted catchment precipitation. As can be seen from the following figure, the trend lines of the river discharge and Butajira precipitation are parallel during the considered period.



Q and P stand for river discharge and precipitation respectively

Figure 8.7 Relationships among Meki River five times exaggerated annual flow; Butajira and weighted catchment precipitation.

In this analysis, five times exaggeration of river discharge refers to the actual river discharge multiplied by five to clearly show its relationship with precipitation.

Figure 8.8 shows that during the past eight years there is inconsistence between river discharge and respective annual Butajira precipitation reflecting the appearance of anthropogenic effects and changes in evapotranspiration in recent years.

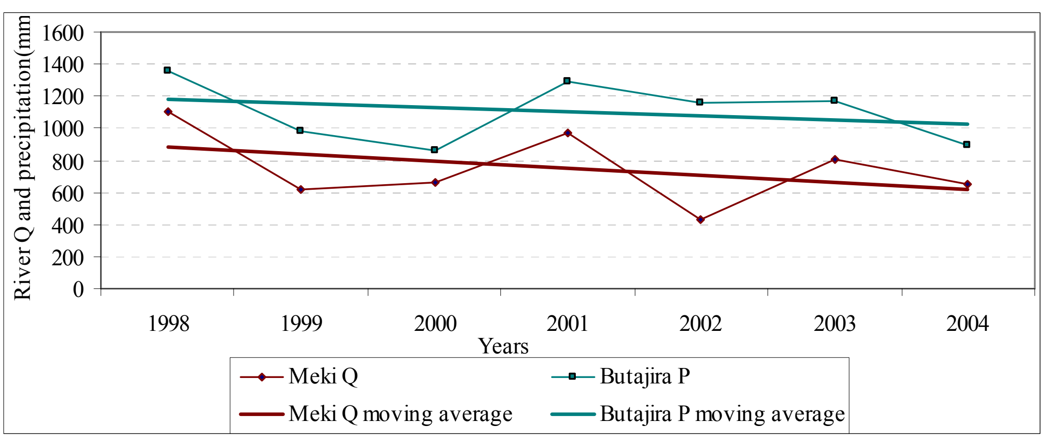
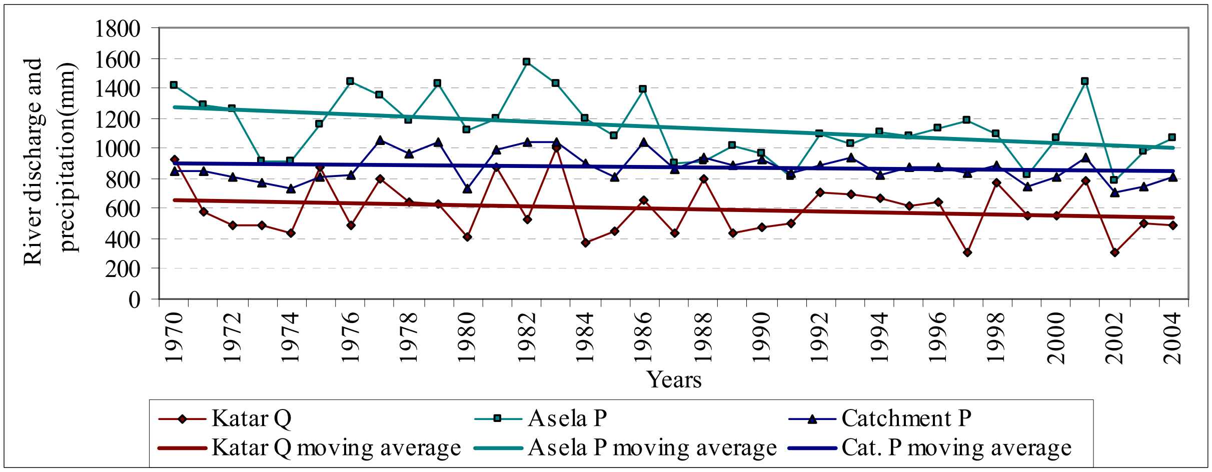


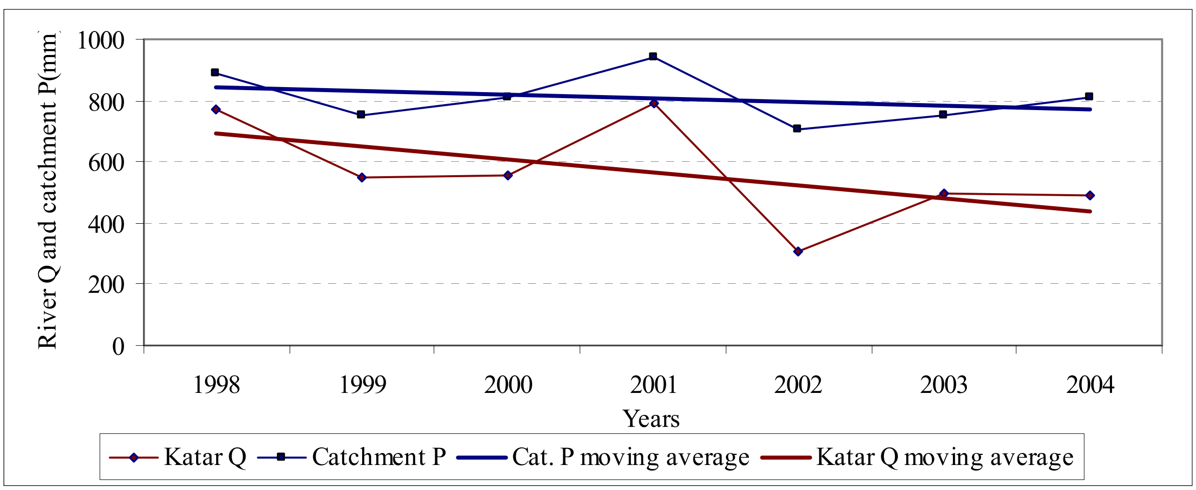
Figure 8.8 Recent changes in consistence between the exaggerated Meki River discharge and Butajira precipitation

When we consider long term discharge of Katar River, the decline in trend is related to climatic change over the catchment. However, when we consider recent discharge, both climatic and human activities are important factors in controlling the trend.



Q and P stand for river discharge and precipitation respectively

Figure 8.9 The relationships among Katar River five times exaggerated annual flow; Asela and weighted catchment precipitation.



Q and P stand for river discharge and precipitation respectively

Figure 8.10 Recent changes in consistence between the exaggerated Katar River discharge and Asela precipitation

8.4.2. Lake storage and outflow

Lakes are vulnerable to changes in climatic parameters and human induced effects. Variations in air temperature, precipitation, abstraction and other meteorological components directly cause changes in water balance and lake storage.

All the above factors considered in this chapter pose changes in lake storage. Table 8.2 shows the correlation between hydrologic parameters in the catchment. The correlation matrix clearly shows that lake level is more sensitive to catchment wise hydrology than its close environment. For instance, it is more affected by catchment precipitation and evapotranspiration than those in the lake surface. The matrix also shows that Katar and Meki Rivers are poorly correlated to lake level than they are for each other; indicating the importance of other factors affecting the lake storage.

Table 8.2 Correlation relationship among lake and other water balance components

	Lake level	Katar River Q	Meki River Q	Land sur. P	Lake surfac. P	Bulbula River Q	Lake surface E	Land surface E
Lake level	1.000	.366	.269	.505	.169	.964	-.626	-.724
Katar River Q	.366	1.000	.804	.669	.169	.552	-.575	-.451
Meki River Q	.269	.804	1.000	.768	.566	.563	-.550	-.403
Land surface P	.505	.669	.768	1.000	.655	.660	-.807	-.727
Lake sur. P	.169	.169	.566	.655	1.000	.404	-.395	-.415
Bulbula River Q	.921	.552	.563	.660	.404	1.000	-.758	-.813
Lake surface E	-.626	-.575	-.550	-.807	-.395	-.758	1.000	.920
Land surface E	-.724	-.451	-.403	-.727	-.415	-.813	.920	1.000

Correlation is significant at the 0.01 level (2-tailed).
Q,P, and E represent are Discharge, Precipitation and Evaporation respectively

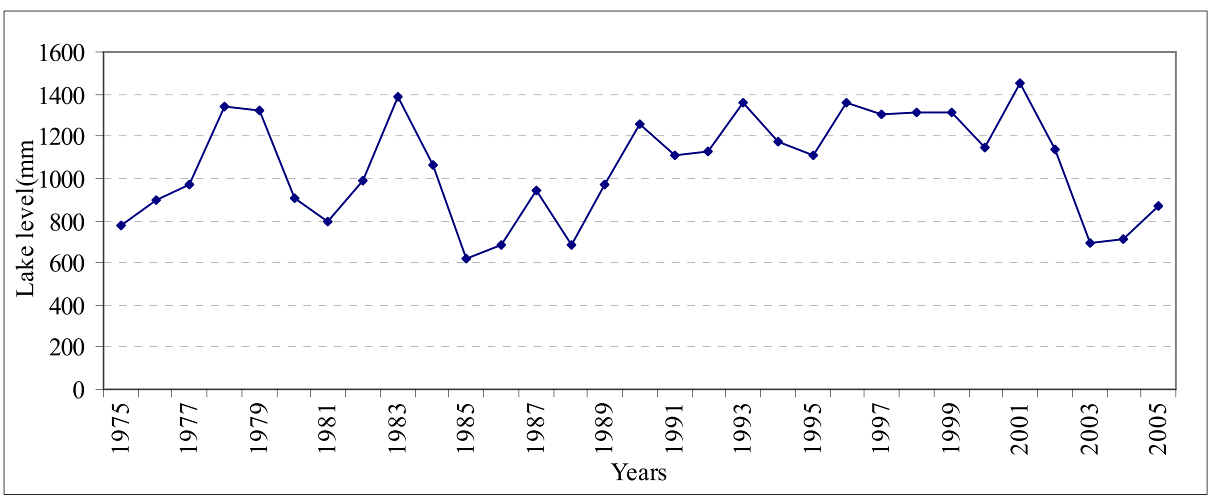


Figure 8.11 Changes in long term annual lake level

When we consider the trends of lake level during the past thirty years, it does not show significant change. This is due to the drought encountered in mid 1980s and hence the occurrence of decline in moisture and associated lake level. However, the level shows declining trend during the past fifteen years as depicted in the following figure.

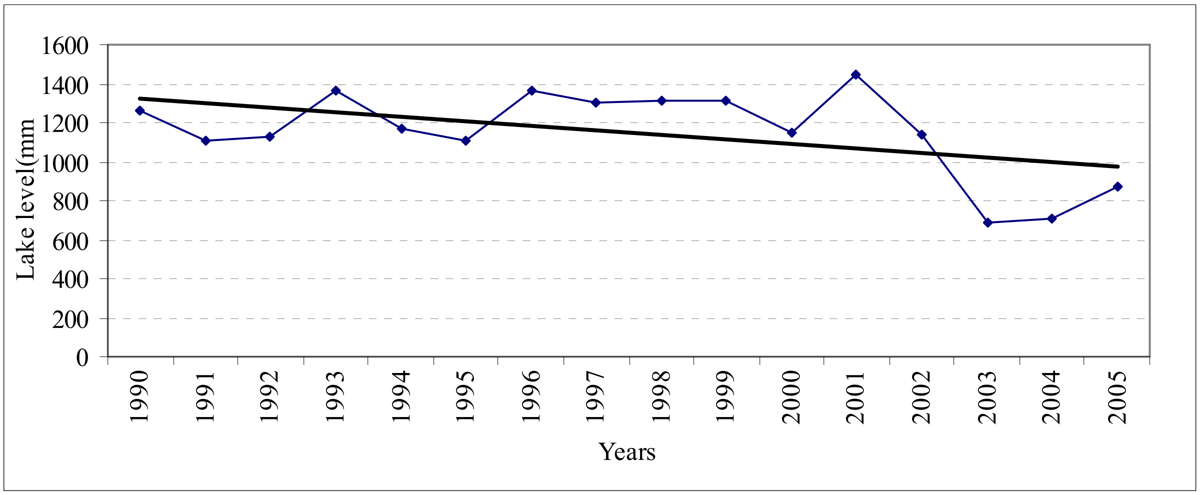


Figure 8.12 Recent changes in Lake Ziway level

The above figure shows that there is high decline in lake level during the last three years. This is due to the fact that inflows are decreasing while evapotranspiration and direct abstraction from the lake are continuously increasing in their trend.

From the correlation table above, lake level has the highest correlation coefficient with Bulbula river flow. This is revealed by the trends in recent discharge of the river.

The regression analysis between lake level and Bulbula River flow shows that the minimum level to generate runoff for the downstream (Bulbula River) is 0.78m above the bottom of current staff gauge.

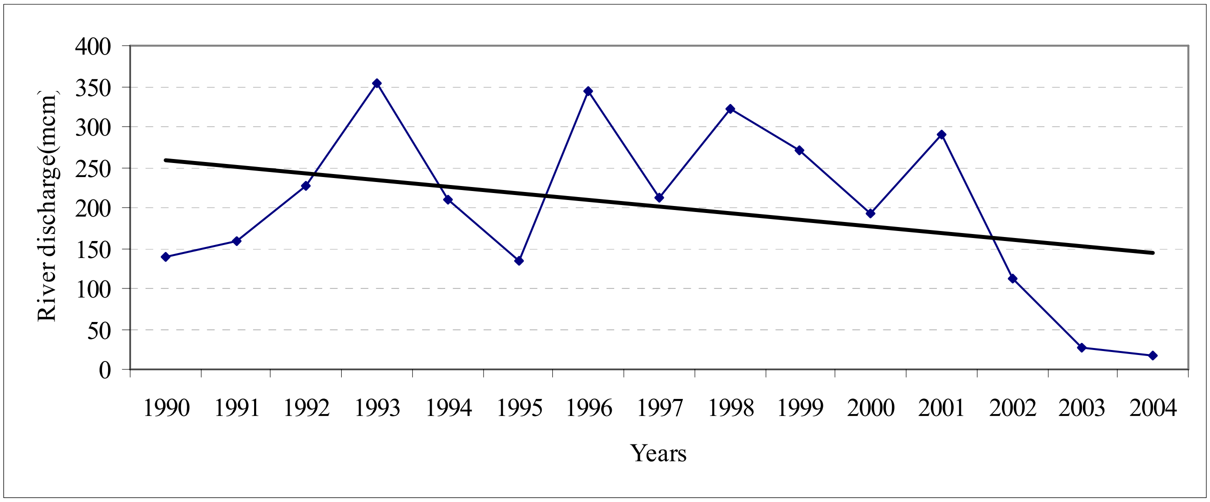


Figure 8.13 Trends in Bulbula River annual flow

8.4.3 Groundwater Recharge

Due to recent changes in climate and human activities there is a possibility of changes in groundwater recharge; and the evidences are described as follows:

As a recharge is a function of precipitation, evapotranspiration, land use, riverbed morphology and its mode of flow, any change in these parameters could result in change of groundwater recharge, although the magnitude may vary over time and space.

As described in the preceding sections, there is decline in precipitation and rise in evaporation trends. Both of these characteristics have their own contribution to decline in recharge. Direct groundwater recharge of a given area is fixed ratio of precipitation and hence affected by its change while increase in evaporation affects the recharge by depleting soil moisture surplus of the area.

Change in groundwater recharge can be resulted from changes in land use. According to Fiseha Itana(1998), there is land degradation in Ethiopian rift valley resulting from over population; impacting the environment by deforestation and poor soil management practices.

The effect of land degradation in hydrology is manifested by increasing the rate of surface runoff and evaporation; and reducing infiltration and percolation to the subsurface system. The effect of land degradation on recharge was analyzed by the change in sustainability of baseflow during dry seasons in the catchment. Figure 8.14 shows the ratio of dry season rivers flow after being adjusted for upstream abstraction to wet season rivers flow of the same hydrologic year.

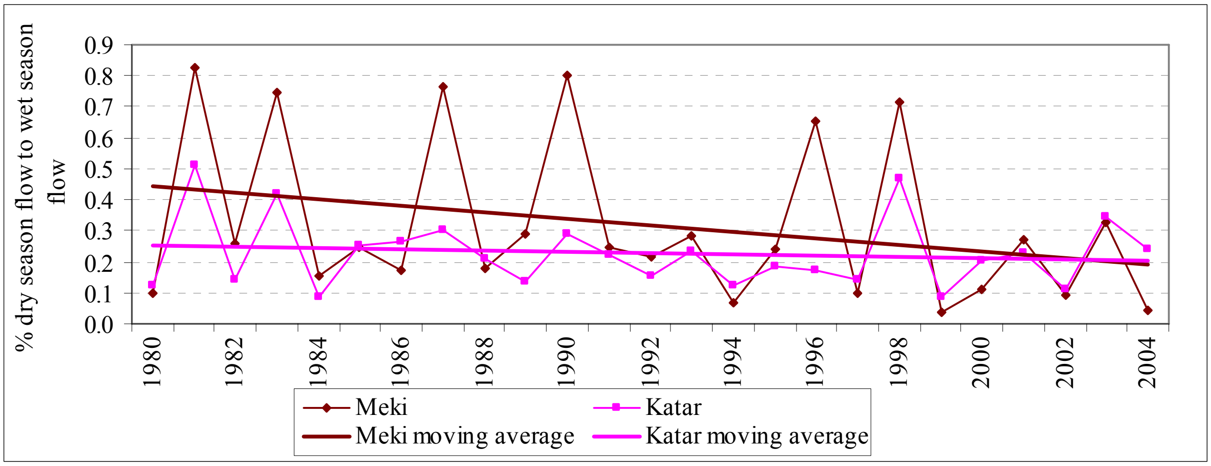


Figure 8.14 Trends in the ratio of dry season to wet season discharges of Katar and rivers

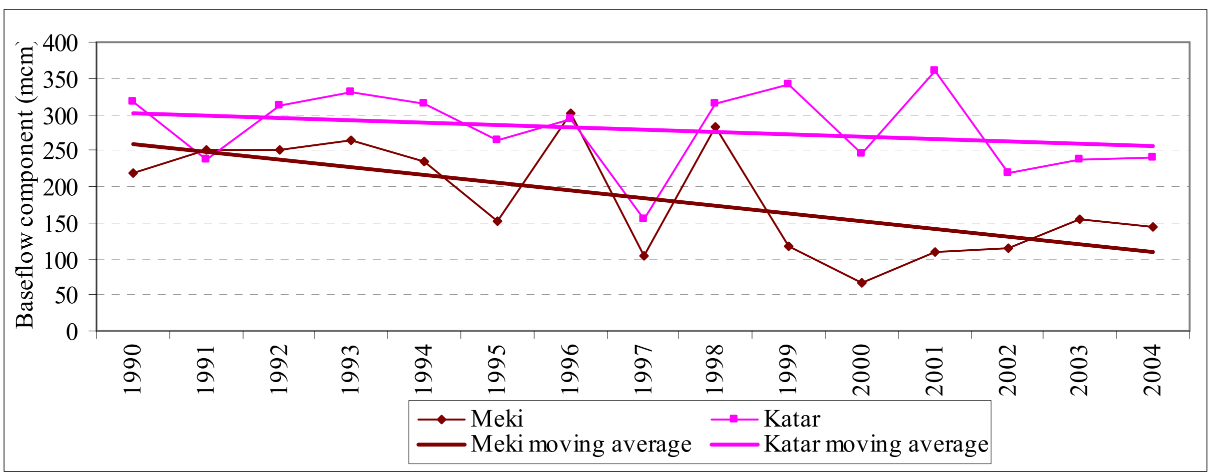


Figure 8.15 Changes in baseflow of Katar and Meki Rivers

From figure 8.15 it is apparent that the trends in baseflow after being adjusted for upstream abstraction, which is best expression of groundwater recharge is declining annually when we consider linear moving average.

The declining trend of groundwater recharge in recent years is attributed both to climate change and excessive human interferences in hydrologic cycle. The rate of decline in Meki catchment is higher than in the Katar catchment.

8. 5 Water balance analysis for the effect of changes in hydrologic components

The starting point of any water balance equation is:

Inflow = Outflow $\pm$ Change in storage

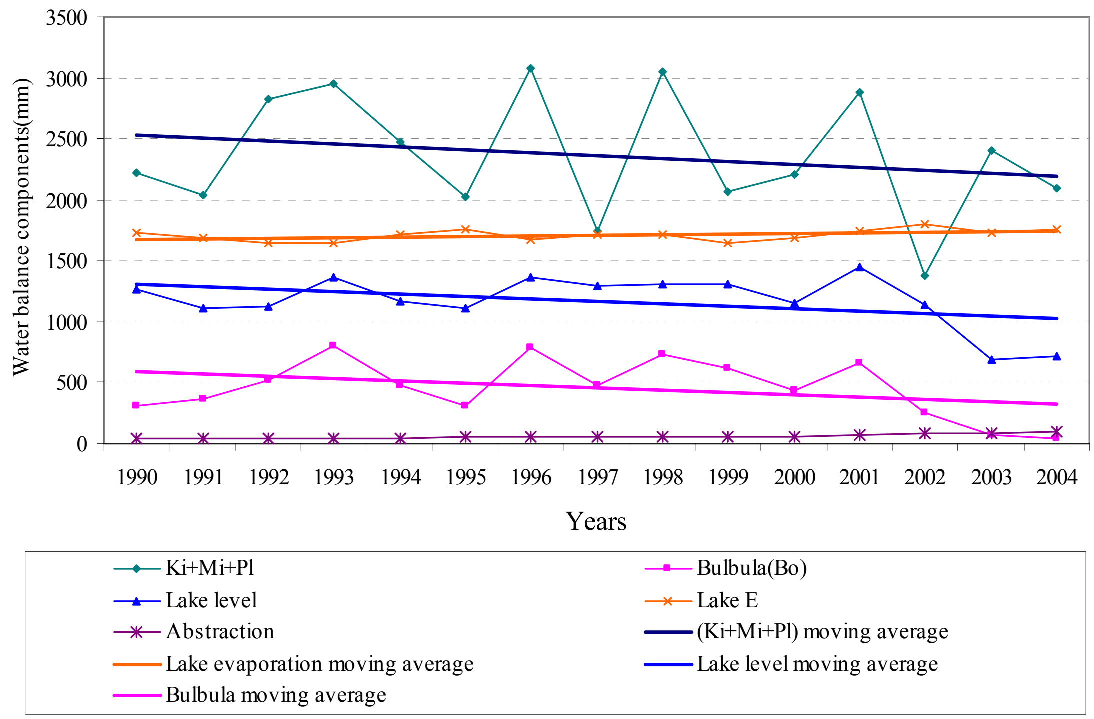
The equation for Lake Ziway will be:

$$K_i + M_i + P_l + G_i = E_l + B_o + A + Go \pm \Delta V \quad (8.1)$$

Where:

- K_i inflow of Katar River
- M_i inflow of Meki River
- P_l lake surface precipitation
- G_i groundwater inflow to the lake
- E_l lake surface evaporation
- B_o Bulbula River out flow
- A abstraction from the lake
- Go groundwater outflow from the lake
- ΔV change in lake storage

If groundwater inflow and outflow are assumed to be annually constant, any reduction in inflow parts as well as increase in lake surface evaporation and abstraction will deplete lake storage and Bulbula River outflow. This condition is happening in recent years and hence communities consuming the water from Bulbula River have been facing serious water shortage during extreme dry season.



Ki, Mi & Pl are Katar inflow, Meki inflow and lake surface precipitation respectively; and E is evaporation.

Figure 8.16 Summarized trends of lake water balance components

CHAPTER NINE

CONCLUSION AND RECOMMENDATION

9.1 Conclusion

The study area is located in central Ethiopia enclosed between latitude of 7^{0}20’54” to 8^{0}25’56” and longitude of 38^{0}13’02” to 39^{0}24’01”. It consists of three physiographic areas namely: highland, fault escarpment and rift floor. The area is drained by Meki River from the west and Katar River from the east; both feeding the lake at rift floor and then outflow to Bulbula River in southwest. The climate varies from arid at rift floor to humid at highlands.

The positions of Inter Tropical Convergence Zone (ITCZ) and topography have great influence on temporal and spatial distribution of precipitation in the area. Bi modal annual precipitation is more apparent in western half of the study area than the eastern side due to Garaghe Mountains that act as barrier to spring rain.

Before computation of aerial mean precipitation, point precipitation records of stations with few year monthly data have been updated by regression analysis; after determination of more correlated stations. The missing data were then replaced by the averages of regression results. The annual mean precipitation was analyzed by Thiessen polygon and Isohyetal computational methods. The Thiessen polygon method gives 887mm mean annual precipitation while Isohyetal method resulted 896mm annually. In the catchment basis, Meki and Katar catchments get annual mean precipitation of 1005mm and 881mm respectively. Based on surface topographic areas, the highland, escarpment and rift floor receive mean annual precipitations of 954mm, 882mm and 730mm respectively.

Analysis of potential evapotranspiration and actual evapotranspiration from land surface has been carried out using Thornthwaite heat index and Penman methods. Lake surface evaporation was analyzed using Penman method and pan; by taking pan coefficient of 0.83. The following table shows the analysis result.

Table 9.1 Summary of potential evapotranspiration (mm)

Method	Physiographic areas			Catchments			Lake surface
	Highland	Escarpment	Rift floor	Meki	Katar	Ungauged catchment	
Penman	1217	1329	1438	1272	1239	1406	1749
Thornthwaite	998	1121	1310	1037	1051	1192	-
Pan	-	-	-	-	-	-	1699

Table 9.2 Summary of actual evapotranspiration (mm)

Method	Physiographic areas			Catchments		
	Highland	Escarpment	Rift floor	Katar	Meki	Ungauged Catchment
Penman	883	871	727	876	814	769
Thornthwaite	869	874	730	865	808	772

Potential evapotranspiration in all three physiographic areas are higher than their corresponding precipitation. In addition, there is large gap between potential and actual evapotranspiration at rift floor that makes it moisture deficit throughout the year.

The close relationship between the analysis results of Penman and Thornthwaite methods for determination of actual evapotranspiration shows that temperature and sunshine hours used as input for both methods are the most important factors controlling the rate of evaporation in the area.

Katar and Meki Rivers have peak discharges in the month of August while Ziway Lake level and Bulbula River discharge reach their peak point in biginning and mid October respectively. Therefore, there is about one month and half lag time between the peaks lake level and inflow while it takes about 15 days between that Bulbula River outflow and maximum point of lake level.

Direct groundwater recharge of the area is strongly related to geology, topography, magnitude of highland precipitation, and degree of water resource management. Groundwater recharge from precipitation (direct groundwater recharge) was estimated using soil moisture budgeting and groundwater balance methods.

The soil-water balance method eliminates groundwater recharge at rift floor while it gives very small amount (8.9mm) at fault escarpments. The method also gives 86mm at highland areas and weighted recharge of 57mm for the whole catchment. However, the method has limitation in its applicability to arid and semi arid climatic zone as well as for highly fractured areas where there is less soil development. The groundwater balance method after determination of considerable losses that do not appear in gauging stations resulted in 83mm of annual recharge. Due to its less limitation in applicability, it is fair to take the result of groundwater balance method (83mm) as annual direct groundwater recharge of the catchment.

Characterization of catchment hydrogeology using rivers discharge, show that the distribution of geological units, geological structures, topography and precipitation control the interaction of groundwater and surface water in the area.

Groundwater table contour has been constructed to determine the position of riverbed in relation to the elevation contour. In the highland areas of the catchment, the elevation of the water table contours lie above the rivers bed indicating effluent characterstics of the rivers. The elevation of Meki River in volcano-lacustrine sediment of rift floor and that of Katar at the central and upper part of Wonji Fault Belt lie above the elevation of the contour showing loosing behavior of the rivers.

Baseflow measurements have been done to identify the areas of effluent and influent along the rivers reach during reasonably uninterrupted time (i.e. short time gap between discharge measurements along river reaches) in order to characterize the hydrogeologic dynamics of the area. Comparison by seepage run (or baseflow) measurements, show that the upstream discharges of Lower Meki in the volcano-lacustrine sediment and Katar in the upper part of the Fault Belt are greater than their respective lower reaches. For instance there is loss of 12.4l/s per kilometer from lower Meki in the sediment and about 964 l/s in stretch of 15.5km from Katar River in the fault belt during the survey. However, above those areas as well as in Lower Katar and Chufa Rivers the baseflow tends to increase downstream.

Channel losses observed in the above assessment have been quantified using channel water balance approach, which is one of the evaluation techniques for the interaction. Accordingly, Meki River has losses of about 43mcm between Dugda and Meki town stations in the stretch of 34.2km; while the Katar River losses about 86mcm water annually between Fite and Abura stations in 36.2km river stretch.

In the hydrograph analysis, the shape, percent monthly flow pattern and baseflow separation of four rivers in the catchment were compared to characterize the hydrogeology of each catchment. Katar River at Fite gauging station shows fast response to daily precipitation, more flow during the rainy reason as compared to other river catchments, and lower percentage of baseflow to total annual runoff. The hydrograph of Meki River has lower irregularities, early rise, and fast recession during dry season than the above mentioned river. The hydrograph of Katar River at Abura is smooth, showing less response to daily precipitation, higher runoff after immediate end of wet season but declining at faster rate. Chufa River has smooth hydrograph with less variation in its flow throughout the year, highest proportion of baseflow and flat recession curve. These behaviors of the hydrographs show that river catchments of the area have different hydrogeological characteristics.

Analysis of the relationship between precipitation and baseflow of major rivers shows that Meki, Lower Katar, Upper Katar and Meki have 7.8%, 9.1%, 9.8% and 12% baseflow to their corresponding catchment precipitation respectively. Meki and Lower Katar have lower proportions of baseflow due to less precipitation, more evaporation and channel losses in their catchment.

Monthly lake water balance indicates that more groundwater outflow over inflow takes place in April and between June and September; while more inflow over outflow is in the other months. The highest groundwater inflow per outflow recession in the months of August occurs due to the lag time between early precipitation and its contribution to groundwater storage; and ultimate flow to the lake. In the month of November groundwater inflow over outflow gets peak point. However, deficit during August makes higher out flow than inflow in the annual basis.

Table 9.3 Summary of annual Lake Ziway water balance

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

The five years moving average of the precipitation in the catchment shows that there is decrease in rainfall by about 30mm every five years. In addition, trends in potential evapotranspiration indicate about 215mm rise on land surface from 1995 to 2004 and 260mm on Lake Surface from 1979 to 2004.

Abstraction of water from rivers and directly from the lake for irrigation and municipal purposes is increasing and currently reached about 76mcm annually. Declines in baseflow as well as ratio of adjusted dry season river discharge to the respective wet season of the same hydrologic year show the recession of groundwater recharge. Lake level and its outflow to Bulbula River are declining recently as a result of cumulative effect of both climatic and anthropogenic factors. The lake level has been declined by about 300mm from 1990 to 2005.

9.2 Recommendation

- Hydrochemical and isotope methods should be employed in future works for analysis of groundwater and surface water interaction in the catchment.
- 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, transmisivity, storage coefficient and aquifer geometery 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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Stat-ion	Abura	Areta	Asela	Bokoji	Bui	Butaira	Diga-lu	Ejer-salele	Katarguent	Kersa	Koshe	Kul-umsa	Meki	Meraro	Sag-ure	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
Boko-ji	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
Sagu-re	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

Annex 2. Integrated vegetation and available water holding capacity of different soil types

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

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

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 Borehole Hydrogeological database

No	Location	Cased diameter(mm)	Ground elevation	Total depth (m)	Transmisivity (m2/day)	Hydr. Conductivity (m/day)	Draw down	yield (l/s)	Aquifer lithology
1	Adami Tulu	168	1650	71	221	8.4	4.92	5.6	lacustrine sed
2	Mitto	240	1800		416	13.87	3.8	5	ignimbrite
3	Ashebeka	250,150	2420	151	1.82	0.03	25.2	8	ignimbrite
4	Alkasa	250,150	2420	125	1.3	0.02	12.5	0.03	ignimbrite
5	Wereseni	250,150	2450	168	780	18.4		0	ignimbrite
6	Waji	250,150	2600	115	1.04	0.02	0.5	1.7	ignimbrite
7	Kulumsa	250,150	2210	120	2.6	0.08	12	0.3	ignimbrite
8	Gora	250,150	2250	105	1040	41.6	0.25	1.1	ignimbrite
9	Gonji	250,150		102	78	4.12	3	1.6	basalt
10	Dugda	203	1920	122	91	2.94	3.6	2	lacustrine sed

Annex 6 Groundwater table elevation (m)

No	Location	XUTM	YUTM	GWL altitude	No	Location	XUTM	YUTM	GWL
1	Meki nucplity	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	55	Udada	495014	884350	1643
18	Koshe	448573	884180	1830	56	Hellanna	513788	870666	2557
19	Faka	447136	880164	1891	57	Mulqiicha	495969	863601	1898
20	W. Gerbi	465881	875514	1625	58	Shola Chabetti	514055	866034	2566
21	Boromo	460735	874769	1604	59	Wanji Gora	516954	884109	2278
22	Woleyie	463164	870844	1617	60	Totoke	473605	827856	1623
23	Shisho Tabo	462052	866226	1614	61	Kurteta	480132	824147	1811
24	Adami Tulu	467301	869468	1609	62	Buku	476682	829321	1621
25	Garbi	468448	871433	1624	63	Gubeta	477268	830389	1622
26	Waji	514202	870371	2528	64	Digalu	510579	859046	2409
27	Abura	500220	889567	1675	65	Doddoba	496886	878152	1675
28	Gonde	521570	887113	2265	66	Mereko Woreda	429307	897130	1871
29	Burkitu	510611	883617	2120	67	Meskan oreda	449039	891512	1825
30	Abargeda	499840	889943	1699	68	Meskan Woreda	440217	886397	1833
31	Adulala	495776	886600	1636	69	Meskan Woreda	439248	896637	1873
32	Andode	505428	890015	1740	70	Meskan Woreda	428001	877580	1824
33	Arba	508715	897993	1694	71	Meskan Woreda	441911	891294	1817
34	Baddara	498435	882864	1613	72	Meskan Woreda	442504	904859	1832
35	Bowenni	501266	889596	1595	73	Meskan Woreda	424189	892802	2179
36	Burka	497049	892945	1641	74	Soddo Woreda	434853	907907	2054
37	Ch.e Burkitu	489704	867598	1793	75	Soddo Woreda	440353	918436	2702
38	Choba	495299	884905	1644	76	Soddo Woreda	449186	933018	2651

Annex 7 Annual discharges of main rivers in the catchment

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 8 Annual level of Ziway Lake

Year	Lake level Average	Max.	Min.		Year	Lake level 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 9 monthly percentage of abstraction as total annual from lake

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 10. Annual precipitation, pan evaporation, estimated lake evaporation and baseflow

Year	Precipitation					Catch-ent	Lake surface E	Base flow (mcm)	
	Catchment	Meki Cat. P	Katar Cat.P	Asela	Butajira	Pan Evapora-tion	(Penman	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