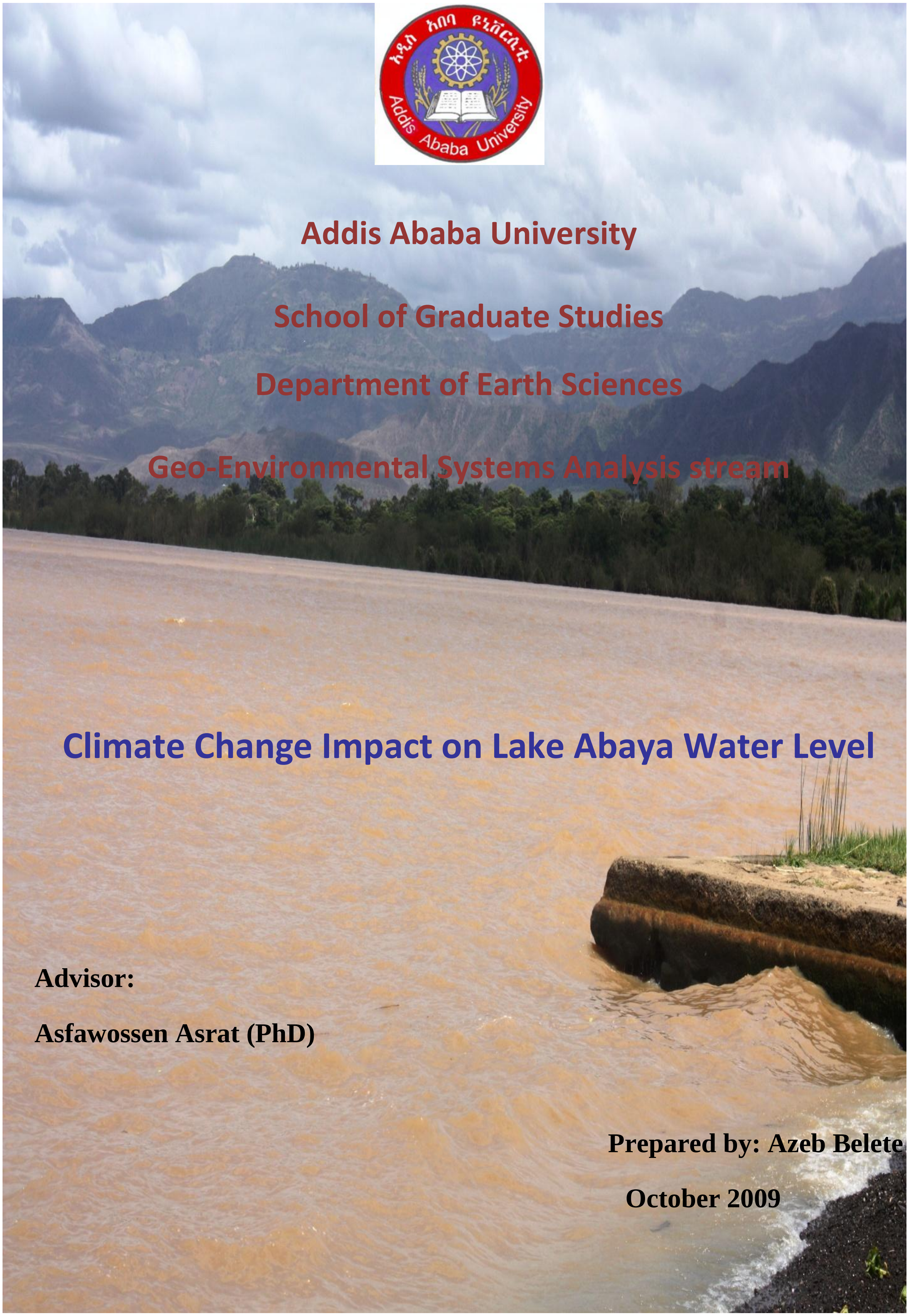

Addis Ababa University

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Climate Change Impact on Lake Abaya Water Level

Advisor:

Asfawossen Asrat (PhD)

Prepared by: Azeb Belete

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Approved by board of examiners:

	Signature
Dr. Balemual Atnafu Chair Person of the Department of Earth Sciences	____________________
Dr. Assfawossen Asrat Advisor	____________________
Dr. Mohammed Umer Examiner	____________________
Dr. Worash Getanhe Examiner	____________________

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A thesis submitted in the partial fulfillment of the requirements for the degree of masters of Science in Geo-Environmental Systems Analysis, Addis Ababa University, Ethiopia.

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Abstract

The present study area is located in Abaya-Chamo basin, in the southern part of the Ethiopian Rift Valley. In this research project climate change impacts on levels of Lake Abaya is assessed by using appropriate techniques and the future lake level is forecasted based on scenario analysis conducted by changing the lake water balance parameters. Available time series data (satellite, hydrographic, climatic, land use- land cover, socio-economic, etc.) of the last two decades, in the area is used to determine the baseline, based on which modeling and lake level fluctuation is assessed .The water balance components of Abaya, the amount of runoff, precipitation, evaporation & storage changes, and their annual changes over the 1987-2005 period is systematically analyzed & formulated as a lake level forecast model. The model shows the average yearly inflow from river discharge, unguaged runoff and precipitation which are 750, 691 and 980 mcm, while the average outflow from evaporation is 2009mcm, respectively.

The formulated model is applied in order to ascertain the effect of these components in the historic and future lake levels based on the sequences of 1987-2005 hydro-climatic conditions with different applications and assumptions. The assumptions are generally aims to test several different values of the observed hydro-climatic for future conditions. Based on the assumptions considered in the applications past hydro-climatic conditions observed and recorded as evidence and questionnaires taken from community living in study area, model applications 1A (tried to show the effect of river discharge and precipitation in the lake level rise), 2(tried to show the effect of lake evaporation in the lake level change), 4(the effect of precipitation amount on the surface of the lake and runoff from unguaged catchment in the lake level change) and 5(the effect of runoff amount increases by 50% of the present due to land use/land cover change by deforestation and agricultural land in the lake change) are chosen as a good predicator of Abaya lake level fluctuation. From the models it is observed lake level fluctuate mostly due to climatic factors and also man-made processes, precipitation and evaporation causes the major changes and also deforestation and agricultural expansion in the catchment had their own role.

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List of Acronyms

MER: Main Ethiopian Rift

ACB: Abaya-Chamo sub basin

NMSA: National Meteorological Service Agency

SNNPRS: southern Nations and Nationalities People Regional State

RVLB: Rift Valley Lake Basin

RH: Relative Humidity

TDS: Total Dissolved Solids

NTU: Nephelometric Turbidity Units

WWDSE: Water Works Design and Supervision Enterprise

UNESCO: United Nation Educational, Scientific and cultural Organization

SPSS: Statistical Package for the Social Sciences

ARIMA: Autoregressive integrated moving average

MoWR: Ministry of Water Resources

ERVL: Ethiopian Rift Valley Lakes

M a.s.l: Meters above sea level

Mcm: Millions of Meter Cube

mg/l: Milligram per liter

mm: Millimeter

CHAPTER ONE

Introduction

Ethiopia is gifted with a variety of aquatic ecosystems, especially a number of lakes that are of great scientific interest and economic importance. The majority of the Ethiopian lakes are confined within the rift valley that extends from the Kenyan border in the South to the Afar Depression in the north. Lake Abaya is among these lakes and the lakes of the rift valley basin, which provide extra beauty to Arba-Minch city. The current status and ability to use and enhance the positive role of water and reduce the negative impacts of water, in Ethiopia in general and the study area considered in here in particular, is low.

The level of Abaya Lake shows continuous changes in the last few decades. There are indicators that the region and the water resources system is affected due to growth of population, deforestation, erosion and sediment transport (Awulachew, 2001). Furthermore, the entire system seems under sensitive ecological balance and vulnerable to natural and manmade impacts. It has been observed, however, that the water volume in Abaya Lake had been decreasing until the latest El Niño event in 1997/1998, which resulted in the complete recovery of Abaya Lake (Awulachew, 2006). The general increasing level trend for the last three decades is attributed to combined effect of land use and climatic changes (Schuett et al. 2003). And also that of lake level changes that took place in Ethiopia may dominantly be natural phenomena rather than anthropogenic, with the exception of lakes Abiyata and Ziway (Ayenew, 2007) by observing the dramatic lake level record fluctuation in half a century but long-term pumping of the Kenyan lakes for horticultural development for example is minimal in size reduction.

Lake level of Abaya has been measured since 1970. During that period the lake level has been subjected to repeated changes and has been continuously increasing since the mid of 1980(Schuett et al. 2003). Climatic conditions during that time also repeatedly changed. Lake Abaya's level might have also been influenced by the dramatic population growth since the late 1970, changes in land-ownership, clearing of forests and bush-land as well as changes in cultivation manners which caused dramatic increase in sediment yield of the tributaries, thus, influencing basin bathymetry and volume. Because of its shallow depth (max. depth of 26 m) the level of lake is sensitive to changes of water and sediment input (Schuett et al. 2003) and, becomes an ideal subject-matter to analyze complex pattern of climatic and human impacts on lake level changes. Nevertheless, as Lake Abaya is located in the Main Ethiopian Rift (MER) Valley also neo-tectonics at the southern sill influencing outflow to Lake Chamo have to be kept in mind and, analyze the water balance of the lakes to mitigate the impact of climate change on the lake level.

1.1 Statement of Problem

Natural ecosystems are “open” systems in the sense that there is free transfer of energy and matter in and out of the system, keeping the system in a dynamic equilibrium. However, the human intervention on environment has induced a challenge on the ecological balance. These interventions are seriously affecting this balance. Changes in lake level resulting from a shift in the regional water balance are among these imbalances; particularly in closed terminal lakes responses are partly from climatic changes but the system tends to maintain equilibrium between input and output. However, slight shifts in the regional climate and withdrawal of water on a time scale of decades, or even less can change the steady-state elevation of terminal lakes by several meters (Ayenew, 2002a, 2009). Therefore, understanding the relative importance of natural and manmade factors in relation to the impacts induced on the hydrological and ecosystems in the MER system help to forecast their evolution in the near future (Ayenew, 2002a, 2009). And this is more relevant in the semi-arid African tropics, including Ethiopia, where there are large interannual climate changes and increasing population pressure making the region more sensitive to the fluctuations of water resources (Servat et al., 1998).

Lakes which are found in the MER are subjected to climatic factors, such as seasonal rain fall, which might change on a regional or global scale (Anna, 2006). Lake Abaya is among them, since the 1970 dramatic population growth, changes in land-ownership, clearing of forests and bush-land as well as changes in cultivation manners caused change of the Lake Abaya level. Consequently, lake level changes of Abaya are controlled reciprocally by: climatic oscillations influencing regional water balance and human impact causing increase of soil erosion rates and, which causes increase of sediment yield of the tributaries and thus, causing changes in basin volume. Doing water balance model of Abaya Lake will help in assessing the impacts of the water resource development activities in the drainage basins on the lake, and the sustainability of the lake under natural degradation and sediment deposition within the lake. Accordingly, this paper focuses on developing a water balance model as well as the hydrometeorological elements of the water balance under a situation of limited data. The developed information is used to simulate the lake water levels. The model is then used to illustrate the significance of individual water balance components. Because analysis of lake level and hydrometeorlolgical records considerably assisted in understanding the response of some lakes to climate change and anthropogenic factors (Legesse et al., 2004). Based on the results obtained, comparisons are made to illustrate the most detrimental factors to the Abaya lake level fluctuation. Therefore, it is important to consider the major factors that contributed most in the past two decades to lake level change and it is also important to identify their degree of contribution in order to assess the fluctuation of lake level scenarios in the future and in order to devise integrated mitigation measures. Thus, this study is be backed up with the available data & supported by suitable techniques, result of which is be used to recommend proper water resources utilization schemes.

1.2 Objectives

1.2.1 General Objective

The purpose of this study is to assess and analyze the impact of climate change on Abaya Lake level fluctuation using all available time series data (satellite, hydrographic, climatic, land use- land cover, socio-economic, etc.) of the last few decades. The results will be used to forecast lake level fluctuation in the near future and to suggest mitigation measures of impacts due to the fluctuation.

1.2.2 Specific Objectives

- To estimate the various hydro-meteorological components of the lake.
- To assess the spatial and temporal variability of the lake level.
- To develop a conceptual model linking the water level of the lake to hydro-meteorological and land use parameters.

- To assess the relative degree of natural and manmade factors affecting the lake level.
- To do qualitative and some quantitative scenario analysis of the effect of climate change on the lake level.

1.3 Significance of the study

The output of the study will be an input for governmental and non-governmental organizations working in climate change studies and environmental rehabilitation programs…in relation with climatic parameters and manmade factors which induces the lake level fluctuation.

1.4 Scope and Limitation of the Study

The study is limited in scope in that the assessment only covers the Abaya-Chamo sub basin (ACB) and the factors used to assess the climate change and lake level fluctuation is only from this catchment. Furthermore, this study is subjected to the following limitations:

- Properly documented time series hydro-meteorological data is scarce. This is because of incompleteness and missed records for the stations needed. Therefore, the study is limited only to the last two decades.
- Secondary data present in different sources collected within the same period of time for the same station showed inconsistency due to problems in proper recording, quality of the personnel assigned to record the data, documenting, and organizing. In short the data available are of low quality and the analysis will try to address first this issue of data inconsistence.

1.5 Methodology

1.5.1 Materials

-To generate map of the catchment 1:50,000 scale topographic maps & Arc GIS 9.1 software is used.

-Images of Landsat are incorporated to refine current land use/land cover of the watershed and also the past.

-Topographic maps and GPS are used in the fieldwork. This field survey includes observation of general geographic setting of the area, workability, accessibility of the catchments and also settlement sites and other infrastructures.

-Available time series data of metrological, satellite, hydrographic, climatic, land use- land cover, socio-economic etc. of the last two decades are used to determine the baseline, based on which modeling and lake level fluctuation is assessed.

- Different literatures

-ERDAS is used for image processing activities and change detection analysis on land use/ land cover map of classified images.

1.5.2 Data Sources

-Land use change of the catchment is analyzed using multi-temporal satellite images. This land use change analysis is used to identify the different land use in the study area in different times.

-Long-term mean monthly records from nearby stations have been taken from National Meteorological Service Agency (NMSA) in order to analyze the spatial and temporal variations in precipitation within the catchment.

-Mean monthly minimum, maximum, and average air temperature of the area have been obtained.

-The mean monthly lake evaporation of Abaya has been obtained from pan evaporation by taking correction factors to approximate the measured evaporation rates to natural open water-surface evaporation.

-Relative humidity in the Abaya sub- basin has been analyzed.

-The mean annual wind speed has been analyzed from National Meteorological Service Agency data of the area.

- Hydrological data, like runoff has been analyzed for Abaya-Chamo sub basin and lake level.

CHAPTER TWO

Review of Literature

2.1 Lake Level Fluctuations in the Main Ethiopian Rift

The principal determinant of a lake's position in the series is the open or closed nature of its individual drainage. At present in Ethiopia there are three major closed systems (the Awash River - Afar drainage, the northern rift lakes, the southern rift lakes), numerous crater lakes with seepage-in and -out, and two cryptodepressions with marine inputs. Salinity is primarily determined by evaporative concentration, enhanced in lakes associated with past marine influence or recent volcanic activity by readily soluble materials in the catchment, and by some thermal-reflux pathways. However, anomalously dilute closed lakes exist, indicative of other processes of solute loss (e.g. past basin overflow, 'reverse weathering', seepage out).

Ethiopia contains some 7000 km^2 of inland water whose scientific interest is largely unexploited. With the exception of Lake Tana, (which includes all the large lakes) are within closed drainage systems, although several are individually open systems.

The Ethiopian Rift system extends from the Kenyan border up to the Red Sea and is divided into four sub-systems: Lake Rudolf, Chew Bahir, the Main Ethiopian Rift and the Afar drainage. The MER contains three separate lake basins holding the Ziway, Langano, Abiyata & Shalla lakes, Lake Awasa, and Lake Abaya- Chamo. The climate is semi-arid in the central part of the MER, semi-arid close to the Kenyan border and arid in the Afar region (Ayenew, 2007). The annual rainfall within the limits of the rift varies from around 100 mm in much of the Afar up to around 900 mm close to Lake Abaya. The elevation within the rift varies widely from close to 2000 m a.s.l at Lake Abaya and around 120 m below sea level in the Dalol Depression. Many of the lakes are located within a closed basin fed by perennial rivers. The major rivers in the region are Awash, Meki-Katar, Dijo and Bilate feeding lakes Abhe, Ziway, Shala and Abaya respectively (Ayenew, 2007). Lakes Abaya and Chamo are seasonally connected by overflow channel. The MER lakes are highly variable in size, hydrogeological and geomorphological setting (Table 2.1).

Lake	Altitude (m)	Surface Area (Km2)	Max. Depth (m)	Mean Depth (m)	Volume (Km3)	Salinity (g/1)	Conductivity (µS/cm)
Chamo	1233	551	13	-	-	1.099	1320
Abaya	1285	1162	13.1	7.1	8.2	0.77	925
Awasa	1680	129	21.6	10.7	1.34	1.063	830
Shala	1550	329	266	87	36.7	21.5	21940
Abiyata	1580	176	14.2	7.6	1.1	16.2	28130
Langano	1585	241	47.9	17	5.3	1.88	1770
Ziway	1636	442	8.95	2.5	1.6	0.349	410
Beseka	1200	3.2	-	-	-	5.3	7155

Table 2 1 Basic Morphometeric data of the lakes (Source: Wood and Talling, 1988; Halcrow, 1989; Ayenew, 1998)

The major input to the MER lakes comes from highland rainfall generating perennial and seasonal flows in the form of rivers and surface runoff. The amount and distribution of highland rainfall strongly controls the level and size of these lakes (Street, 1979; Ayenew, 1998). Groundwater recharged by direct rainfall is also vital to many lakes (Ayenew, 2002a, 2007).The lake level records show extreme fluctuations over half a century; the Ethiopian case is more dramatic. Despite long-term pumping of the Kenyan lakes for horticultural development, the reduction in size is minimal. This signals that the lake level changes that took place in Ethiopia may dominantly be natural rather than anthropogenic, with the exception of lakes Abiyata and Ziway.

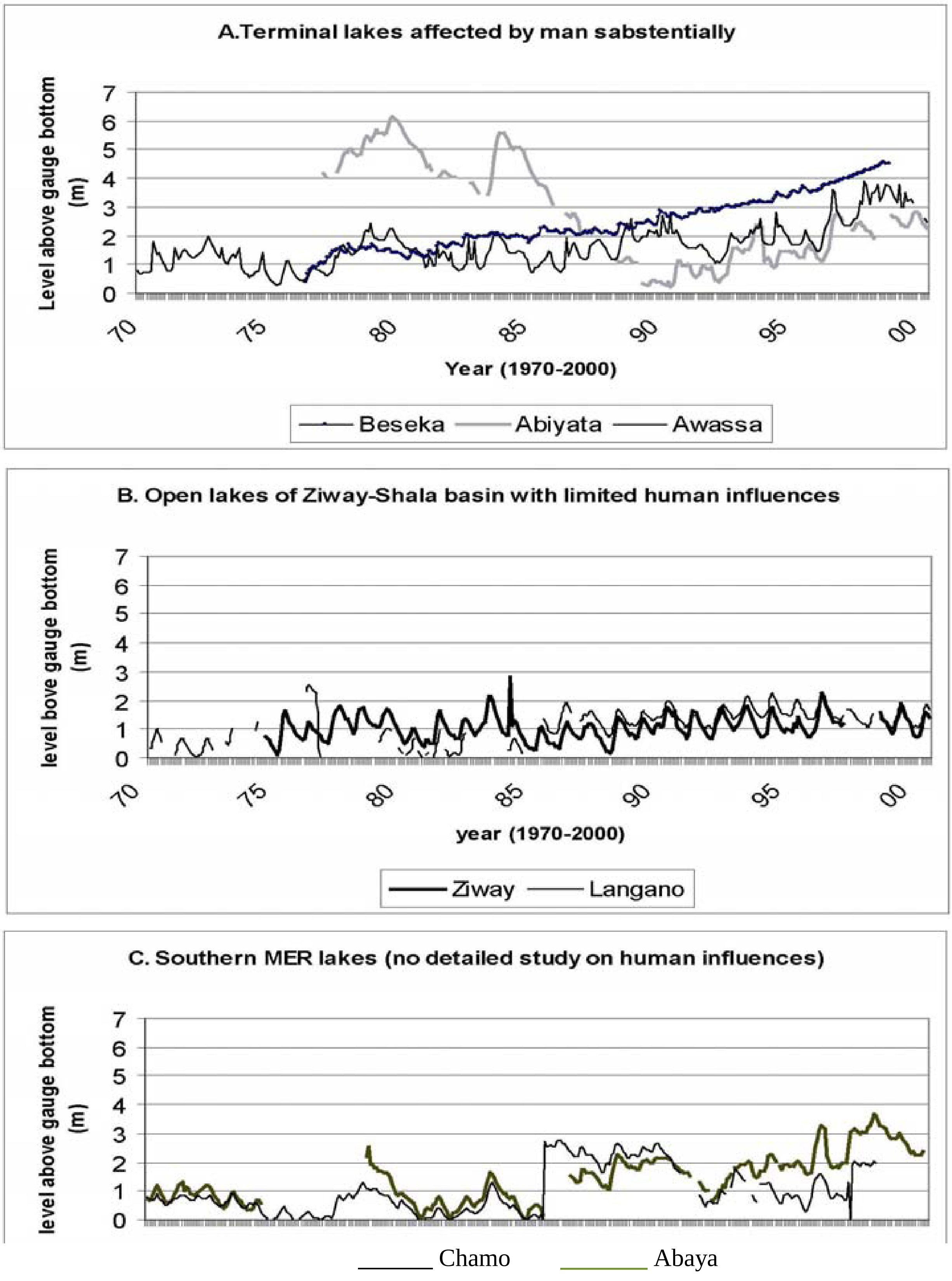


Figure 2 1 Lake level fluctuations in the Main Ethiopian Rift (Source: Ayenew, 2007)

2.2 Abaya –Chamo Sub Basin General Description

The Abaya–Chamo drainage sub-basin (ACB) mainly comprises the two lakes and numerous rivers and streams entering both lakes. The two lakes are connected via surface hydrology. The water outflows from Lake Abaya enter Lake Chamo through Kulfo, and an overflow from Lake Chamo through Metenafesha joins Sermale stream and subsequently the Sagan River, ending up in a terminal lake at the border of Ethiopia and Kenya known as Lake Chew-Bahir, when there is a lake level rise that makes the lakes to overflow. This overflow takes place when the precipitation in the region is above long-term average (Ayenew, 2009). But with increasing diversion of water from tributary rivers for irrigation, the overflow to Chew Bahir and the surface water connection between Lake Abaya and Chamo will likely cease to exist. Thus, this Abaya-Chamo sub-basin is a quasi–endoric system in the southern Ethiopia Rift valley lakes. This basin is treated as a single basin and because the two lakes are hydrologically interconnected (Awulachew, 2001). But in this study Abaya Lake only is considered because of the scarcity and inaccuracy/factual error of data needed for Lake Chamo.

Abaya Lake is the largest lake in the Ethiopian Rift. The lake is fed by the Bilate River which flows from the north, and other rivers from the eastern and western highlands. The rivers in the Abaya –Chamo sub-basin input amount (discharge) to Abaya Lake is 383,119,189 and 60 mcm for Bilate, Gelana, Gidabo and Hare, respectively. The colour of Abaya is distinctly brown due to the sediment derived from surrounding highlands. The rivers are summarized below for the sub-basin.

Perennial River flowing in to Lake Abaya	Intermittent River Flowing in to Lake Abaya	River out flowing from Lake Abaya(if there is overflow)	Perennial River flowing in to Lake Chamo	Intermittent River Flowing in to Lake Chamo	River out flowing from Lake Chamo (If there is overflow)
Gelana	Dimo	Kulfo	Kulfo	Sile	Sermale
Bilate	Basso			Sego	Sagan
Gidabo	Hamessa			Argoba	
Hare				Wezeka	

Table 2 2 Rivers Flowing in to and out of Abaya and Chamo Lake.

2.3 Basic Data on Lake Abaya and Chamo

Parameters	Lake Abaya	Lake Chamo
Altitude (m)	1169	1110
Basin Area ,including lakes (km^2)	16,328.78	18,599.8 (with lake Abaya contribution)
Area ,including Islands(km^2)	1,139.78	316.72
Maximum Effective length (km)	79.2	33.5
Maximum Width, Perpendicular to length (Km)	27.1	15.5
Mean Width (Km)	14.13	10.1
Maximum Depth(m)	24.5 around the islands	14.2 near the middle
Depth (m)	8.61	10.23
Shoreline (Km)	268.78	108.1
Volume (M^3)	$9.81x10^9$	$3.24x10^9$

Altitude: from Ethiopian Mapping Agency 1:50,000 map of 1975

Table 2 3Morphometric Characteristics of Lake Abaya and Chamo (Awulachew, 2006)

CHAPTER THREE

Project Description and Baseline Information

3.1 Project Description

3.1.1 Site Description

Lake Abaya is located about 510 km south of Addis Ababa between 5^{o} 3'19"and 6^{o} 45'11" North latitude and 37^{o} 18'55"and 38^{o} 7'55"East longitude .This lake is located within the Main Ethiopian Rift (MER), which extends from the southern Afar to the Konso highland in the southern Ethiopia.

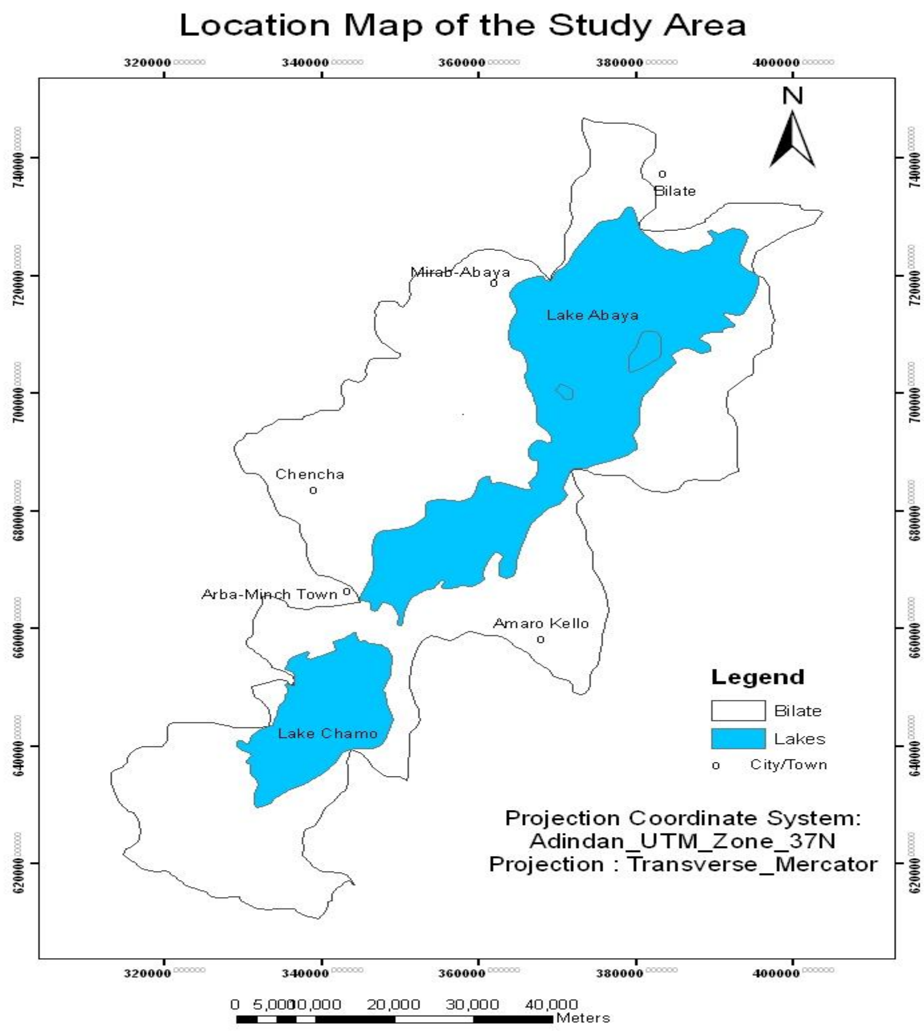


Figure 3 1 Location Map of the Study Area.

3.2 The Physical Environment

3.2.1 Climate

The climate of Ethiopia is influenced by four pressure systems which cause different rainfall regimes throughout the year (Osman 2001, Endelcher 2000). However, most part of the Abaya-Chamo basin show bimodal annual rainfall distribution with short rain in spring (Belg) and long rains in summer (Kremet) (Tato 1964). Average annual rain fall ranges from 521mm at Bilate to 2105 mm at Chencha with average maximum temperature (33.2^{0}c) at Arba-Minch in the month of February and March.

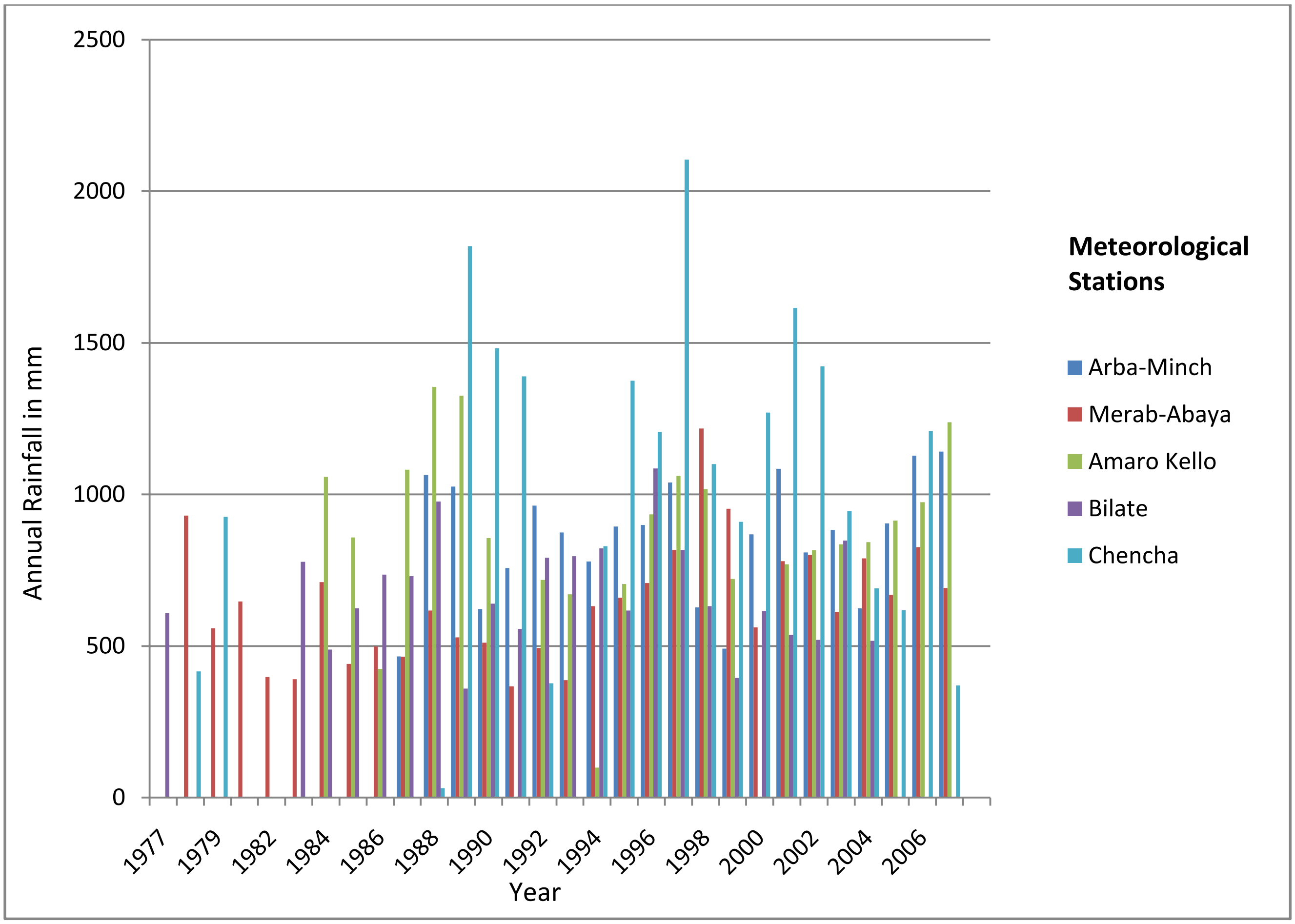


Figure 3 2 Long-term Mean Annual Precipitation

The rainy season of the study area is from September -November and April -June, with mean minimum monthly rainfall 34.5 mm in January and maximum of 170 mm in April. From October to February hot and dry weather is predominant. From the long-term temperature data obtained from NMSA, the mean monthly temperature in the area is between 22 and 26 ^{o}C. Mean maximum and mean minimum temperature of the area is 33 ^{o}C and 14.5 ^{o}C, respectively. As the available data of evaporation for this study area is for very short period of time, the mean monthly Class A pan evaporation of the catchment based on Mirab–Abaya and Arba-Minch stations, taking the average 0.85 pan coefficient to get the exact lake evaporation of lake Abaya, ranges from118 mm in October to the maximum of 272 mm in June and 106 mm. Long-term monthly values of climatic variables are presented in the following tables and figures.

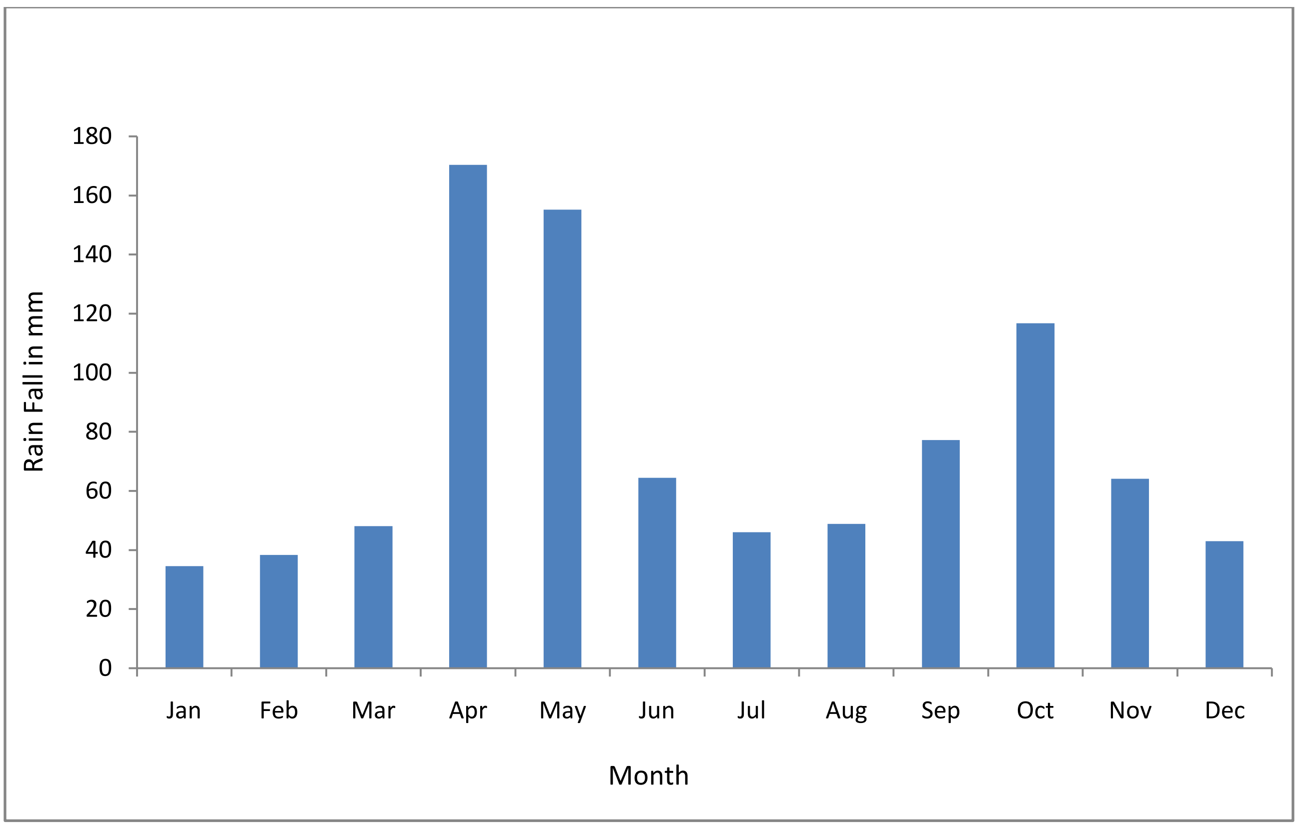


Figure 3 3 Mean Monthly Rain fall at Arba- Minch Station since 1987-2007

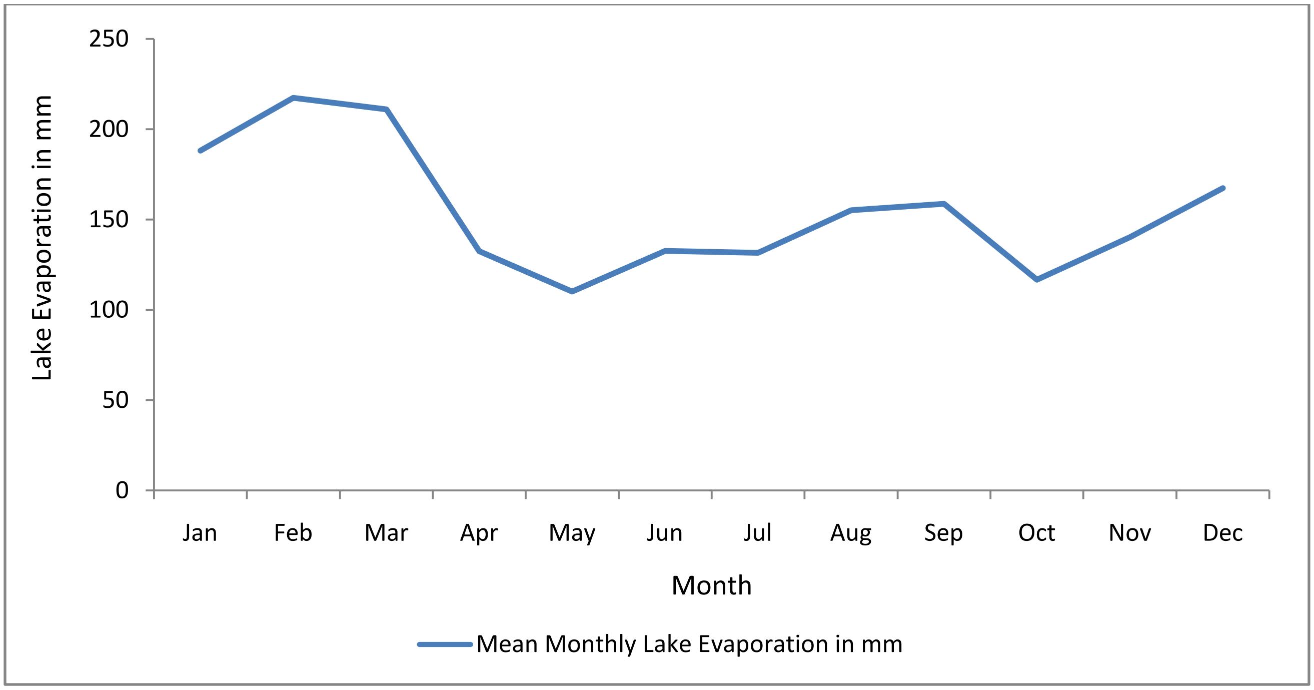


Figure 3 4Mean Monthly Lake Evaporation at Arba-Minch Station since 1985 to 2005

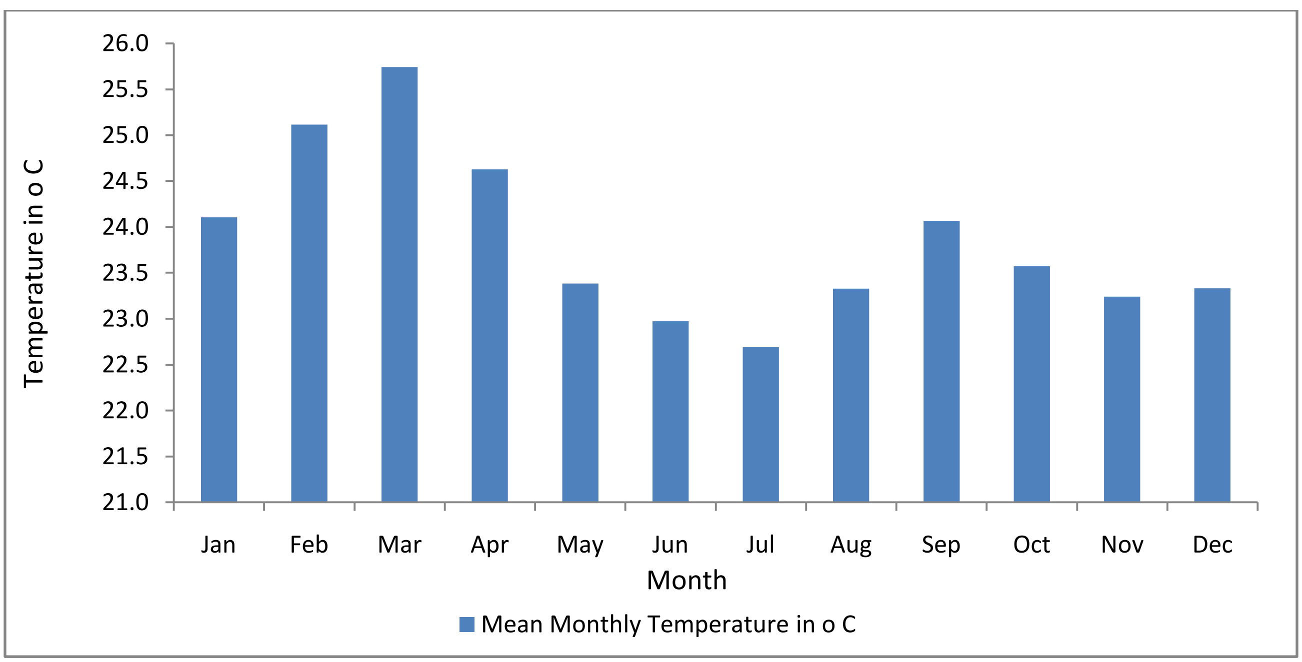


Figure 3 5 Mean Monthly Air Temperature of Arba-Minch Station (1987-2007)

3.2.2 Geology and Structures

Geology

The MER attains a width of about 100 km in the central sector, between Fonko and the Langano Lake area, but narrows southward in the Abaya region, where it is bifurcated by the N-S-striking Amaro horst (Boccaletti et al.. 1998). Distribution of volcanic rocks along the MER boundary faults shows a discontinuous sequence ranging in age from the Late Eocene up to the Plio-Quatemary (Mohr, 1970; WoldeGabriel et al., 1990, 1991; Ebinger et al., 1993). Late Pliocene-Quaternary volcanism is mainly localised in the rift floor (Morton et al., 1979), although volcanic activity is also present in the Ambo area (WoldeGabriel et al., 1990) and in Southern Ethiopia (Davidson, 1983). However, the rift valley basin are dominated by young volcanic and sedimentary rocks (Miocene to Recent), which lies within old (Precambrian) shield rocks (McConnel, 1972). Quaternary basalt flows (recent basalts) are found near Arba-Minch town and the hill separating the two lakes Tosa Sucha or "YeGzire Dildiy". The rift valley floor near Lake Abaya and Chamo is filled with alluvial sediments. The bedrock in the region consists of basalt, trachyte, rhyolite, and ignimbrite and the western edges of Lake Abaya and Lake Chamo are covered by approximately a 1- to 2-km-wide plain of lacustrine and swamp deposits (Chernet 1982). Throughout the valley there are extensive north–south fault zones (Baker et al. 1972).

North of Lake Abaya Quaternary faults appear to reactivate the northern segment of the Chencha escarpment. The Quaternary activity in the MER can be traced southwards along the eastern border of Lake Abaya to the land bridge (Tosa Sucha) separating the lakes Abaya and Chamo (Boccaletti et al.. 1998) .In this area, the fault geometry suggests roughly E-W/WNW-ESE-trending extension.

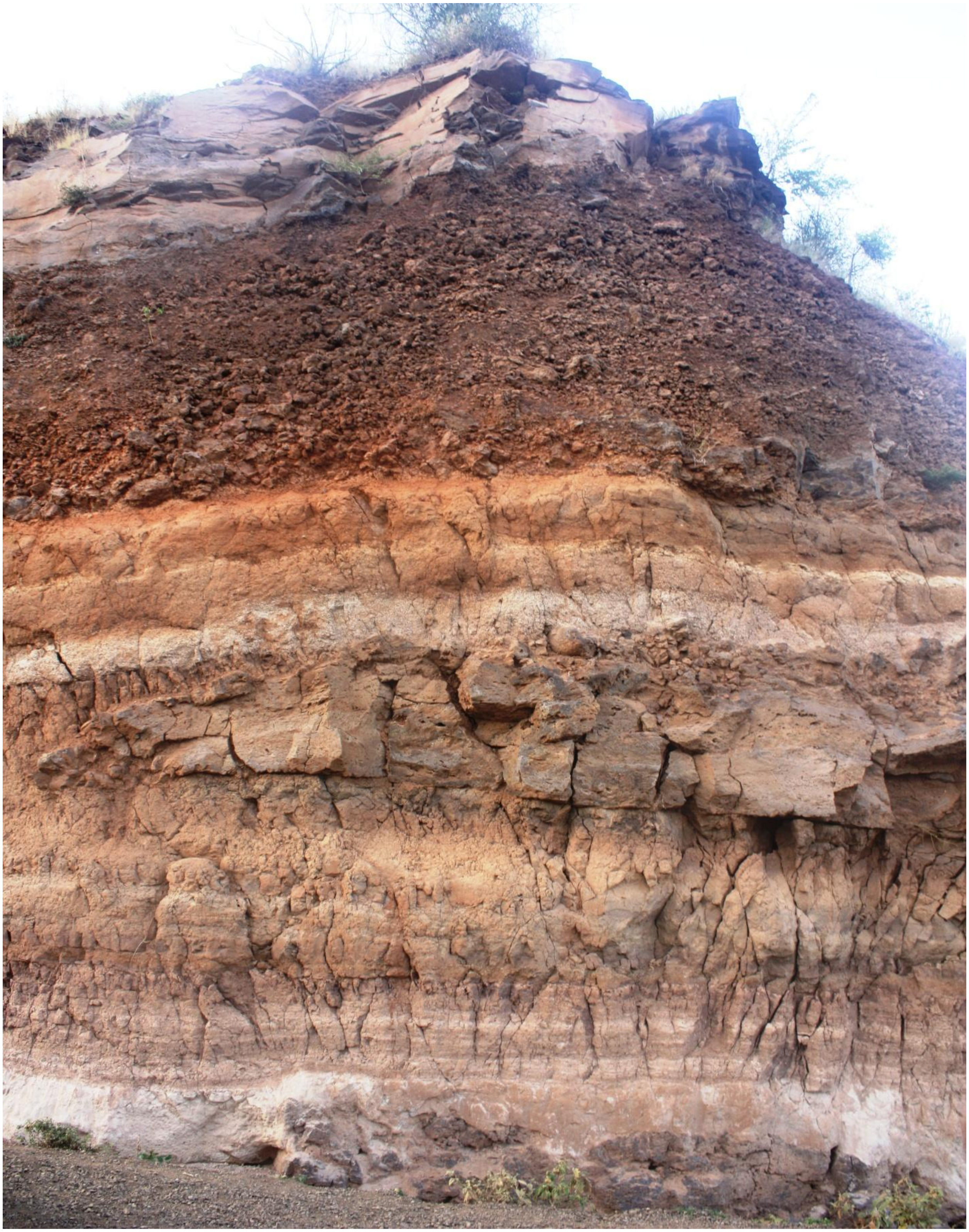


Figure 3 6 Litological units in the study area (from top to bottom basalt, alluvial deposits and a sequence of lacustrine deposit)

3.2.3 Hydrology and Hydrogeology

Hydrology

The hydrological data for major river basins in the catchment is obtained from Ministry of Water Resources and from Arba-Minch University. The main rivers considered in the basin are Bilate with catchment area 5756 km^2, Gelana (3463 km^2), Gidabo (3440 Km^2), Kulifo (455 Km^2) Hare (183 Km^2), and Sille (237 km^2) including other small seasonal rivers. From the main rivers in the study area Bilate, Gelana, Gidabo and Hare flow into Lake Abaya and Kulfo and Sille flow into Lake Chamo. No properly identified river flows out of the two lakes, although there is sometimes overflow of the lakes to the nearby rivers during high level of the lakes.

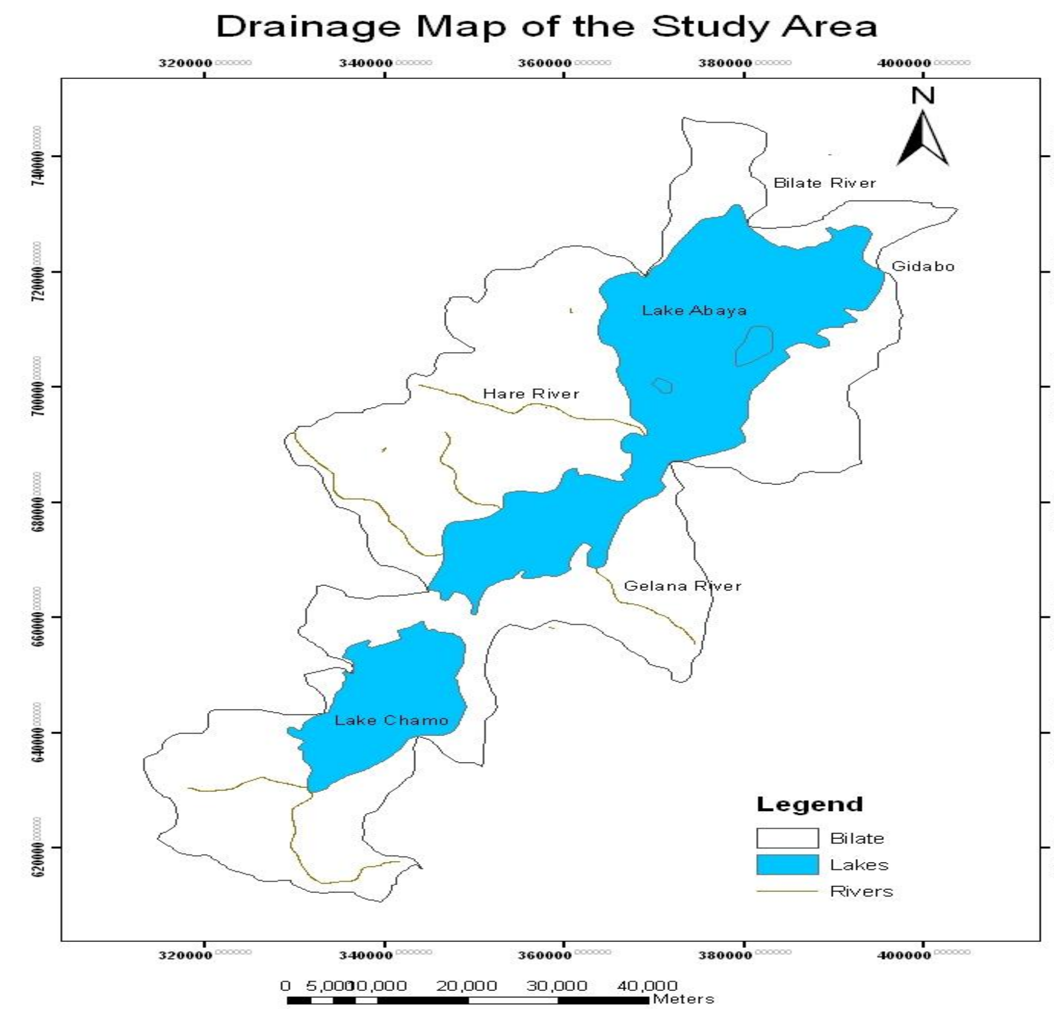


Figure 3 7 Drainage Map of Lake Abaya-Chamo sub-basin.

Hydrogeological Setting

The evapotranspiration potential for the region is approximately 2,300 mm/year (Shahin, 1985). The volcanic aquifers are fractured, and yield modest amounts of water to wells and springs. Water wells usually have a specific capacity of about 0.5 L s–1 m–1 and the mean permeability of the aquifer is in the order of 2 m/d (Chernet, 1982). The groundwater has very low total dissolved solids, generally less than 500 mg/l (Chernet, 1982).

3.2.4 Land Use / Land Cover

The land use of Lake Abaya–Chamo sub basin has been changed rapidly due to extensive deforestation as a result of increased number of population in the area. The extensive deforestation results in replacement of vegetation cover by cultivated land. Agriculture is the main land use practice in the catchment and occupies the flat alluvial land of the catchment surrounding the lakes. Thick bush lands, open woodland, forest, grassland with cultivated land are found on the floor of the catchment. The western parts of the two lakes are extensively used for big state farm (i.e. Arba-Minch and Sille State farm are among this) and recently for privet investors. The farms are irrigated by rivers entering Lake Abaya and Chamo (figure.3.9). During the field survey woodland and bush land have been observed changing to open bush land and cultivated land. The increase in the demand of wood land for charcoal, fuel and construction materials has highly affected the land cover in recent years. As deforestation of the natural vegetation cover continues soil loss due to erosion may have led to an increase in sediment load to lake.

Figure 3 8 Privet Investor cotton plantation near Lake Abaya

Figure 3 9 Sagon River and Sille State farm on the side of the river

Figure 3 10 State Farms near Lake Abaya

Figure 3 10 State Farms near Lake Abaya

Figure 3 11 Deforestation activities around Lake Abaya

a

b.

Figure 3 12a and b Charcoal Production in the study area

3.2.5 Socio-Economic and Cultural Environment

Ethiopia is among the least urbanised countries of Africa and the RVLB (Rift Valley Lake Basin) is the least urbanised area of Ethiopia, with less than 13% living in urban areas. Within the basin, 74% of the population is in SNNPRS and 26% in Oromiya. Population density of the basin as a whole is 167 persons per km^2, which is three times the average for the country. There is significant variation of population density within the basin. Those areas within SNNPRS have a density of 202 persons per km^2, about twice that of areas within Oromiya. Population density ranges from as low as 30 persons per km^2 in Borena to 614 persons per km^2 in Gedeo (Halcrow and GIRD, 2008). As discussed above, the current growth rate is very high and has an adverse effect upon development in the basin. In Table 3.4 the population growth is revealed for the census years 1994 and 2007. In urban areas the population almost double 1994 census results (e.g. the population in Arba-Minch Zuriya Wereda was 40,020 in 1994 and in 2007 it became 74,843).

Wereda	Total Population		Urban Population		Rural Population	
	Census Year 1994	Census Year 2007	Census Year 1994	Census Year 2007	Census Year 1994	Census Year 2007
Arba Minch Zuriya-Wereda	153,550	240,523	40,020	74,843 (only Arba-Minch town)	113,530	165,680
Chencha-Wereda	88,040	111,680	7,851	13,301	80,189	98,379
Merab Abaya-Wereda		74,901		5,831		69,070

Table 3 1 Population Size in Lake Abaya Surrounding Area (Central Statistical Authority, 1996 and 2008)

As population increases in the RVLB, land pressures increase, and the land degradation will be more and more by deforestation and also by erosion. In this study area the society destroy forest covered land for farming purpose and production of charcoal. The land cover of this area is changing rapidly as a result of the population growth in the area and the need to generate income for their survival.

Moreover, urbanization and resettlement in the shore of Lake Abaya is observed. The proximity of the lake to the city of Arba-Minch and the availability of infrastructure (i.e. main roads) make the shore of the lake conducive for urbanization which finally led to change the land cover of the area (figure 3.13 a, b & c).Resettlement program is also there because of the fertile land (i.e. alluvial deposits surrounding the lake), this program around the shore of the lake is being completely changing the land use /land cover of the area in a short period of time (figure 3.13 a, b & c).

a

b

c

Figure 3 13 a, b and c Resettlement around the shore of Lake Abaya

Despite the generally abundant water resources in Ethiopia, the poor rural population usually does not have access to a clean water supply. Although 36% of people in Sub-Saharan Africa have access to safe drinking water (Ethiopian Central Statistical Authority, 1996), only 15% of the population of the southern region of Ethiopia has access to potable water. A survey on these area shows that the vast majority of people rated water as the most important problem in their communities (Mangin, 1991).

CHAPTER FOUR

Abaya-Chamo Lake Level Change & Hydro-Meteorological Data Analysis

4.1 Meteorological Data

4.1.1 Precipitation

Rainfall data was obtained from National Meteorological Service Agency for about twenty one years (i.e. 1987 to 2007) and this period is the period that we can get complete data for the study area .The mean annual rainfall is about 854.6 mm (Fig.4.1,Arba-minch station).The wettest years on the record were 1988,1989,1997,2001,2006 and 2007 with annual rainfall amount of 1064mm,1026mm,1039mm,1084mm,1128mm and 1141mm, respectively . After these wet rainy years a rise in Lake Abaya level were observed but in 1988 and 2006 the level of the lake slightly decreases with respect to the previous year. Whereas, Lake Chamo shows a rise in the years 1989, 2006 and 2007 only; El Ninõ event in 1997/1998 which caused heavy rainfall and run-off in southern Ethiopia doesn’t cause any lake level rise on this lake. This is because Lake Chamo doesn’t have any substantial tributaries that fed it and this El Ninõ event doesn’t cause overflow of Lake Abaya to Lake Chamo by Kulfo River (Awelachew, 2006).

The rainfall in the area is well distributed throughout the two rainy seasons. The rainfall pattern is bimodal, from September -November and April – June. These rainy seasons contribute 71.5% of the total rainfall in the area, during April-June about 43%; and 28.5% during September-November.

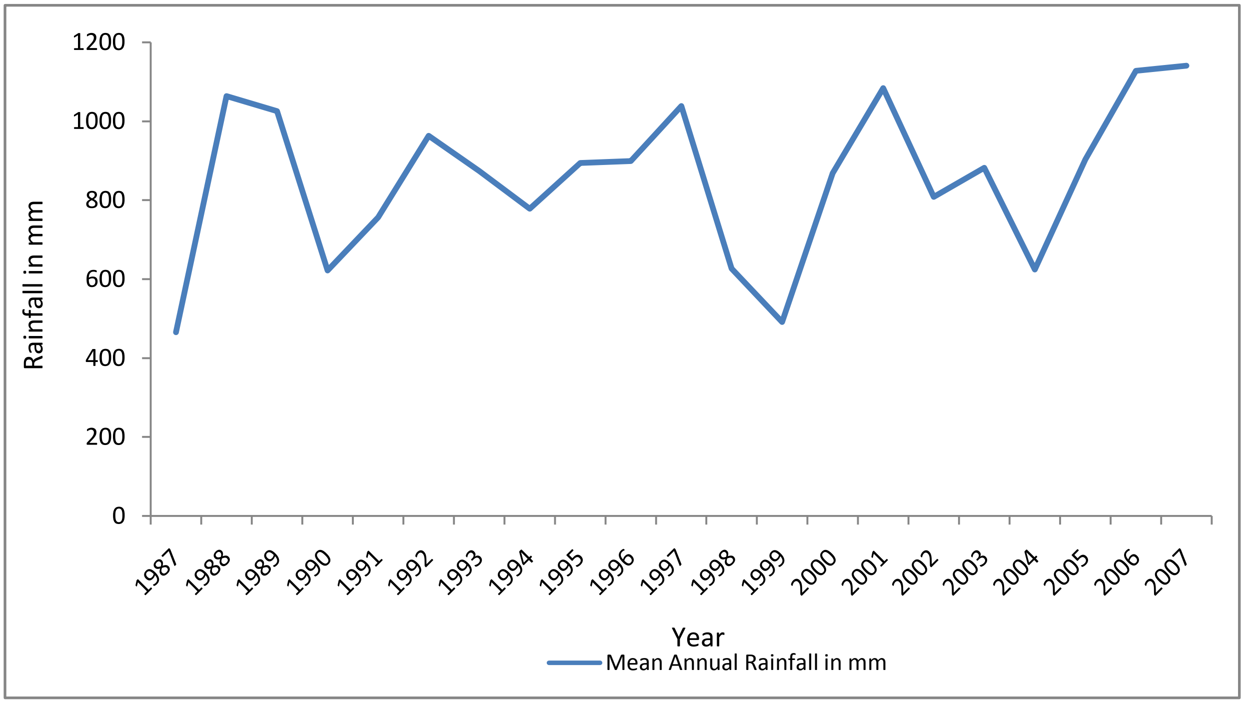


Figure 4 1 Annual Rainfall at Arba-Minch Station

Long –term meteorological data for the Abaya-Chamo sub basin is more complete in five stations and these stations are taken for analyzing the precipitation in the area. These meteorological data gathered from NMSA are used to analyze the spatial and temporal variations in rainfall within the sub-catchment.

The mean monthly rainfall in these stations ranges from 61-197mm for the first rainy months April – June and 33-162mm for the second rainy season, from September –November (Figure 4.2).The long-term rainfall of different stations in the plateau and the rift, does not show high variability temporally. But spatial variation for the plateau stations and the rift is there (figure 4.2).

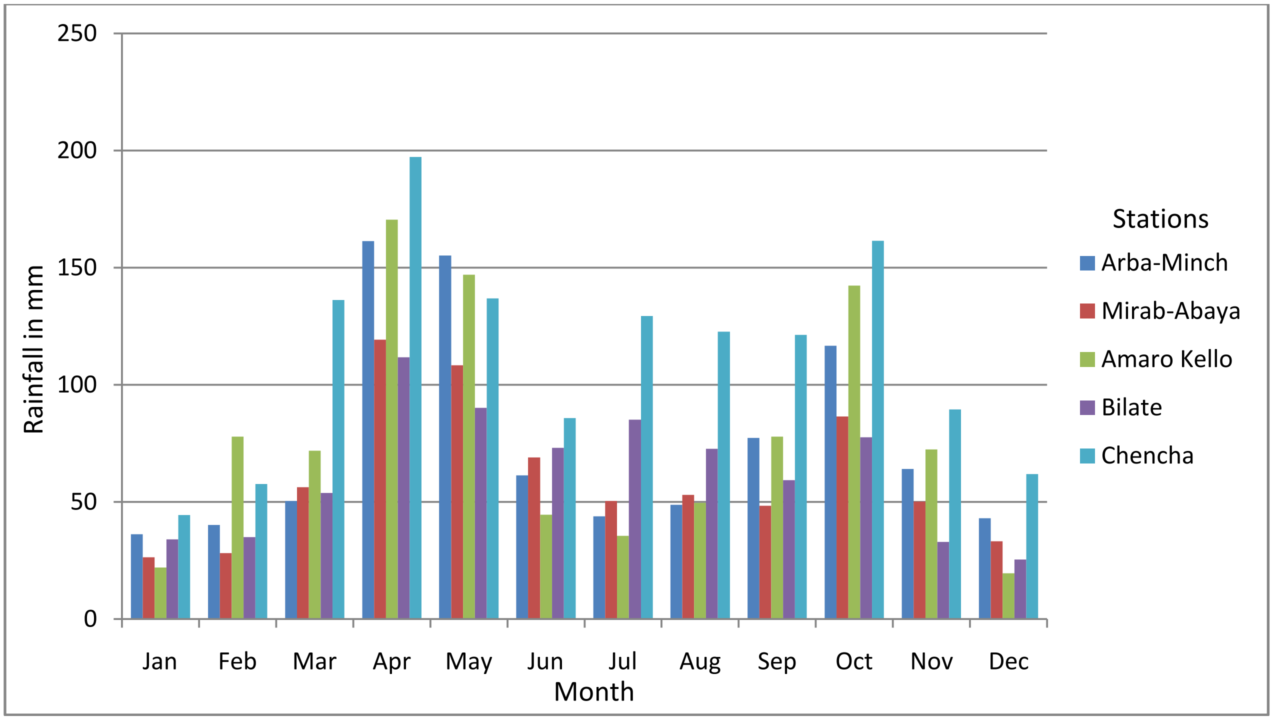


Figure 4 2 Mean Monthly Rainfall (1985-2005)

The areal depth of precipitation was estimated using arithmetic mean method. Based on the arithmetic mean method the sub-catchment precipitation is estimated to be 944mm.

Station Name	Altitude (m)	Mean Annual Rainfall (mm)
Arba-Minch		901
Mirab Abaya		734
Amaro Kello		954
Bilate		756
Chencha		1374
Arithmetic Mean		944

Table 4 1 Mean Annual Precipitation

4.1.2 Evaporation

Factors that affect the evaporation process include energy supply, temperature of the water and air, water vapor capacity of the air and wind speed. The pan is placed on the surface of the earth and far from the lake where the pan receives large quantities of energy from radiation and conduction through its base and sides because it is exposed to air and sun. To obtain actual evaporation from open water surface or potential evapotranspiration the pan evaporation should be multiplied by pan coefficients. Class A pan coefficient is usually about 0.75, (Willson, 1990). But values vary as low as 0.35 and as high as 0.85 (Maidment, 1993).However, pan coefficient of 0.75 to 0.85 are commonly used for class A pan (Zemenu, 2000; Yemane, 2004) for the Ethiopian Rift Valley Lakes (ERVL). Therefore, taking the average can be appropriate to get evaporation rate of natural open water surface evaporation.

Pan evaporation data from Arba-Minch and Mirab–Abaya station has been obtained from NMSA for the period 1985 -2005.The pan in these stations is placed far away from the lake where the pan receives large amount of energy from radiation and conduction through its base and sides because it is exposed to air and the sun. Thus, correction factors are necessary to approximate the measured evaporation rates to natural open water surface evaporation. But this correction factor will be different for different color of water in the Lakes. This is because of heat absorption capacity or conversely the reflectance of the sun energy is affected by the color of the water in the Lakes and causes in having different pan coefficient. Therefore, due to more heat absorption and lesser reflectance of Lake Abaya compared to clear water, the pan coefficient could be higher and is on the upper limit. Hence, there is a difference in heat absorption and reflectance of Lake Abaya; 0.85 pan coefficient for Abaya Lake has been considered.

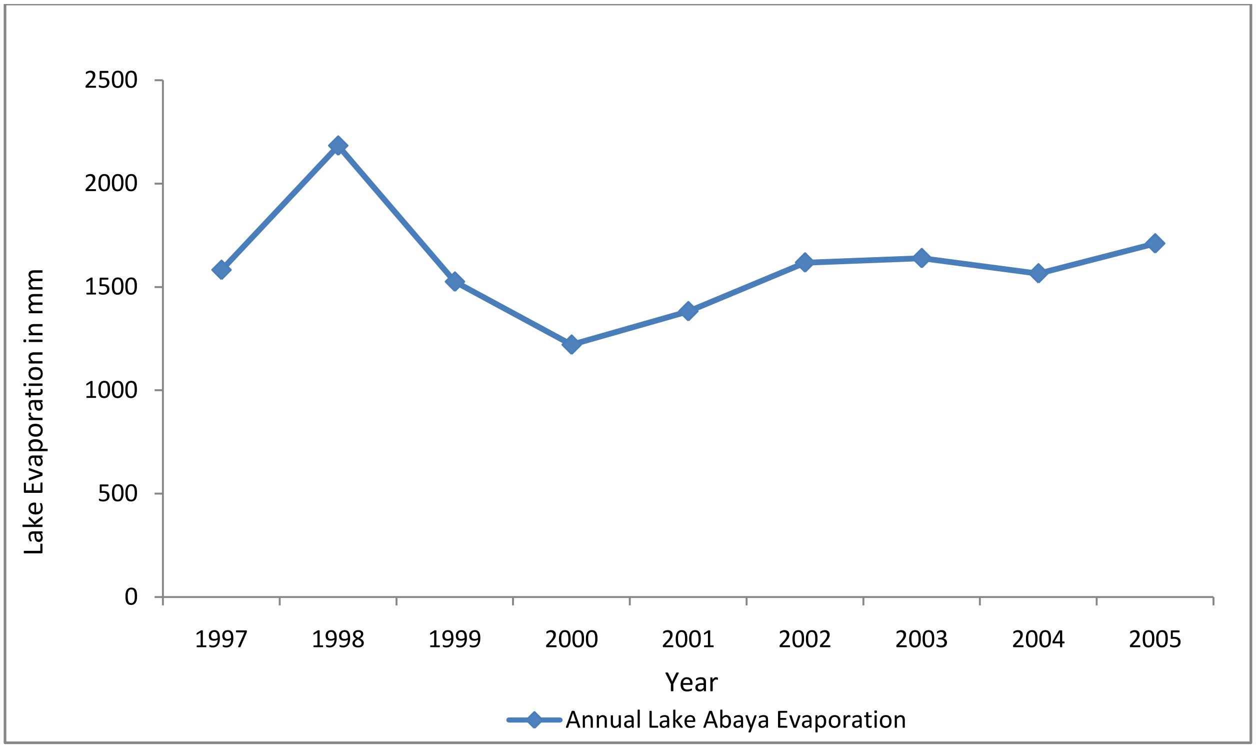


Figure 4 3 Annual Pan Evaporation at Arba- Minch (Source: Ministry of Water Resources, 2009)

4.1.3 Temperature

Air temperature records for the study area are obtained from NMSA and Arba-Minch station is taken for analysis. From the data obtained, the annual mean minimum and maximum temperature are 16 and 31 ^{o}C respectively. The hottest and coldest months are February and December, respectively (Fig. 4.5).

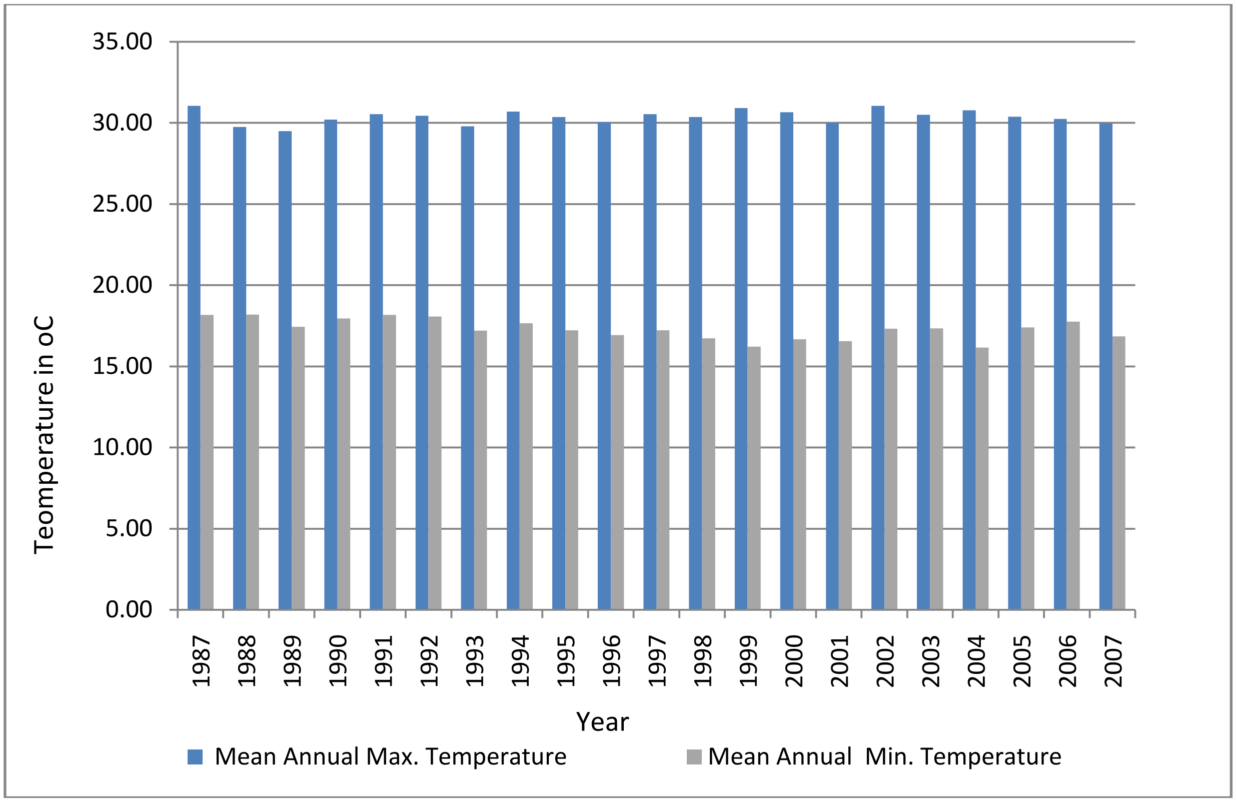


Figure 4 4Mean Annual Maximum, Minimum and Average Temperature at Arba-Minch(Source: Ministry of Water Resources, 2009)

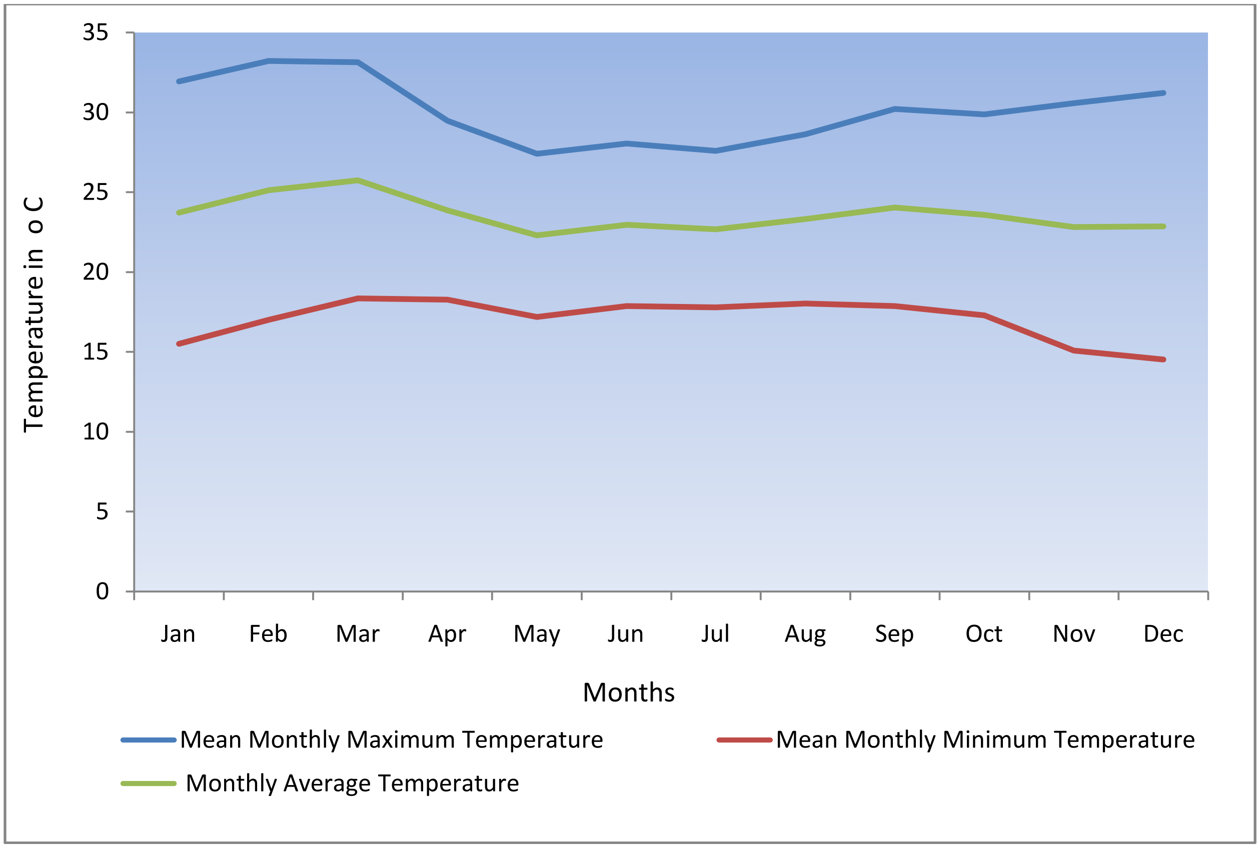


Figure 4 5 Mean Monthly Maximum, Minimum and Monthly Average Temperature at Arba-Minch Station (From 1987-2005). (Source: Ministry of Water Resources, 2009)

4.1.4 Relative Humidity (%)

Relative humidity data from Arba-Minch station shows an increasing trend when we see the long term data of RH (1987-2005).The mean monthly relative humidity ranges from 48% in February to 69% in May.

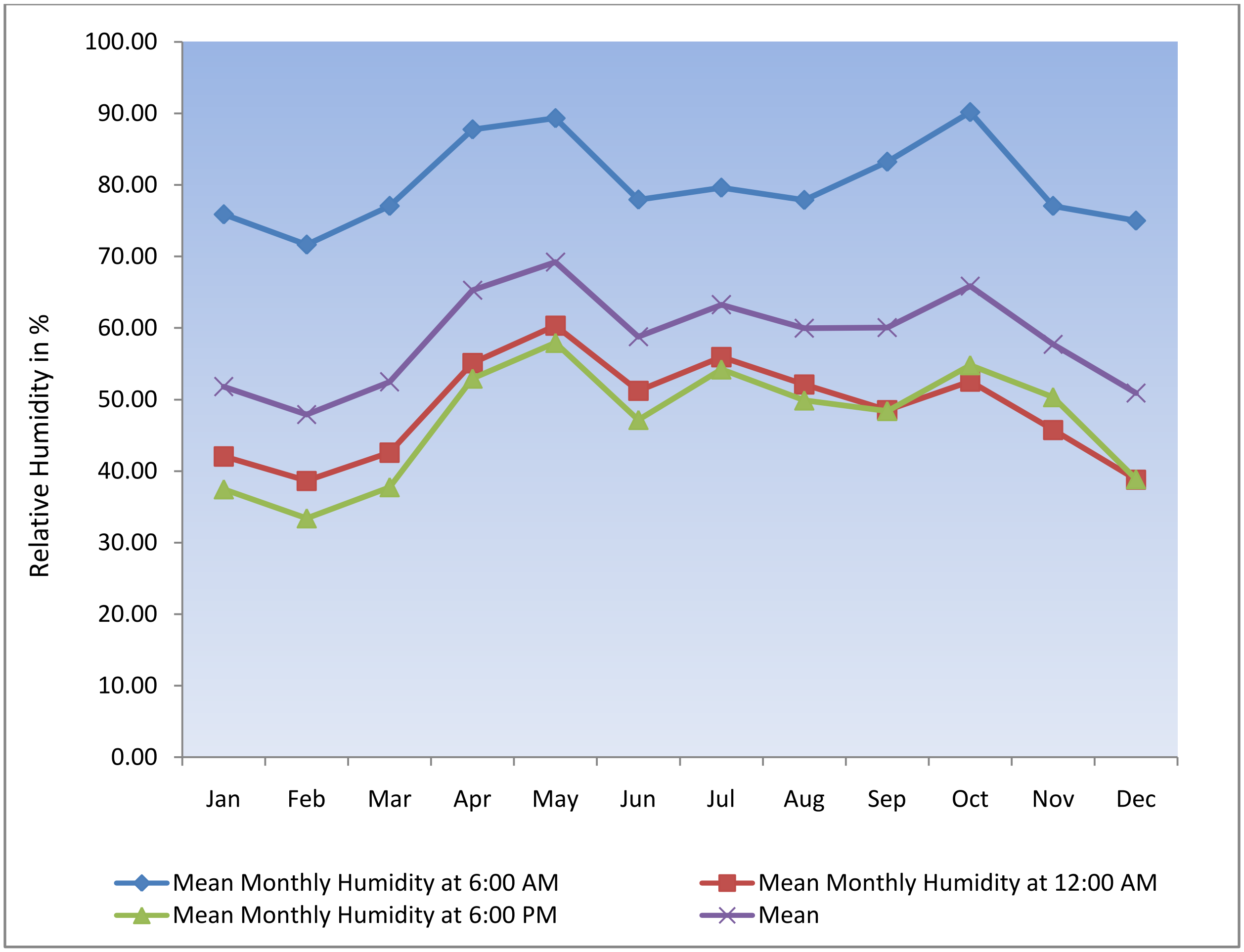


Figure 4 6 Mean Monthly Relative Humidity in % at Arba-Minch in different Hours (from 1987-2005). (Source: Ministry of Water Resources, 2009)

4.1.5 Wind Speed (m/s)

Wind speed data was collected from NMSA for this study and the data from 1987-2005 is used for analysis. From this long term series, the mean annual wind speed varies from 0.99 in 1989 to 0.45 in 1998 and this could be the result of deforestation. Wind speed remains relatively constant to a given average, it doesn't fluctuate as such.

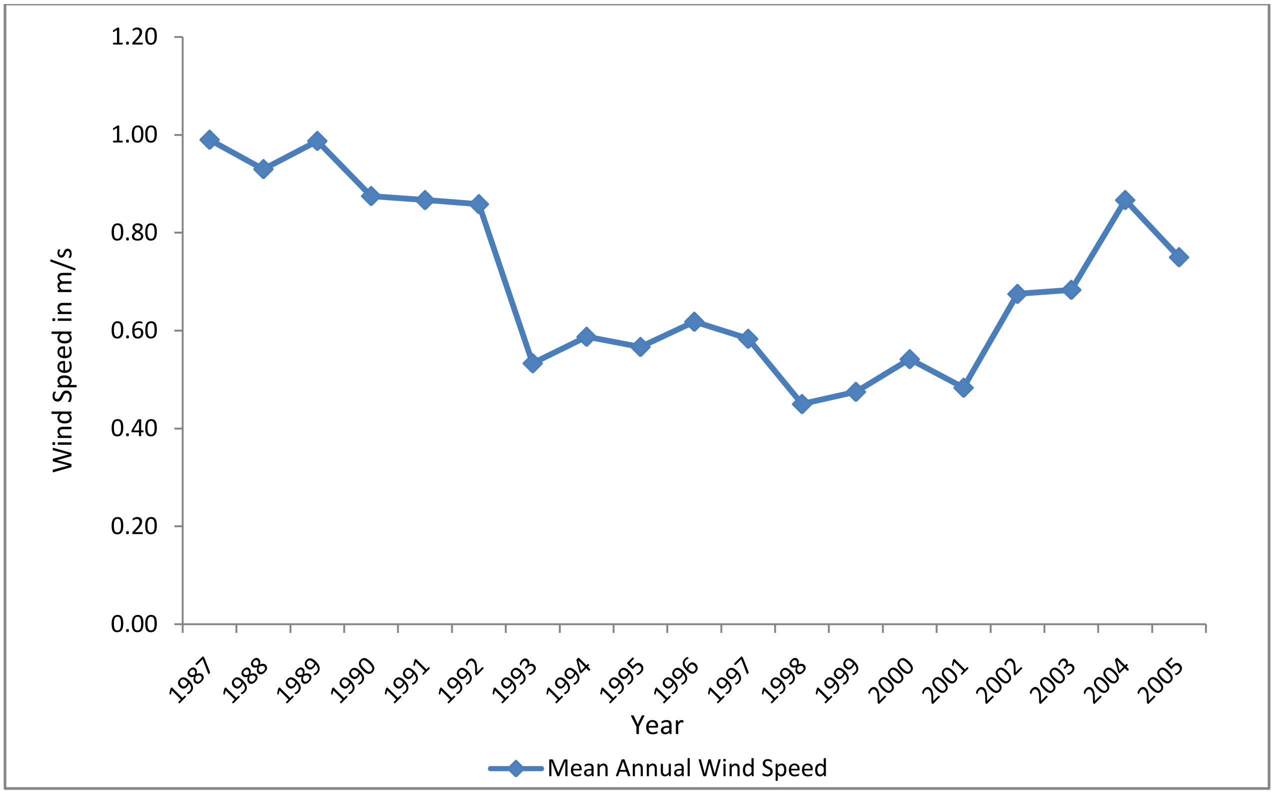


Figure 4 7Long-term Annual Wind Speed at Arba-Minch Station (Source: Ministry of Water Resources, 2009)

4.1.6 Sunshine Hours

The Sunshine hour for the study area is gathered from NMSA. The sunshine hours vary for this period of gap is 5.2 in July and 9.14 in November (Fig 4.8).

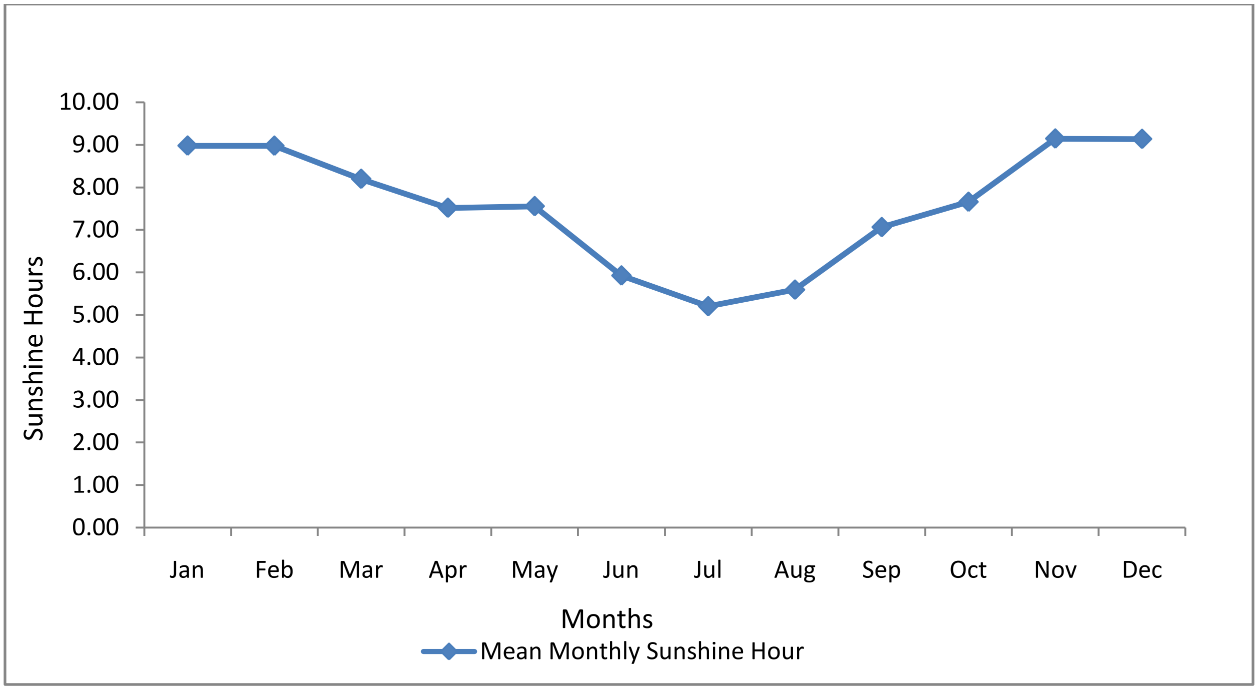


Figure 4 8 Mean Monthly Sunshine Hours at Arba-Minch Station (1987-2005). (Source: Ministry of Water Resources, 2009)

4.2 Hydrological Data

4.2.1 Runoff

The rivers Gelana, Gidabo , Bilate, Hare and other small tributaries contribute major amount of run off to the lakes. Bilate, Gelana, Gidabo, and Hare, are a few perennial rivers entering Lake Abaya.

4.2.2 Bilate River

Bilate River is one of the major catchment areas of the Ethiopian Rift Valley Lakes zone that drains to the Lake Abaya. The basin covers an area of 5650 Km^2 and the altitude in the area ranges between 3280 m a.s.l in the north and 1180 m a.s.l in the south.

The Bilate watershed is densely populated. Moreover, most of the soils in the watershed are sandy and silty clay with high erodible nature. This erodability of the watershed has been reflected in the water turbidity of the Bilate River. Turbidity test result of the water sample varies from 2750 NTU to 3900 NTU and TDS varies from 3670 mg/l to 6504 mg/l (WWDSE, 2006) suggesting very high concentration of solid and suspended particles. Similarly, sediment load analysis of Bilate River at Alaba Kulito gave 2,817,214.75 tons per year which is very high as compared to Gidabo and Gelana Rivers (WWDSE, 2006) .This sediment load causes impact on Lake Abaya level fluctuation. There are also two dams constructed on Bilate River, from which construction debris and soil contaminate the downstream water and increase turbidity and soil particles in the river. In addition to this, the level of Lake Abaya will be reduced because of the diversion of water from Bilate River for irrigation purpose and this is because Bilate River contributes significant inflow to Lake Abaya.

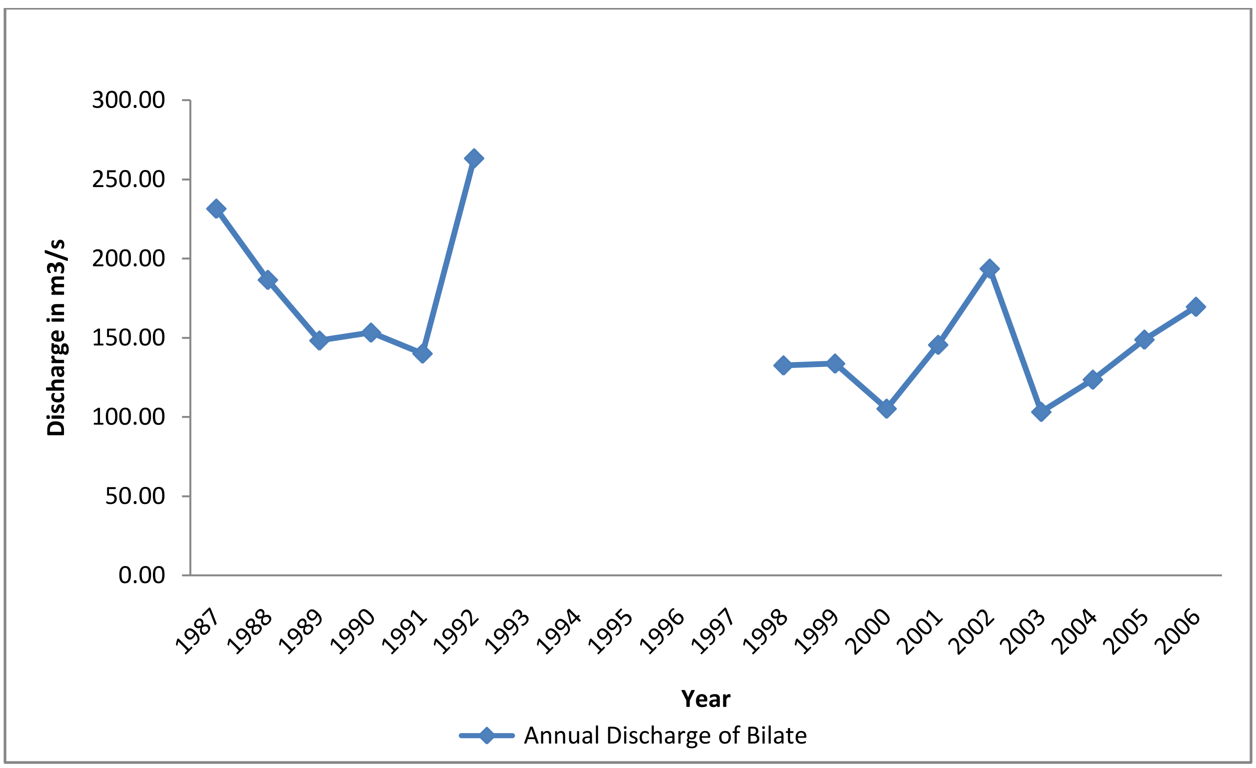


Figure 4 9 Hydrometric Discharge Data of Bilate River at Bilate Tena Station (from 1987 to 2006). (Source: Ministry of Water Resources, 2009)

4.2.3 Gidabo River

The Gidabo river rises in the highland area of the Wondo escarpment and the main Gidabo river's extreme catchment boundary extends in between $6^0$57'20" and $6^0$57.3'and joins the Abaya Lake as an Eastern tributary at $6^0$33'and $38^0$2.5'. The total drainage area of Gidabo is 3446.62 Km^2.Acording to Makin et.al (1975), the low flow rate in dry season in the Gidabo river would not allow big irrigation development. But the water quality is reported to be good throughout the year.

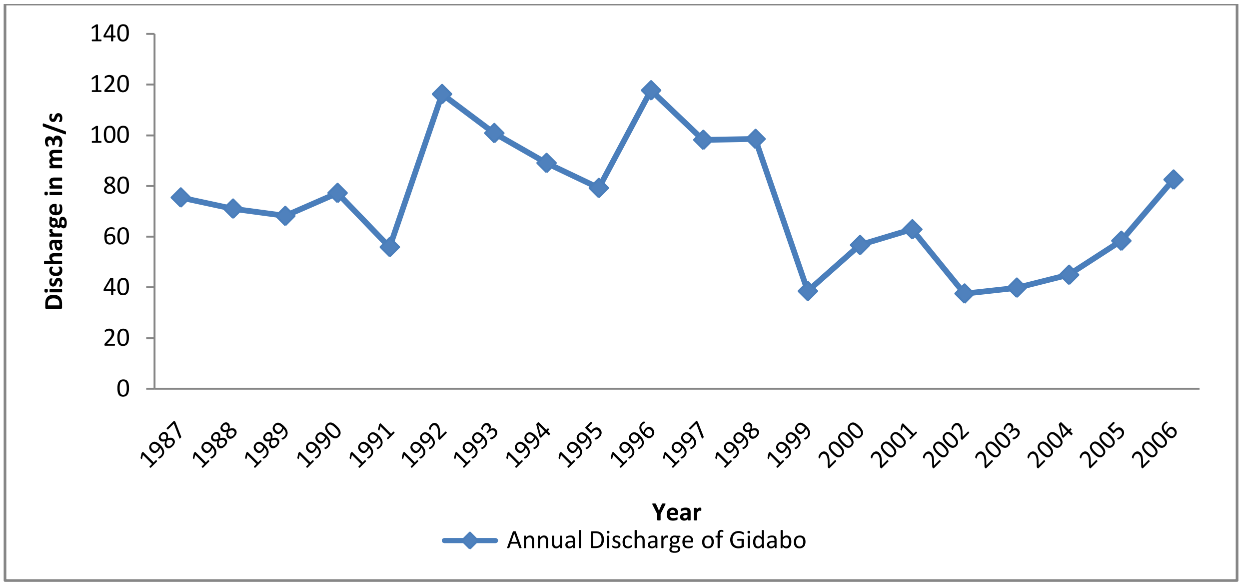


Figure 4 10Annual Discharge of Gidabo River at Aposto Station (1987-2006). (Source: Ministry of Water Resources, 2009)

4.2.4 Gelana River

Gelana River originates from Yirgachefe area in Gedeo zone. Due to the agro –forestry practice of the Gedeo people, especially the land cover of the upper catchments has been maintained well. When it is compared to Bilate and Gidabo watersheds, the Gelana watershed is in a better condition in terms of land cover and environmental degradation. As a result of better land cover, the flux of the sediment from the watershed would be relatively low. Sediment load and turbidity of the Gelana River is lower as compared to the Bilate and Gidabo River (WWDSE, 2006).

Gelana River flows towards Lake Abaya and contributes significant flow to the lake. The Gelana River contributes about 10% of the total inflow to Lake Abaya and it has been estimated that diversion of the river to irrigation would reduce the level of the Lake Abaya by 56mm per year (WWDSE, 2006). Lake Abaya is the final receptor of Gelana river flow and it is observed that in dry season much of the Gelana flow is absorbed by the delta grassland of Gelana. Therefore there is no significant flow down to the lake in dry season. In addition to these, the reduction in Gelana river flow due to the irrigation project constructed along the river basin has greater impact on the reduction of the lake level.

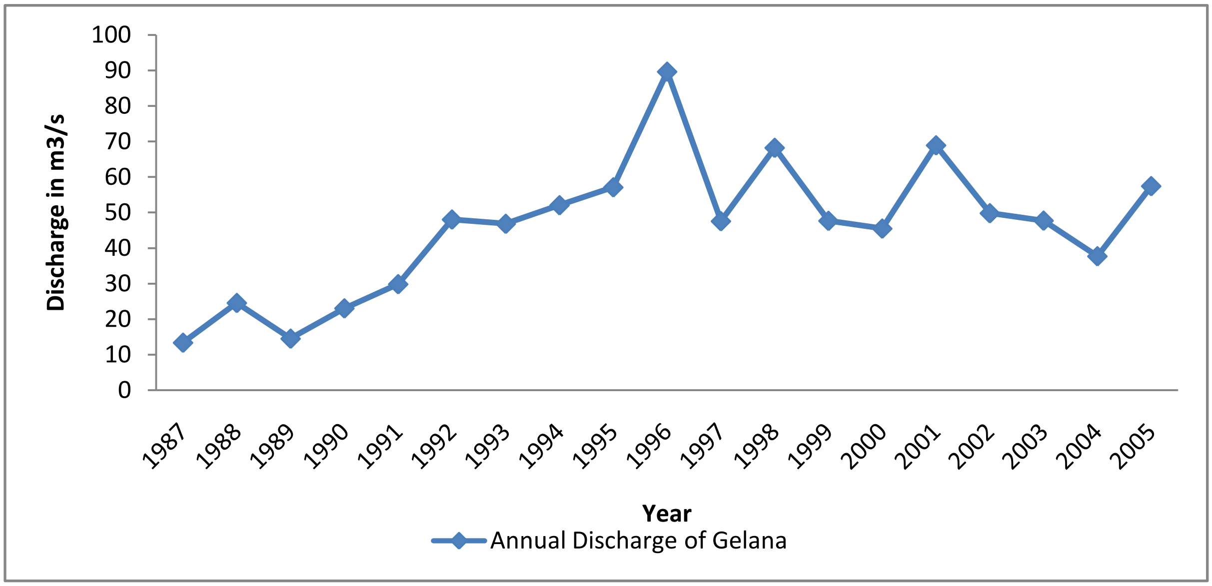


Figure 4 11Annual Discharge of Gelana River at the bridge near tore town (1987-2005). (Source: Ministry of Water Resources, 2009)

4.2.5 Hare River

Hare River originates from the south-Western side of Abaya Lake and from Gugae and Chencha mountains. The total area of this river catchment is about 183.29km^2.Hare is a small river, but it is also extensively utilized by the farmers in the surrounding area. There is also a diversion wire constructed across the river, which is aimed at irrigating a command area of about 1300ha.Therefore, the river discharge of Hare is not going to be directly used for water balance calculation .The water used by the farm land has to be subtracted from the river discharge.

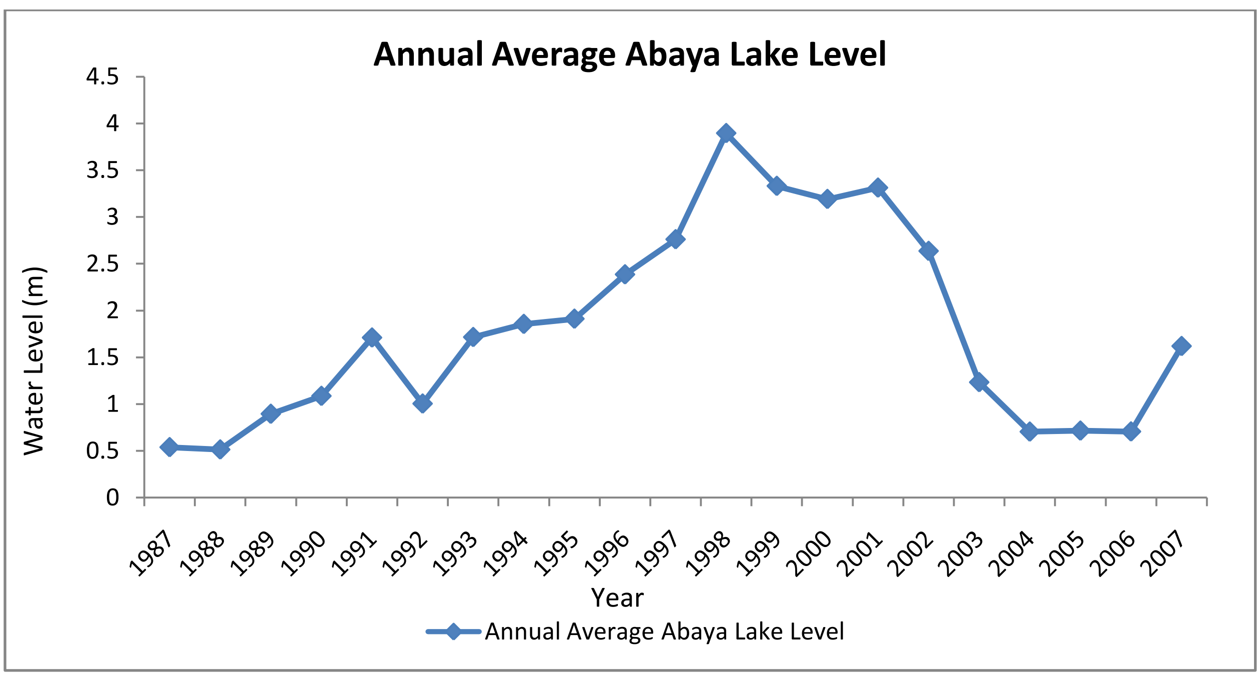
The hydrological data for Hare River gathered from Ministry of Water Resources, starts from 1980 to 2006 with period of no data for some years .The mean annual flow of Hare river reaches a value of $2.1m^3/s$.

4.2.6 Lake Level

4.2.6.1 Abaya Lake Level

Lake level of Lake Abaya is measured since 1969 by the Ministry of Water Resources and the data shows a general increasing trend (Fig.4.12). Even though the general trend shows an increase there were periods with lake level decline with respect to previous periods. The summery of these conditions are stated below;

a. From 1987-1998(12 years) the lake rise was about 3.35m.
b. From 1998-2006 a 3.12 m decrease in level was recorded.
c. From 2006-2007 a 0.91m rise in level was registered.

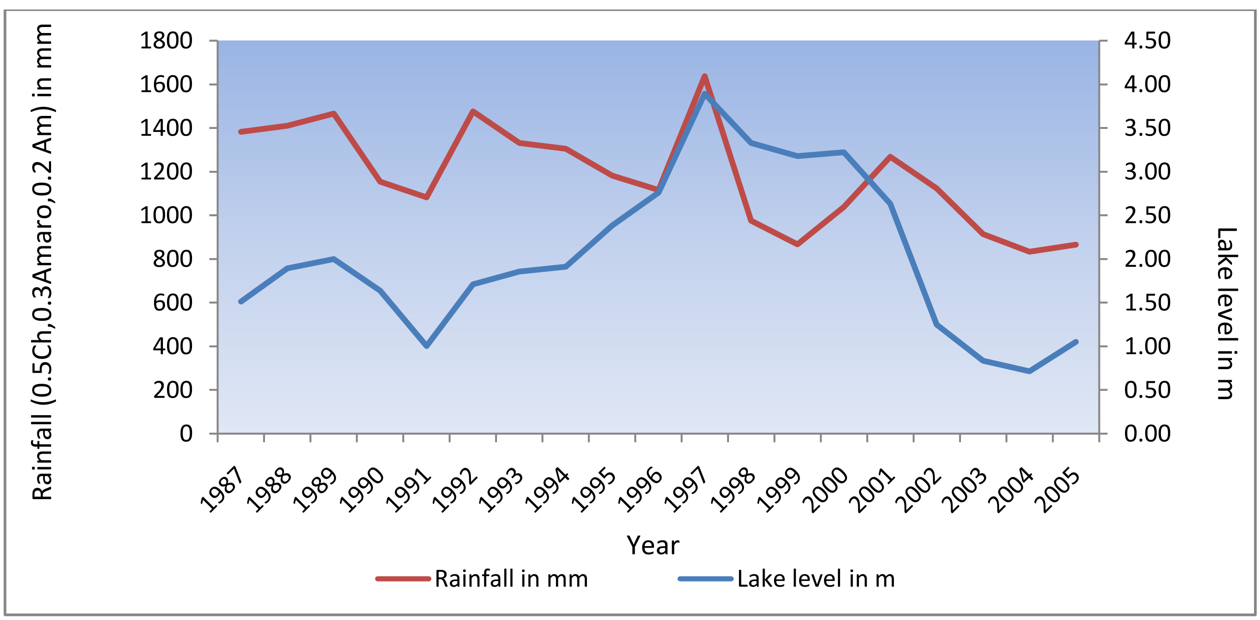


Zero lake level represents 1171m a.s.l.

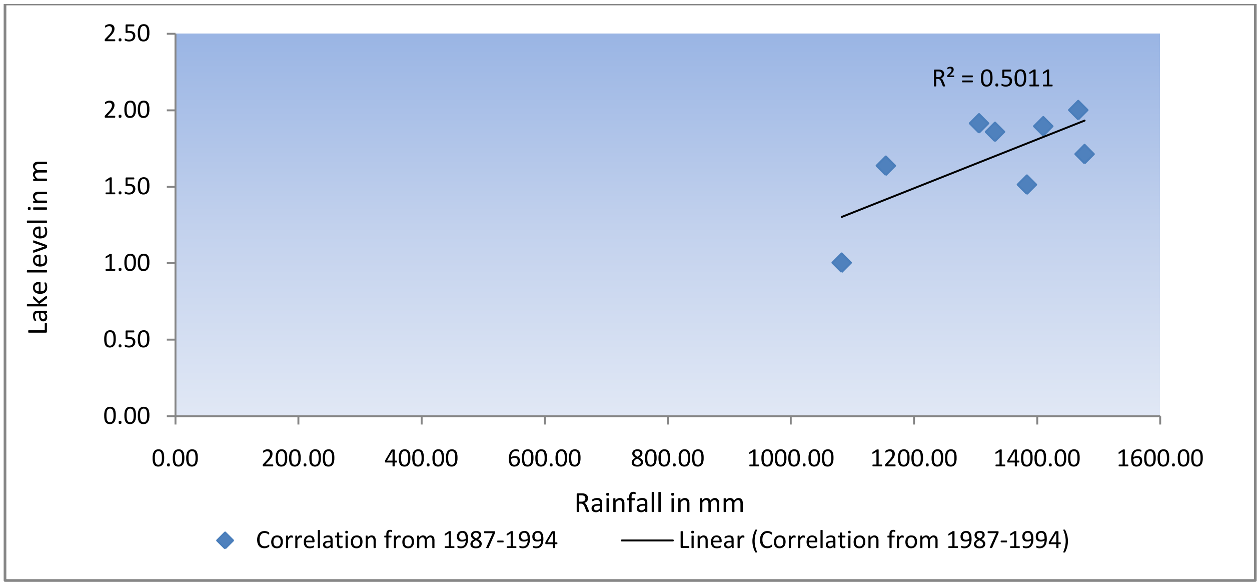
Figure 4 12 Abaya Lake Level Fluctuation (1987-2007). (Source: Ministry of Water Resources, 2009).

Since 1987, the highest lake water level was recorded during 1997/1998 which was the El Ninõ event that causes heavy rainfall and run-off in southern Ethiopia. The lake shows continuous increase in water level until 1998with the exception of the year 1992; when the water level decreased by 0.71m.

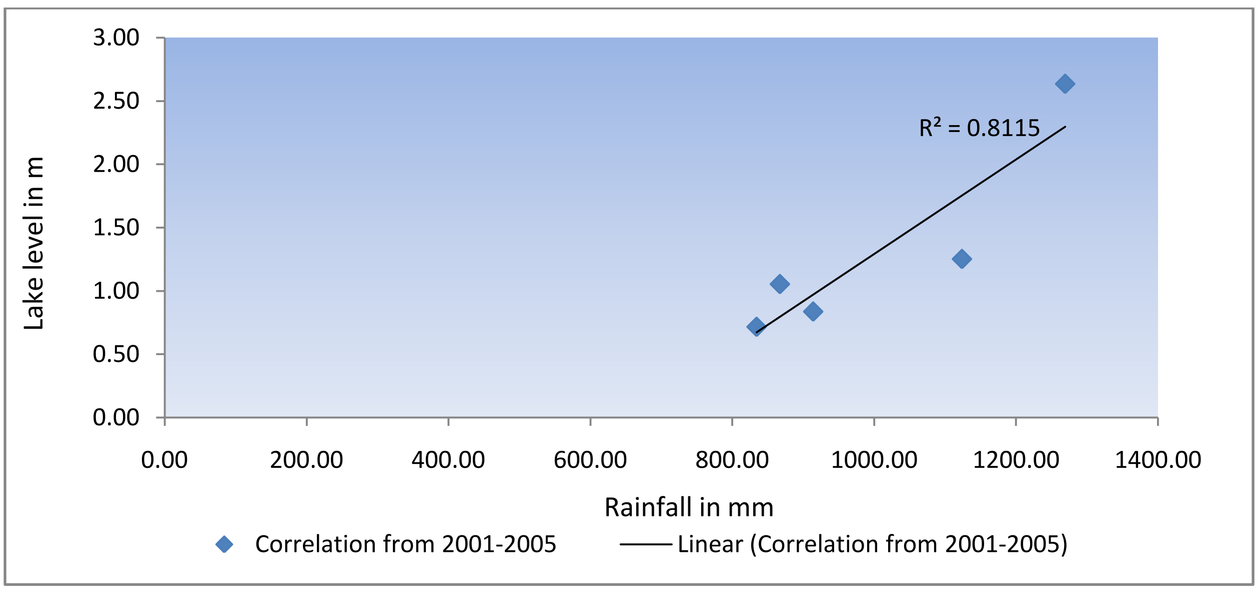
Considering the significantly higher amount of precipitation of the Plateau and proximity of the lake to the plateau margin, correlation of Abaya Lake level with the input components has been conducted assuming different proportion of the plateau and the rift stations (figure.3.1 Location map).Thus to see the different contribution proportion of the plateau and the rift stations, it is logical to divide the total discharge of the rivers that drain the plateau by the annual precipitation amount (in Chencha, Amaro Kello and Arba-Minch) .Therefore, the factors of 0.5, 0.3 and 0.2 were given to the precipitation in the Chencha, Amaro Kello and Arba-Minch stations respectively. In all the correlation the troughs in 1991, 1999, 2003, 2004 and the peaks in 1989, 1997, 2006 perfectly fit, the intermediate levels on the other hand shows poor correlation, probably due to the fact that when there is no peak rainfall or peak drought, the lake level maintains its "memory", and it maintained raising/lowering even though the precipitation has been the opposite; this is clear in the years 1993-1996 and 2000-2001.



a. The three stations mean annual rainfall and the Abaya lake level



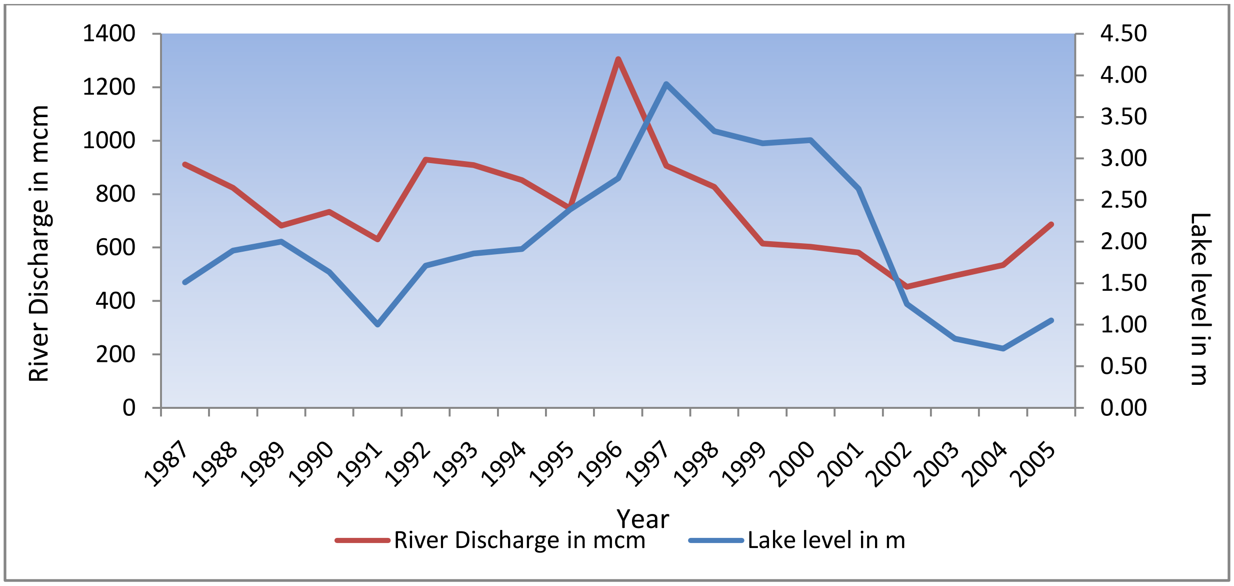
b. Correlation between mean annual rainfall and lake level from 1987-1994



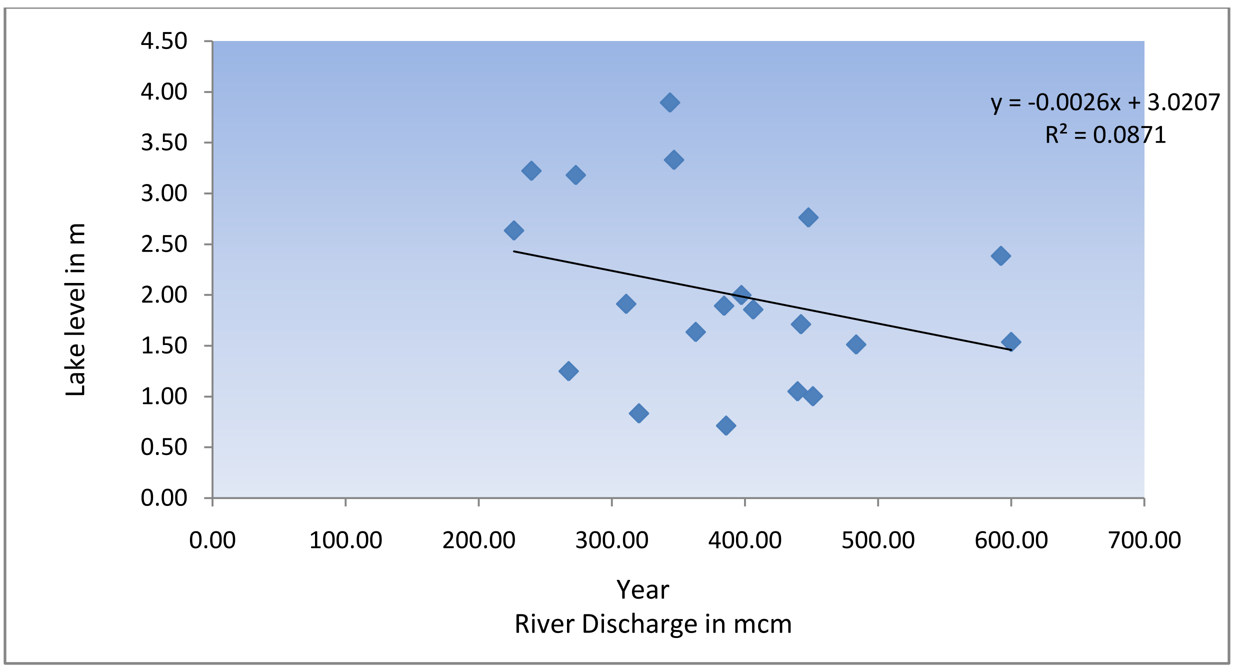
c. Correlation between mean annual rainfall and lake level from 2001-2005

Figure 4 13 Correlation between Abaya Lake level and Average Rainfall Depth

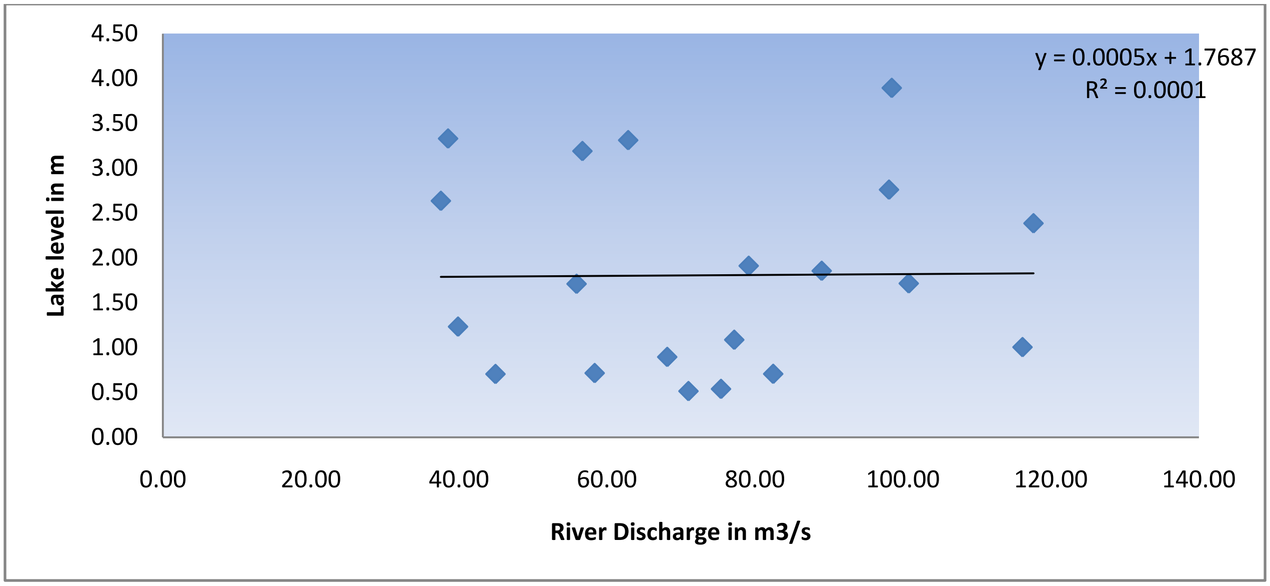
To see the correlation of lake level with that of river discharge in the area the same thing is used here also but the graph does not fit in a good way. Here for the river discharge correlation is done one by one for the river which has significant inflow amount to the lake. Gelana River only shows a good correlation with the lake level. This could be because of the diversion of the river for irrigation purpose before entering to the lake.



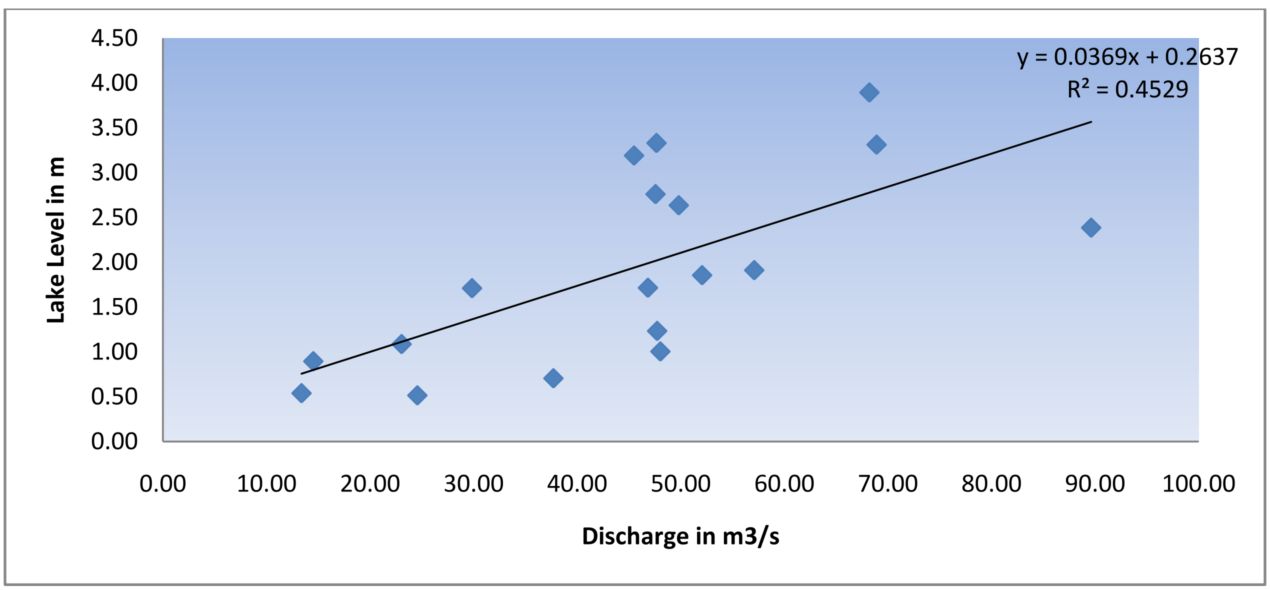
a. Bilate, Gelana and Gidabo River discharge and Abaya lake level



b. Bilate River at Tena Bilate



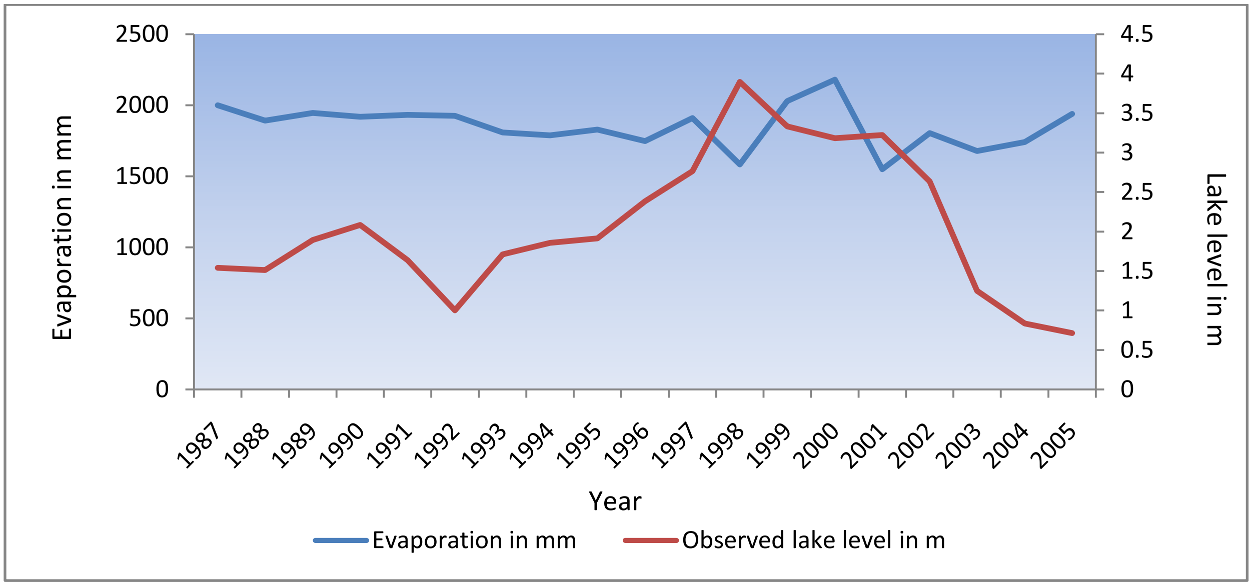
c. Gidabo River at Aposto



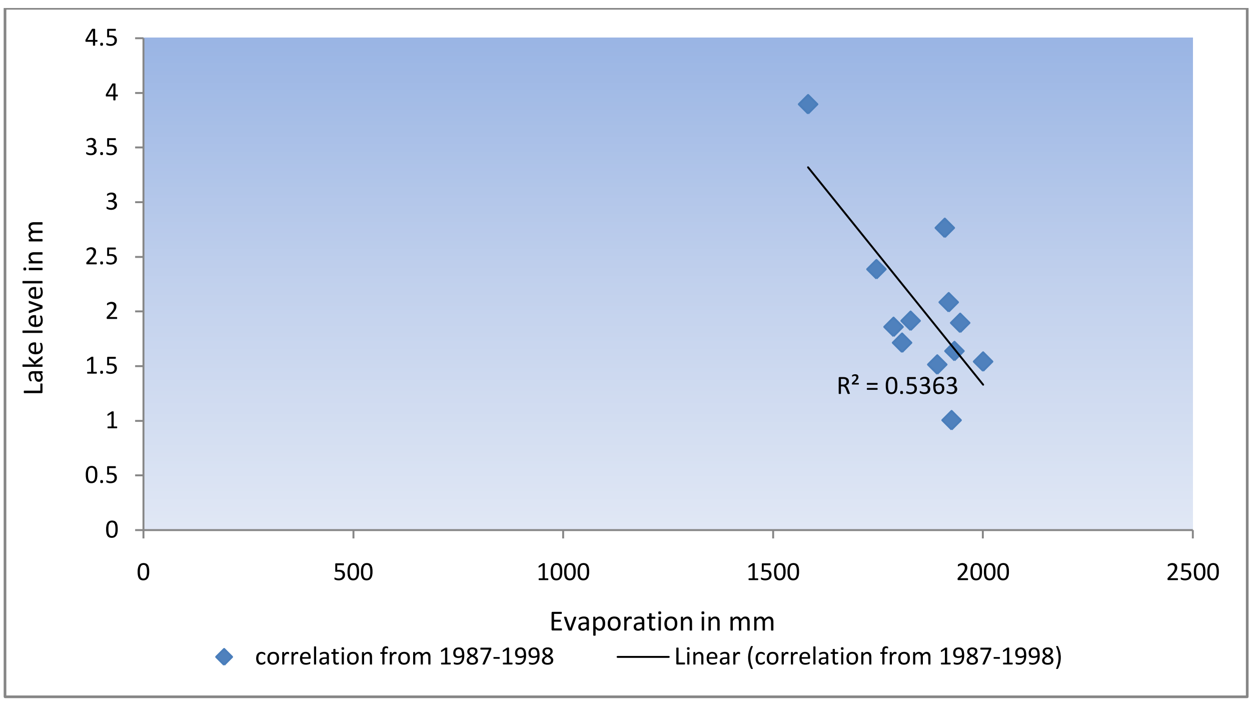
d. Gelana river at the bridge near Tore town

Figure 4 14 Correlation between Abaya Lake level and River Discharge

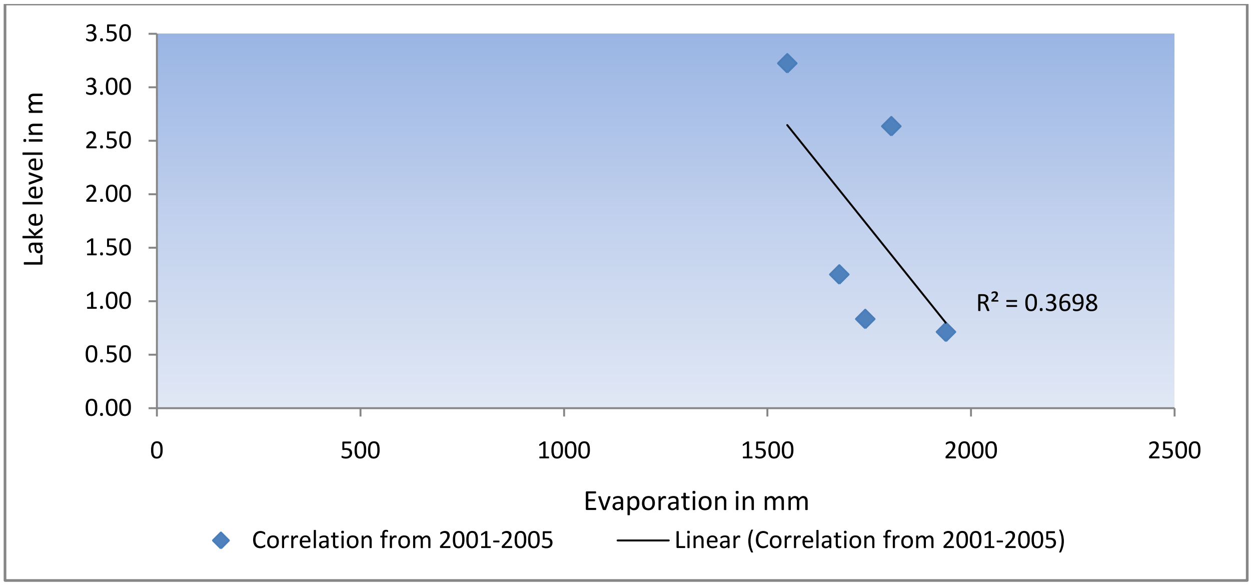
In an evaporation vs. lake level graph the troughs in 1998, 2000 and 2001 in evaporation and the peaks in 1998, 2000 and 2001 in the lake level record are negatively correlated. But after the 1998 high lake level, the lake level did not respond to the high evaporation rate in 2000, longer time is required for such a significant change. When we exclude these periods which make the lake to maintain its memory and don't have good fit with evaporation, we will have a good fit of evaporation rate with that of lake level (figure 4.15 b and c).



a. Abaya Lake level and Evaporation amount for the period 1987-2005



b. Correlation between evaporation amount and lake level from 1987-1998



c. Correlation between evaporation amount and lake level from 2001-2005

Figure 4 15 Correlation between Abaya Lake level and Evaporation

As we see the above correlation graphs, Lake Abaya shows a good correlation with the rainfall depth in the catchment and the evaporation amount in the area. But Lake Abaya water level doesn't show good correlation with river discharge even for some selected years were the graph seems to have good fit.

CHAPTER FIVE

Land Use/Land Cover

To investigate the impact of land use/ Land cover change on the water balance parameters (like runoff, etc) in the study area Landsat images of Lake Abaya sub-basin have been used. The 1986 and 2000 images of the area have been classified by using ERDAS and ArcGIS software and finally the images have been used for change detection analysis.

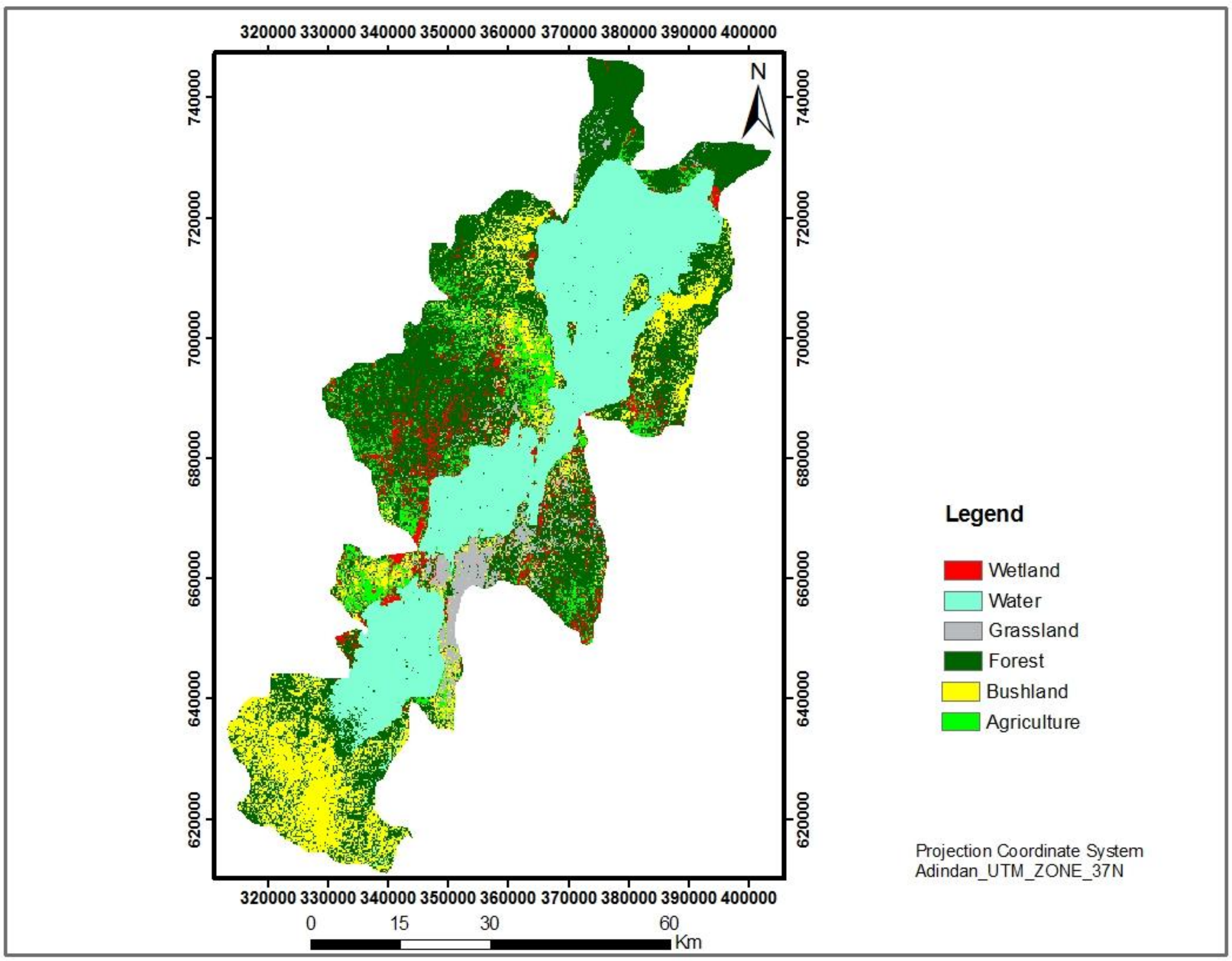


Figure 5 1Land use/Land Cover map of Lake Abaya sub-basin in 1986

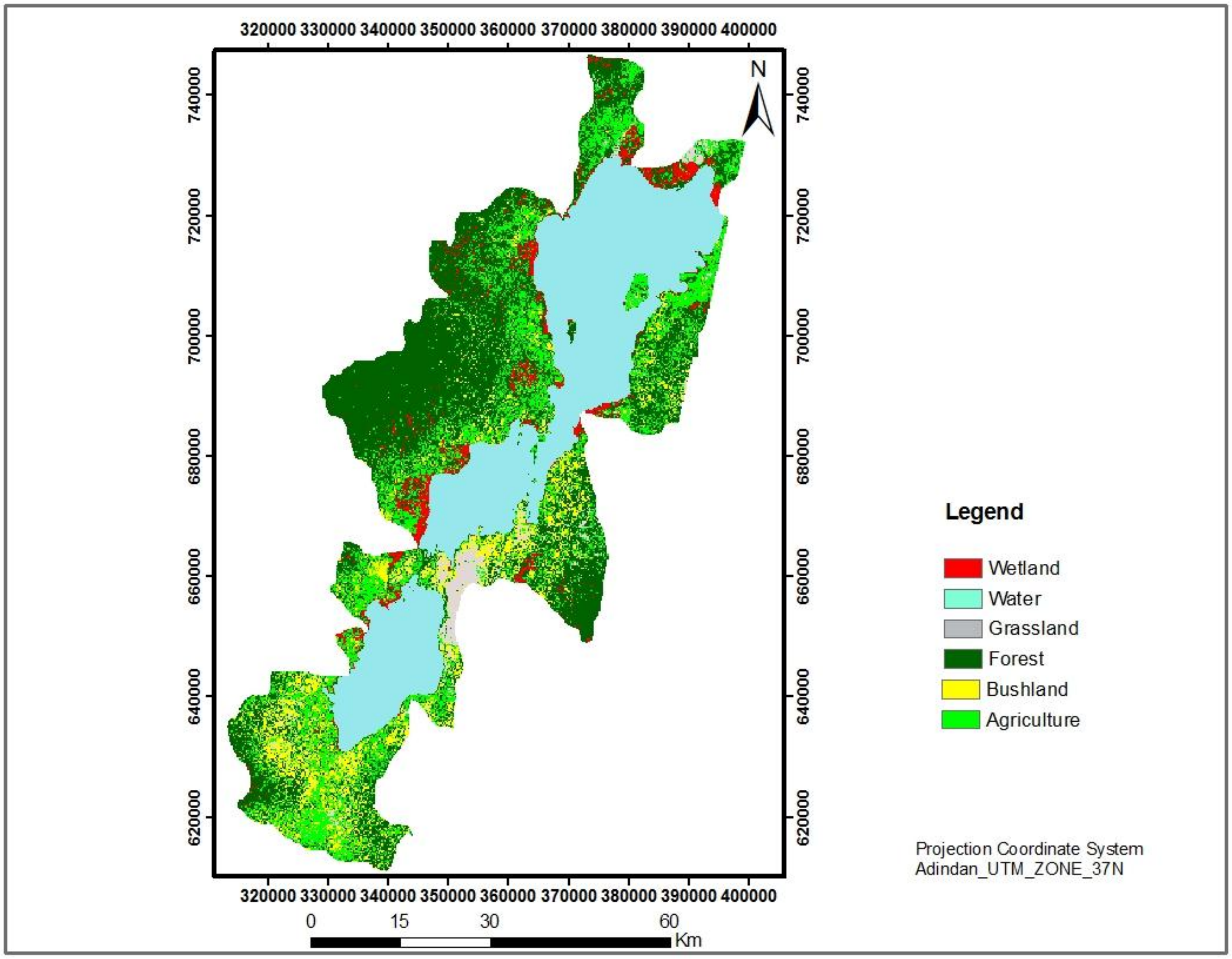


Figure 5 2 Land use map of Lake Abaya Sub-basin in 2000.

The image analysis shows that there is a considerable depletion of forest coverage in the sub catchment between 1986 and 2000. The decrease in the forest cover is more apparent in the along western shore of Lake Abaya where agricultural expansion is observed. Next to agricultural land expansion, conversion of forest to bush land due to increasing deforestation for charcoal production is the major land cover change observed. The change as analyzed by the change detection parameter in the ERDAS software is presented in the following figure 5.3.

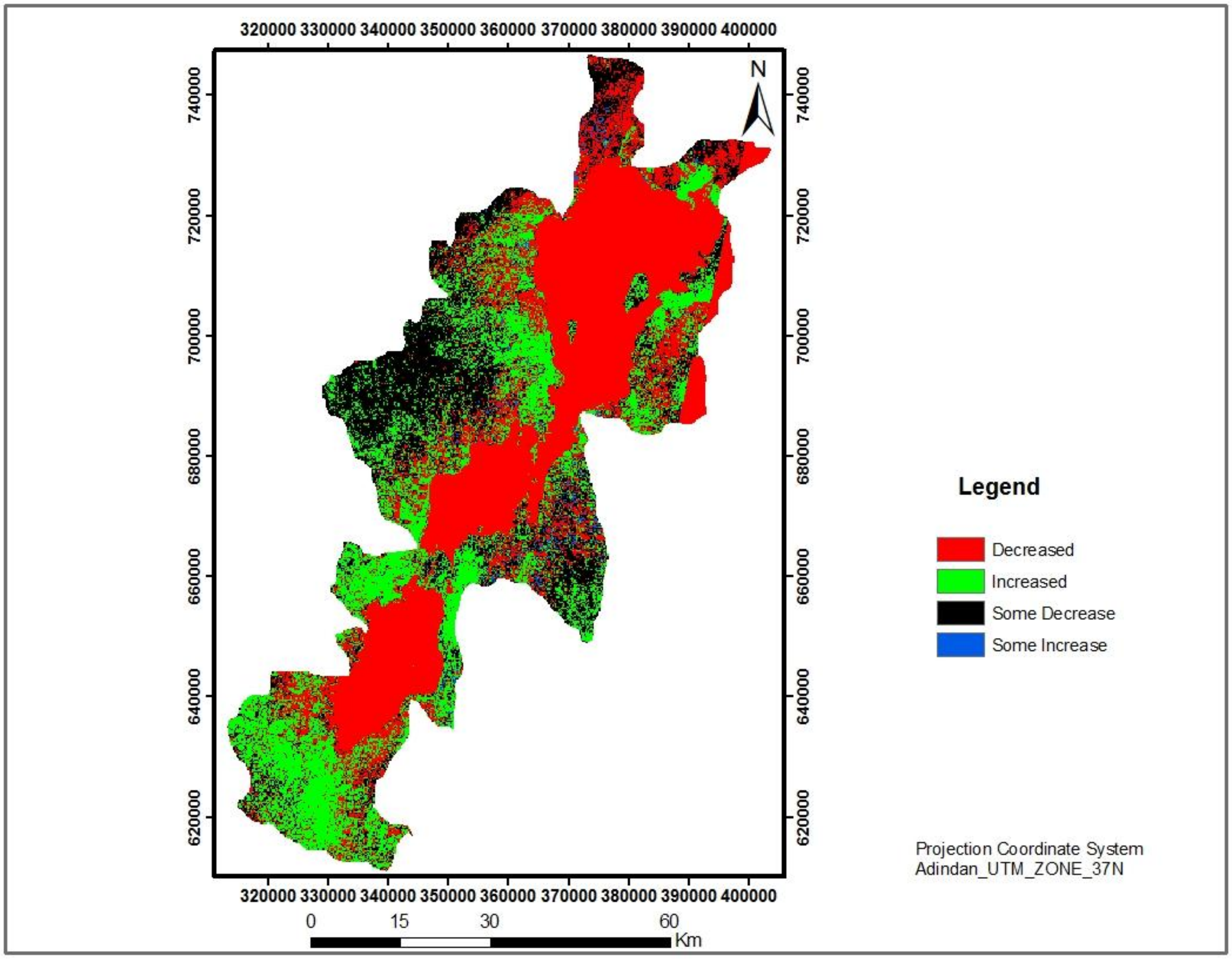


Figure 5 3 Change detection map by using 1986 and 2000 images of Landsat.

Where red colored land cover type represents land cover with more than 10% increase in 2000 and the green colored land cover represents land cover with more than 10% decrease and the black colored land cover once represent land cover decrease less than 10% from that of 1986 condition and the blue colored land cover type represent land covers that increase less than 10% from the 1986 coverage.

Land use/Land cover	In the year 1986 , Area in hectare	In the year 2000, Area in hectare	Change in percent
Bush land	50459.8	59442.4	17.8
Wet land	31512.7	20790.8	-34
Forest	180832	143195	-20.8
Agriculture	24506.7	72254.3	194.84
Water	137734	137320	-0.3
Grassland	17150.2	9192.48	-46.4

Table 5 1 Land use/Land cover Changes in Lake Abaya Sub-basin.

Agricultural land shows an increase of close to 200% in the year 2000, from 1986, while bush land increased by 17% during the same period, which can be explained by continuous deforestation for agriculture and charcoal production for commercial and community use. Deforestation causes soil loss due to erosion and increase runoff, and sediment load in the catchment which leads to lake level change. The forest land cover is not the only land cover that is changed to agricultural land; it is also the grassland and wet land. This situation is observed during the field survey of the study area, almost all the wet land in the western shore of Lake Abaya has been changed to agricultural land, which also causes an increase runoff and sediment load which finally leads to lake level change.

CHAPTER SIX

Lake Abaya Water Balance Model

6.1 Water Balance Theory

It is generally assumed, the total amount of water remained constant on global level Ferguson and Znamensky (1981), and the term "Water balance" expresses the idea that the amount of the earth's water is fixed Sanderson (1990) means inflow, outflow components and the change of water volume are at equilibrium. Therefore, the water balance equation for lakes at any time interval is a continuity equation. The continuity equation, in turn, is governed by conservation of matter, which described by equilibrium between inflow components, outflow components and the change of water volume for each interval of time. This equilibrium is described by the water balance equation (UNESCO, 1974):

$$I_S + I_G + P_L - E_L - O_S - O_G \pm A = \Delta S \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where

$I_S =$ Surface inflow into the lake (I_{Sg} and I_{Sug})

$I_{Sg} =$ Gauged surface inflow into the lake

$I_{Sug} =$ Ungauged surface inflow into the lake

I_G = Ground water inflow

P_L = precipitation on the surface of the lake

E_L = evaporation from the lake

O_S = surface out flow from the lake

O_G = Ground water outflow from the lake

$\pm A$ = Abstraction (agricultural, industrial etc...)

ΔS = change in the water storage in the lake for the balanced period.

The I's, $P_{L,}$ O's, $E_{L,}$ A and the Δ S are known as the components of the water balance equation. The components represent the stochastic (i.e. random) hydrologic processes and/or the deterministic anthropogenic (human-induced) processes that can be quantified for a specified area and interval of time. For any lake the imbalance between these components results in a change of storage that is reflected by changes in area and/or level. When the inflow is greater than the outflow, lakes may expand or rise; if outflow exceeds the inflow, lakes shrink the opposite happens.

Determining the water balance of any accounting unit, whether it is a lake, wetland or drainage basin requires consideration of the entire hydrological system (Ayenew, 2009). Thus lakes can be divided into two main categories: open (exhoric) lakes with outflow, and closed or terminal (endhoric) lakes without outflow. Therefore, by definition Abaya Lake is a terminal lake because under natural conditions all runoff in Abaya Lake sub basin eventually terminates in the lake.

For closed lakes, where the underground flux components (I_G and O_G) don't contribute significantly to the balance, the equation for mean water balance under equilibrium can be written as:

$$I_S + P_L = E_L \quad \text{……………………………………….(2)}$$

However, many studies showed the importance of groundwater flux in estimating water balance of lakes (Winter, 1976a in Ayenew, 1998). In this study the components of groundwater flux are not considered in the water balance of Lake Abaya, because these components are not as such significant in the study area and not identified in the area (Seifu et al., 2009). Thus, the equation can be rewritten as (assuming insignificant amount of abstraction from the lake) (Awulachew, 2001):

$$I_{Sg} + I_{Sug} + P_L - E_L = \Delta S \quad \text{………………………….(3)}$$

Because the components are quantified for a time/space variety from point data and with imperfect measurement and estimation techniques, errors always occur. The error in each component value is summed into what is called discrepancy, residual, or overall error term of the water balance, so that equation 3 is rewritten as (UNESCO, 1974):

$$I_{Sg} + I_{Sug} + P_L - E_L \pm E = \Delta S \ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (4)$$

It must be emphasized that “E” represents the net effect of all component errors and that sum may cancel each other. "E" also includes components not taken into account. Thus, a zero or low value of the error term is no assurance that the values of the components are correct. Winter (1981) observed that the component error and the overall error are often neglected in a water balance but they are a general problem in its practical application especially since "water budgets determined by poor methodology without estimates of errors can be very misleading; can give a false sense of security about how well the budget is known; and can lead to considerable waste of lake management and restoration money."The possible source of error in estimating the components of Abaya Lake could be the evaporation component, which has been converted from the pan evaporation amount to open water evaporation by multiplying some coefficient and the runoff.

By using the relationship of lake level to volume (as determined by the lake basin morphometry), a lake level change is forecasted by adding the lake storage change calculated by equation 4 to a known lake volume. The following balance equation expresses the forecasting relationship:

$$V_{Initial} + \Delta S_{calculated} = V_{New} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

Where

$V_{Initial}$ is the lake volume at the beginning of a specified time interval,

$\Delta S_{calculated}$ is the lake storage change calculated by equation 4 and

V_{New} is the lake volume at the end of the time interval.

Equation (5) is the basic equation for a water balance lake level forecast model as each V_{New} becomes the $V_{Initial}$ in each succeeding time interval. Lake Abaya is considered as a terminal lake as a result of its insignificant outflow through groundwater and overflow components. Although other models have been used to forecast terminal lake levels, a model based on the water balance is the best method because:

(1) It is conceptually simple and scientifically correct;

(2) Its accuracy is limited only by the accurate development and prediction of the inflows, outflows and errors;

(3) It helps for the assessment of the effect of human-induced and natural changes in the hydrologic system; by identifying the major variables which determines most the storage change of the lake (i.e., if runoff is the major factor which has a major role in the storage change variation during increased or decreased runoff). Here we can assess the effect of human –induced change in the hydrologic system due to the runoff amount change; because runoff is the function of slope, vegetation cover and soil texture and these conditions can be changed due to human-induced causes and cause runoff amount variations.

(4) Its results are conditioned by previous lake levels;

(5) It allows the forecast to be short or long term (day, month, and year) as the data permits (James et al. 1979).

6.2 Model Development

Because of the circular nature of reasoning that goes into some water balances, an unreliable water balance developed with imprecise methods can look as good on paper (i.e. have as low an overall error) as one developed with the best computational and methodological techniques. Ideally, the water balance forecast model should be developed using a systematic procedure that allows its accuracy and reliability to be evaluated. As cited in UNESCO (1974), Voster (1985) and Habtom (2007), the general modeling process - formulation, calibration, verification and application are the best guidelines for developing a reliable terminal lake level forecast model. Each of the major phases is considered below and shown in the following figure.

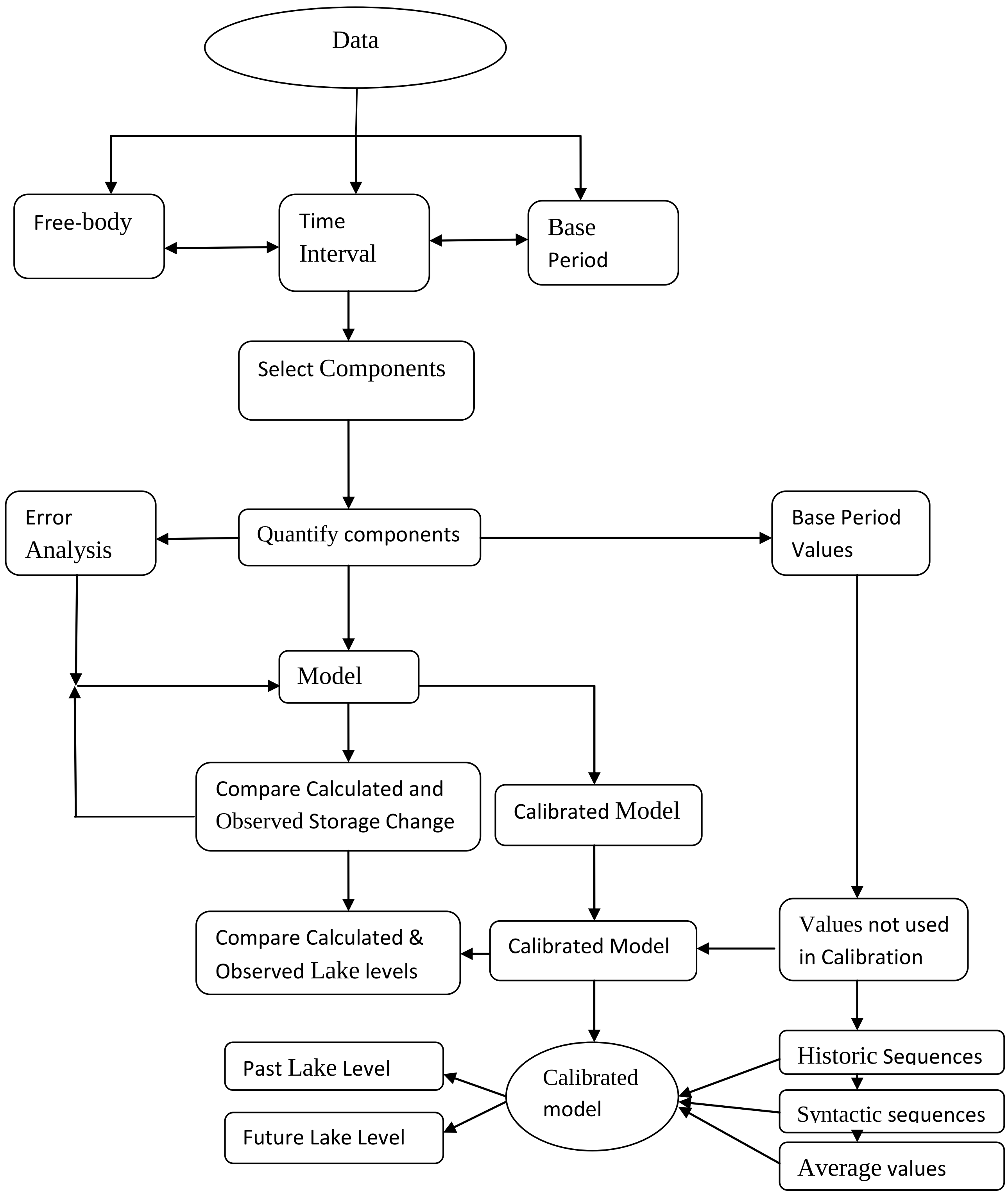


Figure 6 1 Schematic Diagram for Development of Lake Level Forecast Model

6.3 Formulation

Water balance formulation is a multi-step process that results in the identification and quantification of the model's components. Thus, the forecast model is formulated through a quantitative assessment of the inflows (precipitation on Lake Surface and runoff - gauged and unguaged), outflows (evaporation from the lake) and storage changes within the lake. The steps should include the specification of the water balance "free-body," time interval, and base period so that the components are properly identified. In addition an analysis of the errors incurred in quantification should be included so that the accuracy of the component values can be evaluated (Winter 1981). These steps are described in the following section.

6.3.1 Free-Body

Free-body is defined as the area for which the water balance is derived. The importance of a suitable free-body is often overlooked in terminal lake water balances even though the free-body determines the nature, magnitude, and accuracy of the water balance components. Choice of a free-body depends on the purpose of the water balance, the availability of information, and the hydrologic and physical characteristics of the system. An ideal free-body should have a boundary that is fixed over time and whose flows are measurable or easy to estimate across its boundary. Lake Abaya is taken as the free-body for forecast model. Most of the inflow to the lake is surface runoff from the catchment. Thus we have a clear boundary of the lake which facilitates a more accurate delineation and estimation of the water balance components.

6.3.2 Time Interval

Time interval is the unit of time for a single execution of the water balance equation. Water balances may be computed for any time interval depending on the purpose of the water balance and the availability of data. Forecast models used to specify future operational plans may require a weekly or monthly time interval, while the prediction of long-term trends in the lake surface elevation usually requires only an annual time interval. The shorter time intervals require more detailed accounting of the storage and movement of water and have more precise computational requirements. The choice of the time interval is often determined by the longest time interval required for an accurate estimation of a water balance component. Terminal lake water balances, like Lake Abaya, are most commonly developed using an annual time interval because it is difficult to make accurate estimates of evaporation for shorter time spans (UNESCO, 1974).

6.3.3 Base Period

Base period is the time period, consisting of successive time intervals in the historic record, for which the components are quantified. The base period ideally would have; wet and dry period, minimized storage changes, end near the present and long, continuous data set. As cited in Habtom (2007); Yevjevich (1972) stated that when the period of record becomes longer, the long-term mean values change, it is important to compare the chosen base period with previously selected base periods.

The base period for Lake Abaya is determined by the availability of reliable measurements of pan evaporation and runoff since evaporation from the lake and runoff & rainfall on the lake area are the principal outflow and inflow to the lake, respectively. Pan evaporation measurements were made starting from 1985-2005 on Arba-Minch and Mirab-Abaya stations. Precipitation measurements were also made regularly from 1987 to 2007 on Arba-Minch, Mirab-Abaya, Amaro Kello, Chencha, Wajifo and Bilate station by National Meteorological Service Agency. Thus the period from 1987-2005 is selected as base period because during this period we will have all component complete.

An analysis of the physical and hydrological characteristics of the free-body, combined with the specification of the time interval and base period provides the basis for choosing the components that should be quantified. Quantification of these components is the core of the formulation phase. Component quantification involves computing the value of each variable of the component for each time interval in the base period. Techniques for estimating the component variables in a lake water balance are summarized in Winter (1981) and Ferguson et al. (1981). All of these works recommend the independent quantification of all water balance components because component values determined as residuals incorporate the error from other components.

Accurate quantification of the water balance components is extremely difficult. It is important, then, to analyze the overall water balance error and to estimate the individual component error, especially since errors in component quantification may not necessarily be reflected in the overall water balance error (due to the canceling effect of component errors). Analysis of the component and overall error should be a fundamental part of model development (UNESCO, 1974; Winter 1981). In addition, error analysis will identify deficiencies in the network of data collection stations.

The error in each component value is the difference between the estimated and observed value. This can be expressed as:

$$E_C = V_e - V_{ob} \quad \text{………………………………………..(6)}$$

Where

E_C = component error

V_e = estimated value

V_{ob} = observed value

Component error can be classified into two general types: systematic error or "bias", and non-systematic or "random" error. Aitken (1973) notes that most hydrological models fail to distinguish between the two types of errors. Systematic error is a deviation from a true value caused by either (1) improperly calibrated measuring instruments, (2) assumptions made in the computation of a component value because of the lack of data, (3) other unexplainable inconsistencies, Non-systematic or random errors result from (1) measurement of any variable used in computing component values, and (2) point data extrapolated over time and space.

The overall error, the sum of the component errors, is called the residual or discrepancy term (UNSECO, 1974). In a lake level forecast model, this is equal to the difference between the calculated lake storage change resulting from the computed inflows and outflows and the actual lake storage change that results from the actual but unknown inflows and outflows: Thus,

$$E = \Delta S_C - \Delta S_{Ob} \quad \text{…………………………………………(7)}$$

Where:

E = overall error

ΔS_C = calculated value

ΔS_{Ob} = observed value

The overall error thus incorporates the systematic and nonsystematic error as well as components not taken into account. A recommended criterion is that the overall error should not exceed the square root of the sum of the square of the error limits of the individual water balance components (Ferguson et al., 1981).

According to UNESCO (1974), the overall error should not exceed the square root of the sum of the square of the error limits of the individual water balance components.

i.e.

$$E \leq \sqrt{e_1^{\,2} + e_2^{\,2} \ldots\ldots\ldots + e_n^{\,2}}$$

Where E is the overall error and $\mathbf{e_1^{\,2}, e_2^{\,2}, e_n^{\,2}}$ are error limits of individual components. Another measure of the relative magnitude of the overall error term is its ratio ("relative discrepancy") to the total inflow or total outflow (UNESCO, 1974 cited in Ferguson et al., (1981)). A large relative discrepancy suggests that one or more components are imprecisely computed; a small relative discrepancy value cannot be interpreted as mean of the component values error since component errors can cancel out each other.

6.4 Calibration

In order to make the water balance model operational for the purpose of forecasting it must first be calibrated (Sooroshian, 1983 cited in Voster (1985)). The objective is to determine the model parameters such that an acceptable match is obtained between the observed behavior of the variable of interest and the computed behavior. Thus calibration of a lake level forecast model is the process of logically adjusting the Component model values so that the difference between the actual and calculated lake storage change is minimized, because the difference is attributable to the overall water balance error. This involves obtaining the best match between the observed and the computed parameters used in the model. According to Sorooshian & Gupta (1983), the purposes of calibration may be:

(a) To obtain a unique and conceptually realistic parameter set which closely represents our understanding of the physical system; or

(b) To obtain a parameter set which gives the best possible fit between the model-simulated and observed phenomena.

According to UNESCO (1974) and Sooroshian (1983) there are two basic approaches to calibration: the manual approach and the automatic approach. In the manual approach the skill, experience, and intuition of the researcher are utilized to adjust the component values and/or the overall error. An example of manual calibration is increasing or decreasing the value of a component variable such as the evaporation rate in order to achieve a better fit between calculated and observed lake levels. In the automatic approach the adjustment to component values is based on mathematical techniques that commonly involve the optimization of an error function. However, Sorooshian & Gupta (1983) described three areas which hinder the accurate calibration of conceptual models:

(a) Model structure representation;

(b) Data and their associated measurement errors; and

(c) Imperfect representation of physical processes by the model.

The model should be calibrated for a portion of the base period that is long enough to contain data considered fairly well representative of the various phenomena the system experiences and that the model intends to simulate (Sooroshian, 1983 cited in Voster (1985)). Ideally a portion of the base period is excluded from the calibration so that it can be used to verify the model.

6.5 Parameterization

The calibration process requires a procedure to evaluate the variable computed with a given set of parameter values and then to adjust the parameters, if required. James & Burges (1982) list three criteria to evaluate a calibration: a subjective judgment on adequacy; some statistic selected as the measurement of goodness of fit; or some user-defined objective function. The least squares criterion is the most widely used in the automatic calibration approach.

6.6 Verification

Verification tests whether or not the calibrated forecast model is an accurate predictor of lake levels. This is done by calculating lake levels for a time period not used in calibrating the model. These results are then compared with actual (observed) lake levels for the same period.

6.7 Application

The forecast model is applied to determine (estimate) past and future lake levels. Hydro-meteorological conditions are specified as model input that determine the values of the model components. Assumptions about the rate can be represented as a time series sequence of values that can either be modeled as constant value or values that differ or equal to the base period average.

In the following sections each storage, inflow, and outflow process for Lake Abaya is examined separately and each quantifiable component is identified separately so that independent determinations of each component's annual value in the 1987 - 2005 base period can be made. However, the input and output components of the water balance of a lake or reservoir depend not only on the physical dimension of the water body, but also on the climatic, hydrological and geological factors affecting the water body and its surrounding areas Ferguson and Znamensky (1981).

6.8 Quantification of Inflow Components

6.8.1 Precipitation on the Lake

The main surface water input to Lake Abaya comes from precipitation, rivers and springs. The rainfall station located at Arba-Minch city has been selected due to its influence on the lake from the other two main stations in the study area. Thus, the available rainfall record for the period 1987-2005 has been considered for computing the inflow magnitude to the lake. Since the water balance is conducted on the basis of yearly time interval, annual rain fall series have been used. The following formula is used for computation of precipitation on the lake surface:

P_L = PPt * A

Where:

P_L = precipitation on lake surface (mcm)

PPt = precipitation in m

A = Mean surface area of the lake in Km^2

6.8.2 Runoff from the Ungauged Catchments

Discharge from the unguaged catchments are computed using the following analogue methods

The first step is selection of river analogue in the Abaya-Chamo sub catchment. There are four major river analogues in the catchment which are gauged at different stations since 1969. The drainage areas of these rivers are described in Selieshi, 1998; the proportion of gauged and ungauged area in the sub-catchment is described in Table 6.1.

Lake Basin	River/ Catchment	Total Area(km^2)	Gauged Area (km^2)	Ungauged Area (km^2)	Gauged Proportion (%)
Abaya	Bilate	5791.01	4231.2	1559.82	73.06
	Gidabo	3473.29	1088.3	2385.01	31.3
	Gelana	3411.51	1612.2	1799.34	47.25
	Hare	199.14	189.85	9.29	95.33
	Total area excluding lake& islands	15,234.1	7121.5	8112.58	46.75

Table 6 1Proportion of Gauged and Ungauged Area in Lake Abaya Basin (Awulachw, 1998)

The annual rain fall of the drainage area, based on the arithmetic mean, is the mean annual rain fall of the five stations in the study area namely Arba-Minch, Mirab-Abaya, Amaro-Kello, Bilate and Chencha stations.

The second is calculating runoff coefficient (K) from the gauged catchment using the following formula:

$$K = I_T / A_T * PPt_T$$

Where

K = runoff coefficient

I_T = Annual discharge of Bilate, Gidabo, Gelana and Hare rivers in mcm

A_T = Drainage area of Bilate, Gidabo, Gelana and Hare rivers in km^2

PPt_T = Annual precipitation on the area in m

6.8.3 Gauged Rivers Flow

Monthly flow records of Bilate, Gidabo, Gelana and Hare River from 1987-2005 have been obtained from Ministry of Water Resources and are considered in the water balance computation.

6.8.4 Ground Water Inflow

Ground water inflow amount in to Abaya lake has not been studied well yet, however some studies (e.g. Seifu et.al., 2009) indicates that the dominant water loss in this area is through evaporation and surface water outflow and the dominant water gain is through surface water. Therefore, the ground water inflow component contribution to the water balance of Lake Abaya is considered insignificant and not used in our computation.

6.8.5 Inflow Reduction Due to Water Use and Intensified Evapotranspiration

Water use and intensified evapotranspiration by marshy/swampy areas downstream of the gauging stations up to the outlet should be accounted so that any consumptive water uses are subtracted from the inflow magnitude. Therefore, in this topic it is tried to get it. Almost all of existing major water uses, which are for irrigation occur in the valley, near the lake and downstream of the gauging stations. But limited information regarding irrigation is available on from Arba-Minch and Sille unit farm. Also in the Abaya drainage, there are considerable marshy/swampy or inundation plain areas. The effect of these factors produced a yearly average reduction of inflow of Abaya Lake by 12.4 mcm and 51.7 mcm due to water use for irrigation and evapotranspiration by marshy areas, respectively (Awulachew, 2001).

6.9 Quantification of Outflow Components

6.9.1 Evaporation from the Lakes

The available measured class A pan evaporation has been used in estimating Lake evaporation by applying pan coefficient of the order of 0.85 as discussed in the previous chapter.

Lake evaporation has been computed from the following equation.

$$\mathbf{E_L = E_P * A * C}$$

Where:

$\mathbf{E_L}$ = Lake evaporation in mcm

$\mathbf{E_P}$ = pan evaporation in m

A = mean surface area of the lake in km^2

C = pan coefficient

6.9.2 Ground Water Outflow

The ground water outflow amount is considered as insignificant, as discussed above.

6.10 Lake Storage Change

6.10.1 Abaya Lake Storage Change

In this model the annual Lake storage change is the calculated sum of all the other inflows, outflows and storage changes in the lake. In order to calibrate the model and use it for forecasting purposes it is required to know the value of the Lake storage change that results from lake level fluctuations and this is because a lake level change is forecasted by adding the lake storage change calculated by the water balance (Equation 4) to a known lake volume. Since Abaya Lake has no outlet, its level and size fluctuate in response to changes in the balance between evaporative outflow and inflow from precipitation and surface water. Therefore, these outflow and inflow components are important for lake level change forecast. The magnitude of lake fluctuations is influenced by the lake's morphometric characteristics (i.e. the level, area, and volume of the lake). These characteristics determine the relationship between the lake's stage, area, and volume. But bathymetry data for Ethiopian lakes is not readily available; the available bathymetries for Abaya and Chamo are by (Awulachew, 2001). For characterization and evaluation of the impact of the Lake Abaya level rise, depth-area and depth-volume curves were used on the basis of the lake bathymetry reported by (Awulachew, 2001) and presented in table 6.2 and figure 6.1.

The fitted elevation-area curve, for Lake Abaya related to depth, is given by:

$$\mathbf{A= 0.0198d^5 -0.06662d^4+7.7116d^3-39.7666d^2+31.023d+1133.4}; \qquad R^2=0.9995$$

Where d is depth in meters below zero water lake level measured positive downwards and A is area in Km^2 .R^2 is coefficient of determination. Zero lake level corresponds to 1171m a. m. s. l(i.e., the boundary of Lake Abaya corresponding to 1979 EMA map of level 1169m a. m. s. l is fixed to depth of 2.0m and this 2m is the bench-mark for the lake level measurement on the station, as per Awulachew, 2001).

The fitted volume curve for Lake Abaya also is given by the following formula:

$$\mathbf{V= -1x10^{-5}d^5+0.0005d^4-0.0057d^3+0.051d^2-1.2242d+9.842}; \qquad R^2=1$$

Where d (m) is depth of water, measured from lake level 1171m a.m.s.l., positive downwards

Depth (m)	Elevation(a. m. s. l)	A(Km^2)	V(Mcm)
15	1156	0.69405	0.327
13	1158	67.57643	43.1
11	1160	385.1694	493.59
9	1162	605.609	1489.18
7	1164	779.6216	2883.623
5	1166	907.98	4576.356
3	1168	1023.684	6508.02
1	1170	1126.449	8685.393
0	1171	1139.786	9818.591

Table 6 2 Values of Area - Capacity Curves of Lake Abaya

(As computed from bathymetry survey report of Awulachew, 2001).

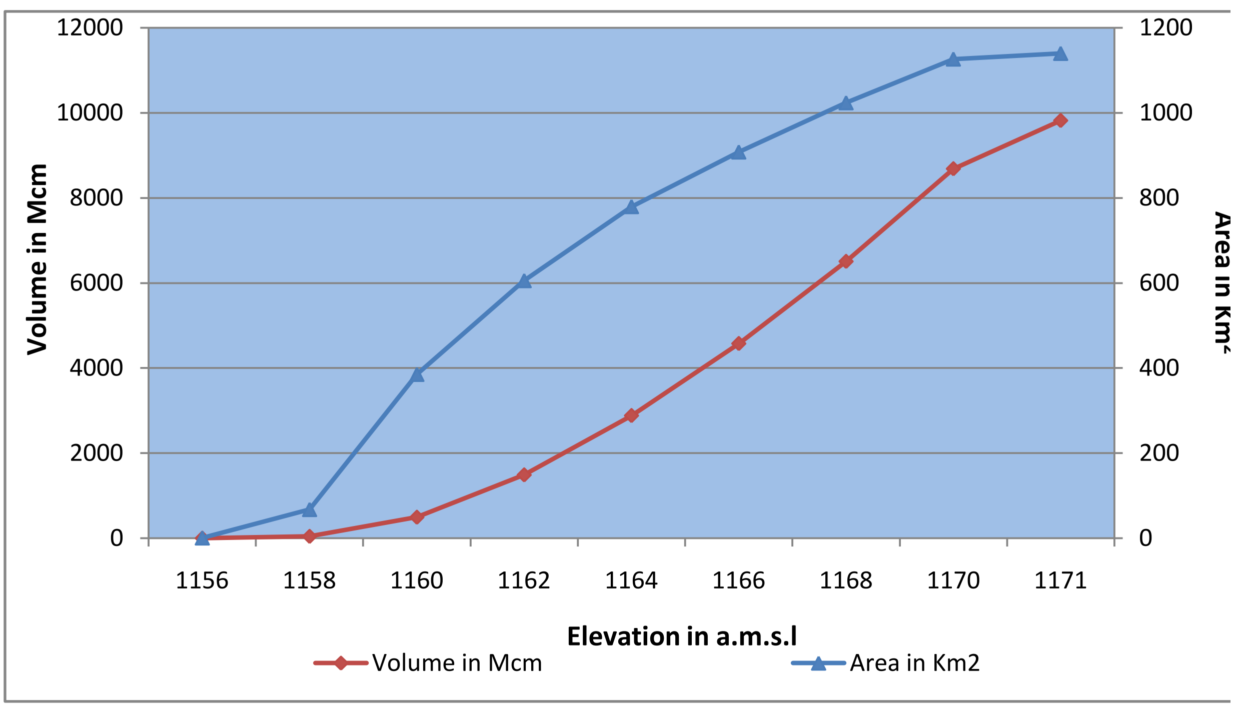


Figure 6 2 Area-Capacity Curve of Lake Abaya

The Components of Abaya Lake Water Balance are provided in the following tables and figures.

Year	Area in Km2	Total Gauged River Flow in mcm	Total Ungauged River Flow in mcm	Precipitation on Lake Surface (mcm)	Lake Evaporation (mcm)	Storage Change(mcm)
1987	1062.00	902.31	688.99	844.87	2124.19	311.99
1988	1087.46	813.16	659.56	1157.17	2056.29	573.60
1989	1090.40	672.31	574.36	1118.86	2121.42	244.11
1990	1068.00	696.73	653.62	664.51	2048.67	-33.81
1991	1026.70	614.61	539.04	777.11	1983.47	-52.71
1992	1081.50	921.01	967.37	1042.03	2081.95	848.46
1993	1087.00	907.28	875.09	950.47	1964.27	768.56
1994	1087.80	818.47	808.37	922.40	1943.57	605.68
1995	1119.07	714.81	731.89	1001.01	2045.02	402.69
1996	1125.00	1198.80	1149.48	1066.47	1964.21	1450.54
1997	1139.78	888.40	863.16	1313.54	2175.71	889.39
1998	1133.00	812.47	885.39	1007.41	1793.58	911.68
1999	1131.00	601.93	486.00	1016.63	2293.83	-189.28
2000	1131.60	583.48	556.37	982.91	2467.07	-344.31
2001	1123.00	638.81	647.60	1217.67	1739.00	765.08
2002	1049.00	523.60	444.26	848.33	1892.44	-76.25
2003	1023.00	580.86	467.30	902.70	1714.84	236.01
2004	1012.80	608.98	485.98	817.99	1762.31	150.64
2005	1034.20	759.38	643.36	963.46	2004.54	361.66
Mean	1084.86	750.39	690.90	979.76	2009.28	411.78

Table 6 3 Abaya Lake Water Balance Component

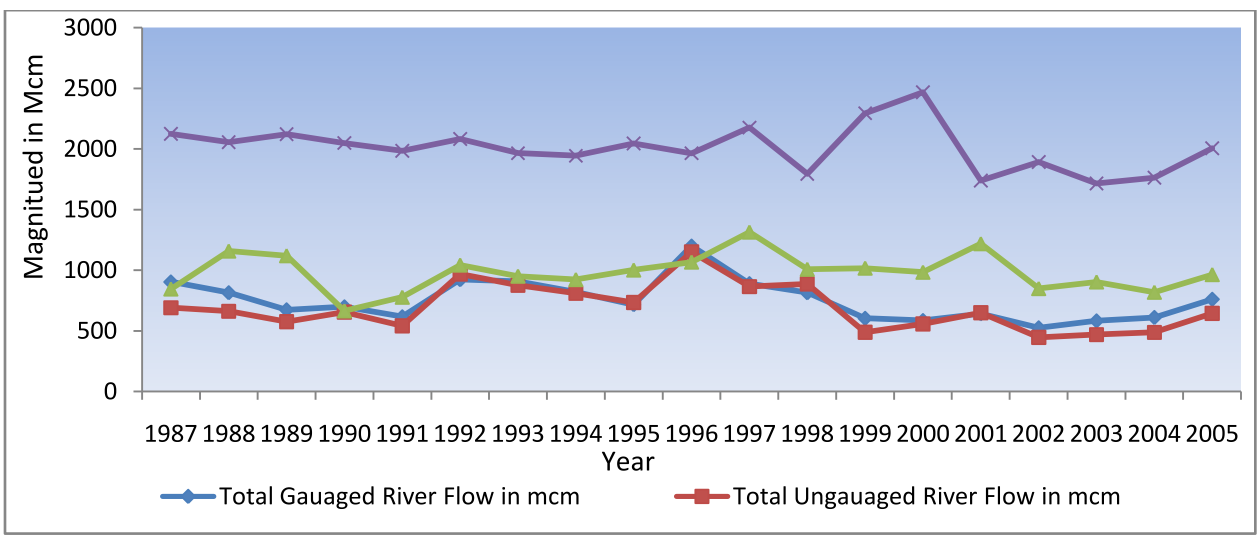


Figure 6 3 Abaya Lake Water Balance Components

YEAR	observed (dh)	Average Area(km2) Taken from Awulachew, 2001	calculated Storage change (dS) (mcm)	Simulated Storage Change (dS)(mcm)	simulated level(dh)in meter	Difference (overall error)of ds/(simulated - calculated ds)
1987	-0.03	1062.00	-28.78	311.99	0.29	340.76
1988	0.38	1087.46	409.56	573.60	0.53	164.04
1989	0.19	1090.40	205.63	244.11	0.22	38.48
1990	-0.45	1068.00	-481.95	-33.81	-0.03	448.14
1991	-0.63	1026.70	-662.80	-52.71	-0.05	610.09
1992	0.71	1081.50	747.40	848.46	0.80	101.06
1993	0.14	1087.00	157.17	768.56	0.71	611.39
1994	0.06	1087.80	60.53	605.68	0.56	545.15
1995	0.47	1119.07	520.64	402.69	0.36	-117.95
1996	0.38	1125.00	424.80	1450.54	1.29	1025.74
1997	1.13	1139.78	1281.09	889.39	0.79	-391.70
1998	-0.56	1133.00	-641.30	911.68	0.80	1552.98
1999	-0.15	1131.00	-169.14	-189.28	-0.17	-20.14
2000	0.04	1131.60	47.23	-344.31	-0.30	-391.54
2001	-0.59	1123.00	-662.48	765.08	0.68	1427.56
2002	-1.38	1049.00	-1503.75	-76.25	-0.07	1427.50
2003	-0.42	1023.00	-430.63	236.01	0.23	666.64
2004	-0.12	1012.80	-122.83	150.64	0.15	273.47
2005	0.34	1034.20	345.86	361.66	0.35	15.80

Table 6 4 Simulated and Calculated storage change and lake level change.

YEAR	calculated Storage change (dS) (mcm)	Simulated Storage Change (dS)(mcm)	Difference (over all error) of ds	Total inflow	Total outflow	Relative error to inflow (%)/(Over all E/Total Inflow*100)	Relative error to outflow (%)/(Over all E/Total outflow*100)
1987	-28.78	311.99	340.76	2436.17	2124.19	13.99	16.04
1988	409.56	573.60	164.04	2629.89	2056.29	6.24	7.98
1989	205.63	244.11	38.48	2365.53	2121.42	1.63	1.81
1990	-481.95	-33.81	448.14	2014.86	2048.67	22.24	21.87
1991	-662.80	-52.71	610.09	1930.76	1983.47	31.60	30.76
1992	747.40	848.46	101.06	2930.40	2081.95	3.45	4.85
1993	157.17	768.56	611.39	2732.84	1964.27	22.37	31.13
1994	60.53	605.68	545.15	2549.25	1943.57	21.38	28.05
1995	520.64	402.69	-117.95	2447.71	2045.02	-4.82	-5.77
1996	424.80	1450.54	1025.74	3414.75	1964.21	30.04	52.22
1997	1281.09	889.39	-391.70	3065.10	2175.71	-12.78	-18.00
1998	-641.30	911.68	1552.98	2705.26	1793.58	57.41	86.59
1999	-169.14	-189.28	-20.14	2104.55	2293.83	-0.96	-0.88
2000	47.23	-344.31	-391.54	2122.76	2467.07	-18.45	-15.87
2001	-662.48	765.08	1427.56	2504.08	1739.00	57.01	82.09
2002	-1503.75	-76.25	1427.50	1816.19	1892.44	78.60	75.43
2003	-430.63	236.01	666.64	1950.85	1714.84	34.17	38.87
2004	-122.83	150.64	273.47	1912.95	1762.31	14.30	15.52
2005	345.86	361.66	15.80	2366.20	2004.54	0.67	0.79

Table 6 5 Comparison of Error relative to inflow and outflow

During comparison of relative error we do see some larger errors which are out of the expected error rang (i.e., in the years of 1996, 1998, 2001, 2002 and 2003). Cross checking with the recorded lake level data and hydro metrological data, indicate that these periods are not periods of extreme meteorological conditions in the region. Therefore, this error could be the result of bad recording of the lake level, moved bench mark without a proper record or alternatively, due to poorly recorded hydro-meteorological data. Thus, the above problems propagate and make the uncalibrated model to differ from the observed phenomena, particularly in the above indicated years. However, calibration of the model shows similar trend of the simulated and observed lake levels.

Year	Simulated level	Observed level	Difference
1987	1.83	1.51	0.32
1988	2.37	1.89	0.47
1989	2.59	2.08	0.51
1990	2.56	1.64	0.92
1991	2.51	1.00	1.51
1992	3.31	1.71	1.60
1993	4.02	1.86	2.17
1994	4.58	1.91	2.67
1995	4.95	2.38	2.56
1996	6.24	2.76	3.47
1997	7.02	3.89	3.13
1998	7.83	3.33	4.50
1999	7.66	3.18	4.48
2000	7.35	3.22	4.13
2001	8.03	2.64	5.40
2002	7.96	1.25	6.71
2003	8.19	0.83	7.36
2004	8.34	0.71	7.62
2005	8.69	1.05	7.64
Mean	**5.58**	**2.05**	**3.54**
STDEV	**2.49**	**0.92**	

Table 6 6 Comparison of Simulated and Observed lake level (uncalibrated)

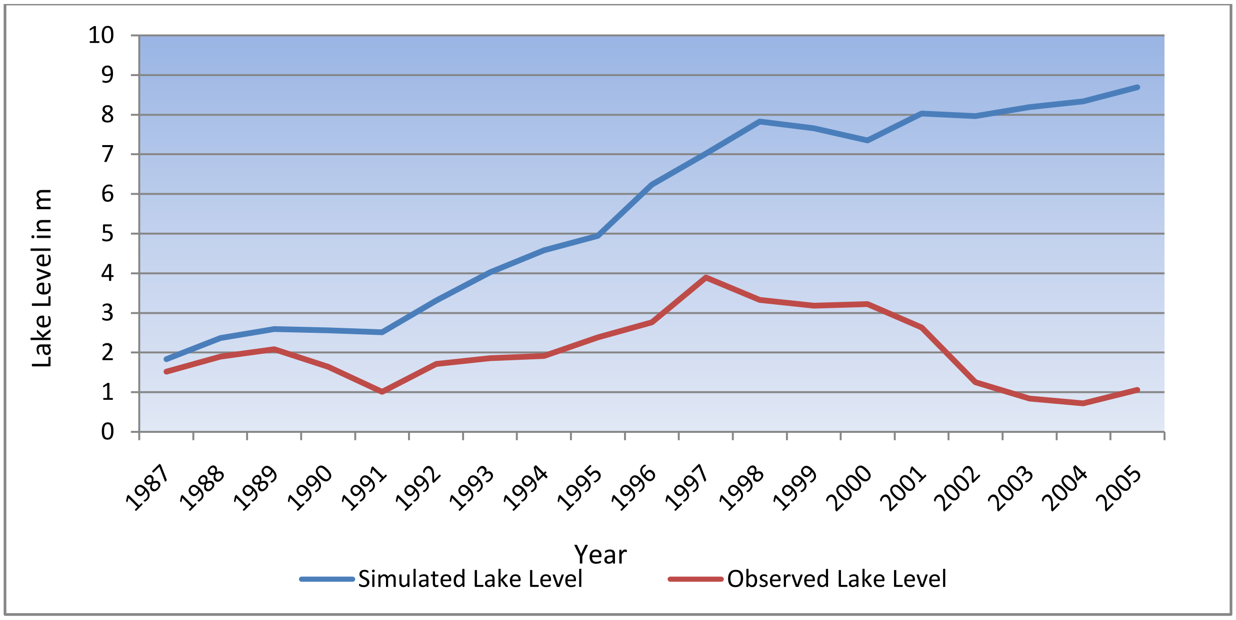


Figure 6 4 Simulated and observed lake level (uncalibrated model)

6.11 Error Analysis

The quantification of the component values in the previous sections involve measurements, approximations, regionalization, and assumptions that result in random and systematic error. Random error results from the measurements and estimates of the basic data and the regionalization of it to larger areas, for example, the precipitation/runoff relationship, or the evaporation estimates. Both systematic and random errors also occur as the result of the assumptions used to derive the component values (Ferguson et al., 1981). If the systematic error could be estimated with any certainty the component value would accordingly be adjusted. The random error of water balance components has been estimated in research studies that assume the true value is quantifiable (e.g. Winter, 1981; Ferguson et. al., 1981). Based on the review of these studies Habtom (2007) suggested the random error magnitudes that are given in Table 6.7. Components with the largest percentage error have little or no basic data or are difficult to estimate and smaller percentage is assumed for gauged since the error is measurement. Errors assumed for evaporation and precipitation are measurement and instrumental error. These error ranges are used as a guide to estimate the magnitude of the random error for the components of the water balance.

The large percentage error of most components translates into relatively small differences in the total inflow or outflow, but the uncertainty in estimating the lake evaporation and runoff rate have the greatest impact on the water balance based on the percentage error given in the Table 6.5.But, in practice the researchers have the problem of deciding whether an observed error is acceptable or not. A recommended criterion, according to UNESCO (1974) is that the overall error should not exceed the square root of the sum of the squared component error of the water balance.

Component	**Error Range (-/+ Percent)**	**Source**
Gauged Stream Flow	5	Ferguson et al. 1981
Unguaged Runoff	10-20 70	Peters 1972, Winter 1981
Precipitation(Annual Volume)	5-30 10-20[1]	Peters 1972 Ferguson et al. 1981
Evaporation - Annual Volume -Annual Rate Using Pan	 10-20[1] 10-20	 Ferguson et al. 1981
Groundwater Storage Change	5-40	Peters 1972

[l] Assumes well-instrumented lake basin

Table 6 7 Range of Random Error in Estimating Water Balance Components. (Summarized by Habtom, 2007)

6.12Model Calibration

Model calibration (parameter estimation) involves the automatic and/or manual adjustment of model parameters to minimize the difference between observed and predicted values, which is called the objective function. Therefore, before the water balance model is going to be applied to forecasting Lake Abaya levels it must be calibrated and verified. The calibration adjusts the model in order to minimize the difference between the calculated storage change and the simulated storage change. Since this difference is equivalent to the overall error, calibration can also be viewed as "explaining" the overall error so that it can be logically predicted.

Much of the overall error is predictable because it is the result of systematic component error. If that portion can be correlated with the factors that cause or explain the systematic component error, then most of the overall error can be predicted. The simplest technique for discerning correlation among several variables is multiple linear regression; multiple regression is one of the few numerical methods that can be used to evaluate the effects of several factors acting simultaneously on a dependent variable. This is a well established technique for predictive purposes in hydrologic investigations. It is generally agreed that multiple regression is preferable if prediction of the dependent variable (in this case the overall error) with minimum error is the desired result (Julian et al., 1967).

6.12.1 Procedure

The calibration procedure used in this model involves determining the linear relationship between the overall error (the dependent variable) and the "explaining" factors (the independent variables). A stepwise multiple linear regression, from the Statistical Package for the Social Sciences (SPSS) is utilized for the data analysis. In the stepwise procedure the independent variables are added in "steps" which will, in combination with those variables previously included, effect the greatest reduction in the unexplained variance of the dependent variable in a single step (Julian et al., 1967).

It is important to use only a portion of the 19-year base period for calibration period because some data are needed for verification. The minimum number of years considered for a calibration time period is 12 years, two third of the base period. After examining a number of possible calibration time periods, the 1992 - 2000 period is chosen for the following reasons:

1) It is a period whose average error and standard deviation are closest to the average error and standard deviation of the base period;

2) It displays the widest range of hydro-climatic conditions (i.e. runoff, precipitation, evaporation), and high lake level changes during observation period.

The selected 1992-2000 period fails to calibrate the model, because multiple regressions explain the variance and not the magnitude of the dependent variable. Therefore, all the factors that might cause or correlate to systematic component error which explain the variance of the overall error are initially included which means the whole period is entered for calibration. The factors and the component error they explain are shown in the table below.

Factors	**SPSS Abbreviations used**	**Component Error Explained**
Annual Gauged River flow	GRFL	Gauged Bilate,Gelana,Gidabo and Hare river flow
Unguaged runoff	UGRF	Unguaged runoff to lake
Annual Rain fall	RFL	Rain fall on Lake Surface
Annual Evaporation	EVAPO	Evaporation from lake water
Overall Error	STCH	Difference between observed and simulated storage change

Table 6 8 Factors that may reflect systematic component error

In this study only the above factors are considered because of the availability of data for the given factors. But ground water inflow and outflow could be some other factors for the overall error observed in the water balance calculation. Unfortunately ground water inflow and outflow data for this study is considered as zero, but this might not be the case, that they may have an influence on the water balance.

Model	*R*	*R Square*	*Adjusted R Square*	*Std. Error of the Estimate*
1	**.024(a)**	**.001**	**-.058**	**600.26163**

a. Predictors: (Constant), GRFL

Model	*R*	*R Square*	*Adjusted R Square*	*Std. Error of the Estimate*
2	**.238(a)**	**.057**	**-.061**	**601.15809**

a. Predictors: (Constant), UGRFL, GRFL

Model	*R*	*R Square*	*Adjusted R Square*	*Std. Error of the Estimate*
3	**.332(a)**	**.110**	**-.067**	**602.89119**

a. Predictors: (Constant), RFL, GRFL, UGRFL

Model	*R*	*R Square*	*Adjusted R Square*	*Std. Error of the Estimate*
4	**.756(a)**	**.572**	**.450**	**432.78366**

a. Predictors: (Constant), EVAPO, UGRFL, RFL, GRFL

Table 6 9 Stepwise regression of independent variables with the overall error (dependent variable)

As shown in the above tables, all are regressed in stepwise addition against the overall error. The purpose is to show the effect of the variables in changing the multiple R and adjusted R^2. The EVAPO variable shows a good correlation with the overall error, suggesting that a good percentage of the overall error is explained by the variation of this factor. The importance of this factor in explaining the larger magnitude error is emphasized by the significantly improved R square results, in which the factor EVAPO is changing the R^2 from 0.11 to 0.572 (Table 6.9). But for the other variables the R square does not improve that much R^2 is 0.001, 0.057 and 0.11 when GRFL, UGRFL and RFL are regressed in stepwise addition against the overall error, respectively. This factor is related to the component with the greatest magnitude error and thus by extension to the magnitude of the overall error. The result is consistent with physical reasoning due to the difficulties in estimating evaporation of water from the lake and uncertainties in annual evaporation data derived from pan measurements. This is because pans do not have significant heat storage, and thus measurements of evaporation would vary more than the actual evaporation from a nearby lake. Annual evaporation derived from these measurements would likely be systematically too high during years of high evaporation, and too low during years of low evaporation (Julian et al. 1967).

Thus, the regression step (4) is chosen for calibration because it has good correlation (R square) and relatively minimum standard error. The step (4) regression coefficients are shown in the table below.

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients		
		B	Std. Error	Beta	t	Sig.
1	(Constant)	5095.035	1224.436		4.161	.001
	GRFL	-1.204	1.671	-.344	-.721	.483
	UGRFL	1.426	1.487	.468	.959	.354
	RFL	-.429	.709	-.116	-.606	.554
	EVAPO	-2.149	.553	-.697	-3.887	.002

a. Dependent Variable: STCH

Table 6 10 Multiple regression statistics for the period 1987-2005 four factor equation

Here also if the significance value for the explaining factors/independent variables is small (smaller than say 0.05) then the independent variables do a good job on explaining the variation in the dependent variable. If the significance value is larger than say 0.05 then the independent variables do not explain the variation in the dependent variable. Therefore, EVAPO which has significance value of 0.002 explain more the dependent variable (Overall error). Thus the error shown in the analysis could be because of the uncertainties in evaporation values.

The equation that results from regressing the variables with overall error is the following:

E= -1.204GRFL+1.426UGRFL-0.429RFL-2.149EVAPO+5095.035 ………………… (11) R^2 =0.57

Where: GRFL is Gauged River Flow, UGRFL is ungauged River flow, RFL is Rainfall on the lake and EVAPO is Evaporation from the lake.

The relevant statistics for the equation are shown in Table 6.10.

When "E" in equation (4) above, is replaced by the above equation, and the appropriate inflows, outflows, and storage changes quantified in the formulated model are inserted, the resulting equation that will calculate storage changes for any given data set is:

$\Delta S = I_S + P_L - E_L - O_G \pm E$ …………………(4)

When we substitute E in the above equation, we will have

ΔS = GRFL + UGRFL+ RFL - EVAPO - (-1.204GRFL+1.426UGRFL-0.429RFL-2.149EVAPO+5095.035)….(12)

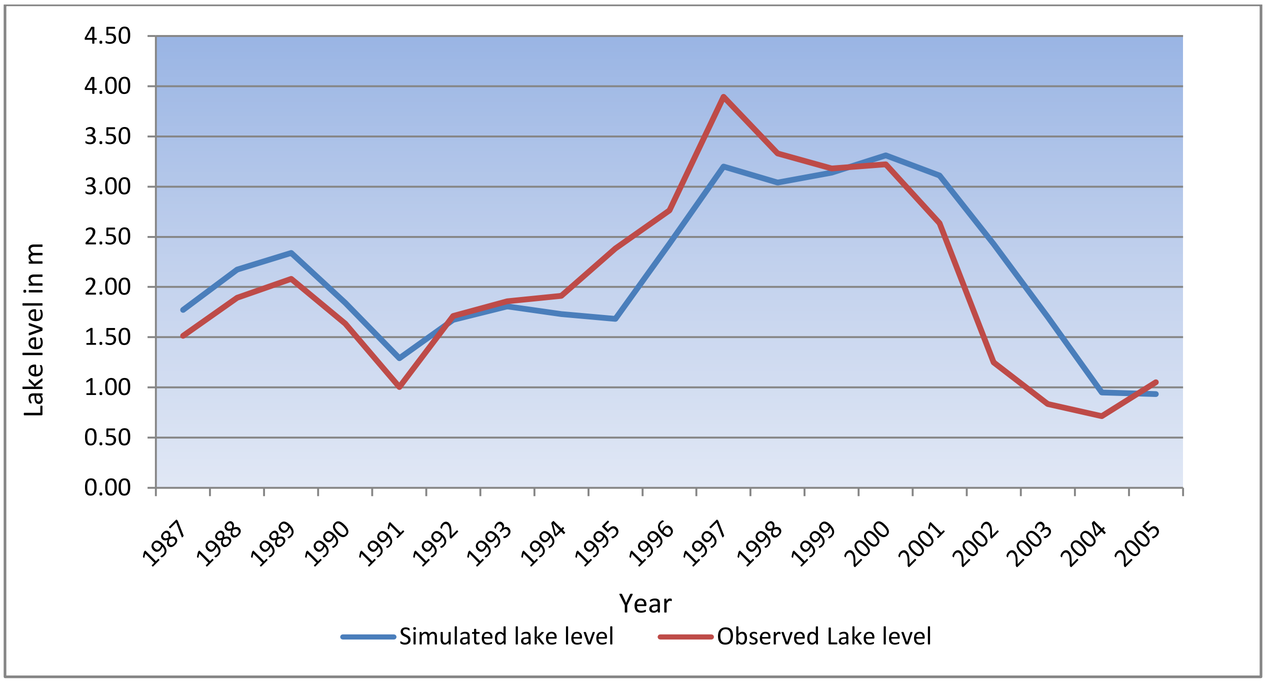


Figure 6 5 Comparison of observed and simulated lake level using the calibrated model

Equation (11) calibrates the model. Equation (12) is thus a calibrated water balance model for Lake Abaya. The figure 6.4 shows a comparison of the observed lake level with the simulated lake level using the calibrated model. Similar trend between the observed and simulated lake level has been achieved for the simulation period. But there are still errors incorporated in the simulated storage change from which the simulated lake level is calculated. Thus, further adjustment has been done to achieve the best fit. Autoregressive integrated moving average (ARIMA) model fit from SPSS package is utilized to bring down the errors incorporated in the evaporation and lake storage change. Because ARIMA models are the best, doubtless and the most accurate way to make prediction applicable in a model, i.e. a mathematical equation, that reflects all the terms contained within a series (O. Valenzuela, 2004). The new model fit for the storage change then regressed against the independent variables to obtain an error equation (13). The relevant statistics for the following equation are listed in the Table 6.12.

E= -0.538GRFL+0.779UGRFL-0.851RFL-2.498EVAPO+6157.063 ……………… (13)R^2 =0.898

Model Summary[b]

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.947[a]	.898	.868	196.7537664

a. Predictors: (Constant), EVAPO, UGRFL, RFL, GRFL

b. Dependent Variable: Fit for STCH from AREG, MOD_1

Table 6 11 Regression of independent variables with the overall error (Fit for STCH from AREG, MOD_1) ARGE is autoregressive part of the ARIMA structure.

The R square value is now closer to one (i.e., R^2 value for the calibrated model was $R^2 = 0.57$ and for the calibrated and optimized one is $R^2 = 0.898$), that means the equation generated from calibrated and optimized model can describe the overall error more.

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	6157.063	556.658		11.061	.000
	GRFL	-.538	.760	-.165	-.708	.491
	UGRFL	.779	.676	.275	1.152	.268
	RFL	-.851	.322	-.247	-2.641	.019
	EVAPO	-2.498	.251	-.872	-9.940	.000

a. Dependent Variable: Fit for STCH from AREG, MOD_1

Table 6 12 Multiple regression statistics for ARIMA model fit

Equation (13) which is the overall error from calibrated and optimized model will be substituted in Equation (4), and the appropriate inflows, outflows, and storage changes quantified in the formulated model are inserted, the resulting equation that will calculate storage changes for any given data set is:

ΔS = GRFL + UGRFL+ RFL - EVAPO - (-0.538GRFL+0.779UGRFL-0.851RFL-2.498EVAPO+6157.063)….(14)

Equation (14) is therefore an optimized and calibrated water balance model for the Lake Abaya. The lake level calculated using equation (14) is presented in Table 5.13 and in the figure below.

Year	**Simulated level**	**observed level**	**Difference**
1987	1.66	1.51	0.15
1988	2.09	1.89	0.20
1989	2.32	2.08	0.24
1990	1.73	1.64	0.09
1991	1.08	1.00	0.07
1992	1.57	1.71	-0.14
1993	1.69	1.86	-0.16
1994	1.60	1.91	-0.31
1995	1.62	2.38	-0.77
1996	2.38	2.76	-0.38
1997	3.35	3.89	-0.55
1998	3.20	3.33	-0.13
1999	3.38	3.18	0.20
2000	3.71	3.22	0.49
2001	3.56	2.64	0.92
2002	2.78	1.25	1.53
2003	1.89	0.83	1.05
2004	0.95	0.71	0.23
2005	0.89	1.05	-0.17
Mean	2.18	2.05	0.13
STDEV	0.91	0.92	

Table 6 13Observed & sequentially simulated lake level using the optimized & calibrated model

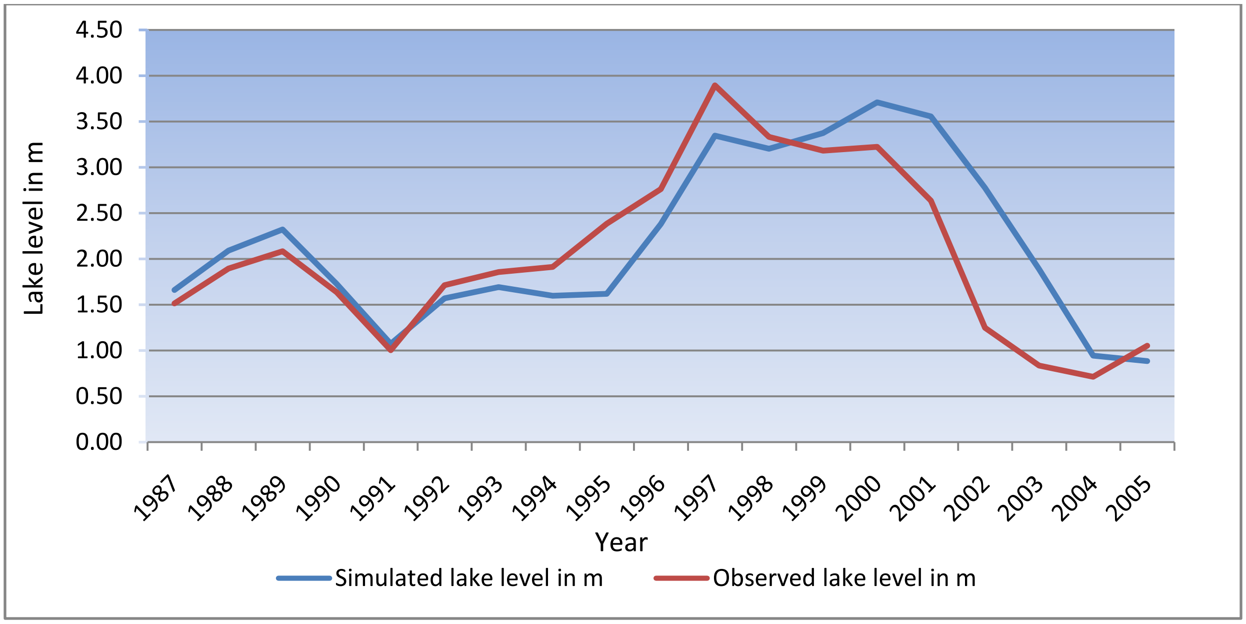


Figure 6 6 Comparison of observed & simulated lake level using the optimized & calibrated Model

6.13 Verification

In the verification phase, the calibrated water balance model is used to calculate lake levels in the 1987 - 2005 periods. The lake levels can be calculated sequentially, i.e., the calculated lake level at the end of one water year becomes the initial lake level at the beginning of the next water year, or the lake levels can be calculated separately year-to-year; i.e., the observed lake level is always used as the initial lake level. The simulated lake levels using the uncalibrated and calibrated model are compared separately with the observed lake levels for the 1987-2005 periods.

Table 6.6 shows that the simulated lake level deviates more than the observed lake level using the uncalibrated model than the calibrated model (Table 6.12). Although no absolute standards exist for determining the adequacy of the calibration or verification results, one test would be to compare the standard deviation and average annual difference between the observed and simulated lake level (Julian et al., 1967). Standard deviation for simulated lake level using the uncalibrated model is 2.49 and for simulated lake level using the optimized and calibrated model is 0.91. The verification thus confirms that a calibrated model is a somewhat more accurate predictor of lake levels than an uncalibrated model.

6.14 Sensitivity

Many assumptions and estimates are used in the formulation and construction of the model. To test the response of the calibrated model to a range of values for various input parameters, a sensitivity analysis is done. Sensitivity analysis can help determine which model parameters have the greatest effect on a model. Results of the analysis can guide future data collection efforts that will reduce model errors. It is done by varying the values of one input parameter while keeping all others constant.

A simple sensitivity analysis has been made to all variables by adding a 10% increase from their base period average values. Results of the sensitivity analysis show that small errors in estimating values of the evaporation and the rainfall amount on the area causes the model to be more sensitive. However, the model is moderately sensitive to river discharge and very less sensitive to ungauged runoff.

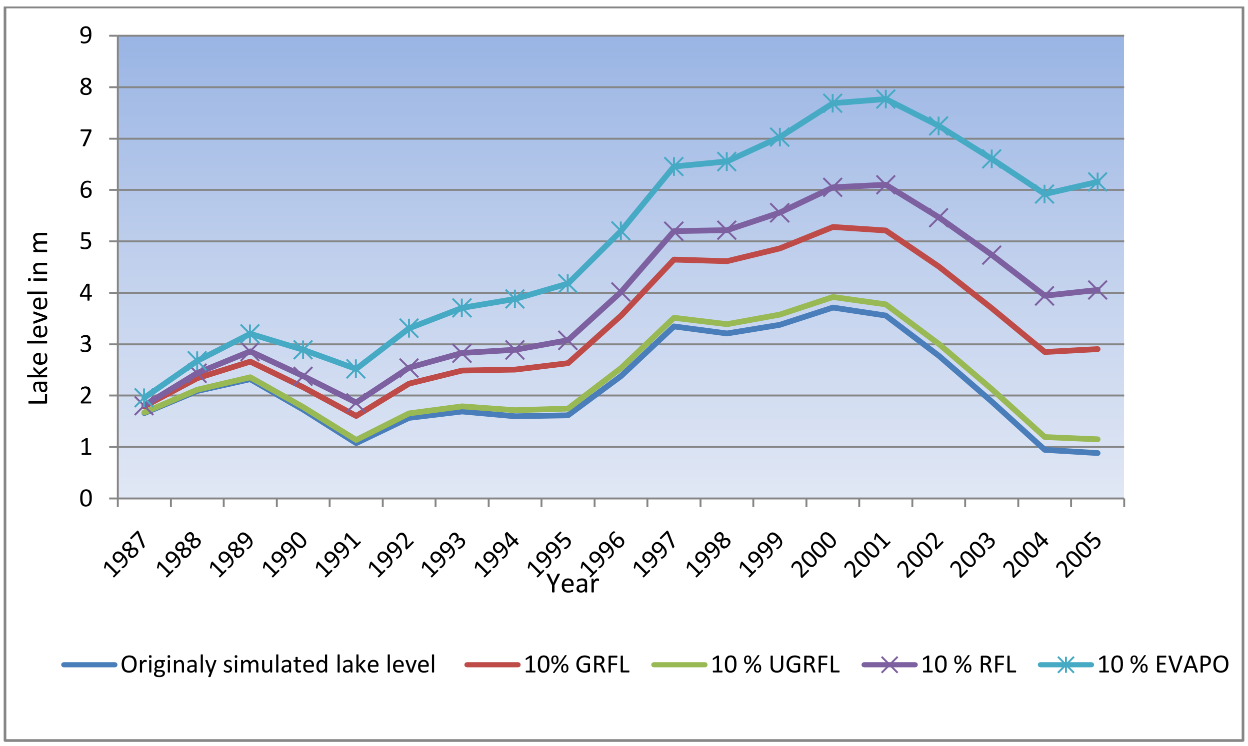


Figure 6 7 A simple sensitivity analysis to the variables by adding a 10% increase from their base period average values

6.15 Model Limitation

The formulated model of the Lake Abaya provides a simulation of lake level for the past 19 years. The formulated model is a simplification of the "real world", which is the case of all water balance models, and has corresponding limitations in model precision and how the model can be used for future applications. As a result errors are generated due to inaccuracy of input data. For example, missing values of evaporation and precipitation rates are filled by comparing and calculating with neighboring stations by using appropriate methodologies. And also ground water inflow and out flow components are considered as zero /insignificant because of the unavailability of proper studies which quantified them. In addition, model uncertainty could also be generated from random error in optimizing the evaporation rate from the water body during model calibration. Thus, limitations of the model should be taken into account when applying the model to water resources management.

CHAPTER SEVEN

Application of the Water Balance Model

In this chapter the calibrated and verified model, is used to forecast the lake level with error margin of -1m using different assumptions. The basic assumption in each one is that the hydro-climatic conditions (i.e. the rate of runoff, precipitation, and evaporation) of the 1987-2005 base period will occur in the future years.

The following assumptions are common to each forecast application. The unique assumptions within each application will be presented separately.

Assumptions

1. Initial lake level is 2.27m in December 31, 2006, obtained from MoWR.

2. The average lake area is 1084.86 km^2.

3. Groundwater inflow and outflow is assumed to be insignificant/zero.

4. Abstraction from the lake is assumed to be zero.

7.1 Model Applications and Results

7.1.1 Application One

Future lake level using the sequence of 1987-2005 hydro-climatic sequences with the 1992-2000 conditions occurring first.

The purpose of this application is to calculate the response of lake to annually varying hydro climatic conditions. The assumption is based on the lake level trend which shows a lake level decrease of 0.58m on average from 1987-1991 after this period the lake level increases to 2.14m starting from 1992-2000. Instead of using the sequence of 1987-2005 conditions in the order that it actually occurred, the sequences are rearranged so that the 1992-2000 conditions occur first. The reason for using the 1992-2000 condition first is the increasing trend observed in the lake level starting from 2005 to 2007 and the increase in the lake level could be the first to occur after the 2005 lake level record.

Application 1A: In this application the total average runoff values and precipitation from 1992-2000 will be used instead of the average values from 1987-1991 in the first six years of forecast (the average total river discharge, unguaged runoff and precipitation on the lake is 822.41mcm, 813.68 mcm and 1033.65 mcm respectively from 1992-2000). The lake evaporation component will remain the same as they actually occurred. The purpose is to show the effect of river discharge and precipitation in the lake level rise.

Year	Area in Km2	Total Gauged River Flow in mcm	Total Ungauged River Flow in mcm	Precipitation on Lake Surface (mcm)	Lake Evaporation (mcm)	Simulated Storage Change(mcm)	Future lake level change	Lake level 2.27
2007	1084.86	827.41	813.68	1033.65	2124.19	390.63	0.36	2.63
2008	1084.86	827.41	813.68	1033.65	2056.29	288.92	0.27	2.90
2009	1084.86	827.41	813.68	1033.65	2121.42	386.49	0.36	3.25
2010	1084.86	827.41	813.68	1033.65	2048.67	277.50	0.26	3.51
2011	1084.86	827.41	813.68	1033.65	1983.47	179.83	0.17	3.67
2012	1084.86	827.41	813.68	1033.65	2081.95	327.36	0.30	3.98
2013	1084.86	907.28	875.09	950.47	1964.27	133.53	0.12	4.10
2014	1084.86	818.47	808.37	922.40	1943.57	-100.77	-0.09	4.01
2015	1084.86	714.81	731.89	1001.01	2045.02	20.37	0.02	4.02
2016	1084.86	1198.80	1149.48	1066.47	1964.21	857.16	0.79	4.82
2017	1084.86	888.40	863.16	1313.54	2175.71	1090.63	1.01	5.82
2018	1084.86	812.47	885.39	1007.41	1793.58	-160.31	-0.15	5.67
2019	1084.86	601.93	486.00	1016.63	2293.83	194.04	0.18	5.85
2020	1084.86	583.48	556.37	982.91	2467.07	378.33	0.35	6.20
2021	1084.86	638.81	647.60	1217.67	1739.00	-172.53	-0.16	6.04
2022	1084.86	523.60	444.26	848.33	1892.44	-848.46	-0.78	5.26
2023	1084.86	580.86	467.30	902.70	1714.84	-920.72	-0.85	4.41
2024	1084.86	608.98	485.98	817.99	1762.31	-959.01	-0.88	3.53
2025	1084.86	759.38	643.36	963.46	2004.54	-60.79	-0.06	3.47

Table 7 1 Application 1A model construction and components

Application 1B: In this application the evaporation values from 1992-2000 will be used instead of the average values from 1987-1991 in the first six years of forecast (the average lake evaporation is 2081.02 mcm from 1992-2000). Other components will remain the same as they actually occur. The purpose is to show the effect of lake evaporation in the lake level change.

Year	Area in Km2	Total Gauged River Flow in mcm	Total Ungauged River Flow in mcm	Precipitation on Lake Surface (mcm)	Lake Evaporation (mcm)	Simulated Storage Change(mcm)	Future lake level	Lake level 2.27
2007	1084.86	902.31	688.99	844.87	2081.02	64.19	0.06	2.33
2008	1084.86	813.16	659.56	1157.17	2081.02	498.63	0.46	2.79
2009	1084.86	672.31	574.36	1118.86	2081.02	192.27	0.18	2.97
2010	1084.86	696.73	653.62	664.51	2081.02	-593.66	-0.55	2.42
2011	1084.86	614.61	539.04	777.11	2081.02	-536.86	-0.49	1.92
2012	1084.86	921.01	967.37	1042.03	2081.02	519.40	0.48	2.40
2013	1084.86	907.28	875.09	950.47	1964.27	133.53	0.12	2.53
2014	1084.86	818.47	808.37	922.40	1943.57	-100.77	-0.09	2.43
2015	1084.86	714.81	731.89	1001.01	2045.02	20.37	0.02	2.45
2016	1084.86	1198.80	1149.48	1066.47	1964.21	857.16	0.79	3.24
2017	1084.86	888.40	863.16	1313.54	2175.71	1090.63	1.01	4.25
2018	1084.86	812.47	885.39	1007.41	1793.58	-160.31	-0.15	4.10
2019	1084.86	601.93	486.00	1016.63	2293.83	194.04	0.18	4.28
2020	1084.86	583.48	556.37	982.91	2467.07	378.33	0.35	4.63
2021	1084.86	638.81	647.60	1217.67	1739.00	-172.53	-0.16	4.47
2022	1084.86	523.60	444.26	848.33	1892.44	-848.46	-0.78	3.69
2023	1084.86	580.86	467.30	902.70	1714.84	-920.72	-0.85	2.84
2024	1084.86	608.98	485.98	817.99	1762.31	-959.01	-0.88	1.95
2025	1084.86	759.38	643.36	963.46	2004.54	-60.79	-0.06	1.90

Table 7 2 Application 1B model construction and the components

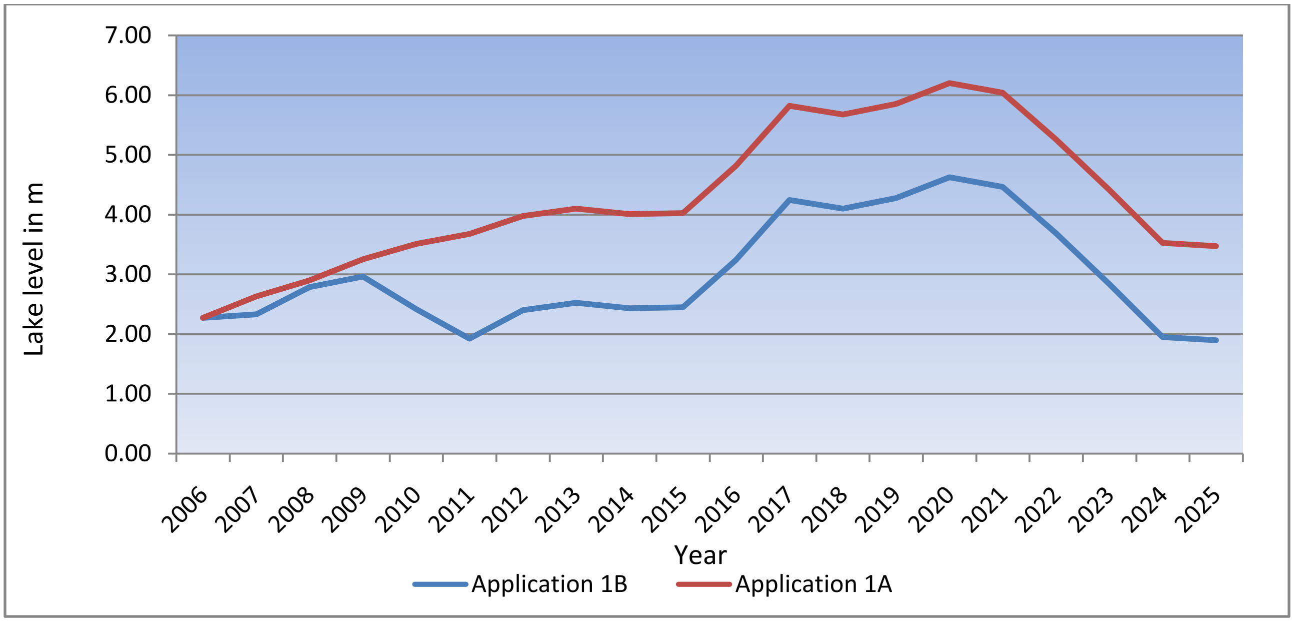


Figure 7 1 Forecasted lake level using Application one

Results: Plotting the result of application 1A (Figure 7.1) shows that after six years the lake level differ by 1.71m then fluctuates and reaches 3.47m by 2025. Recall, the assumption used, that an increase by 89% in runoff and 88% precipitation on the lake values causes the lake level to increase by 1.71m, but with the original values the level increases by 0.2m which means the role of runoff and precipitation during lake level rise was significant. But the result of application 1B shows minor changes in lake level rise. Thus, this assumption indicates that the role of lake evaporation for short period of time alone can't make significant change in lake level rise.

7.1.2 Application Two

Future lake level using the sequence of 1987-2005 hydro-climatic data sequences with 2001-2005 conditions occurring first.

The purpose of this application is to calculate the response of lake to annually varying evaporation values. The assumption is based on the value of lake evaporation which shows a decreasing trend from 2001. Thus, the values from 2001-2005 will be used instead of the original values from 1987-2000 and vice versa. Other components (runoff and rainfall on the lake) will remain the same as they actually occurred.

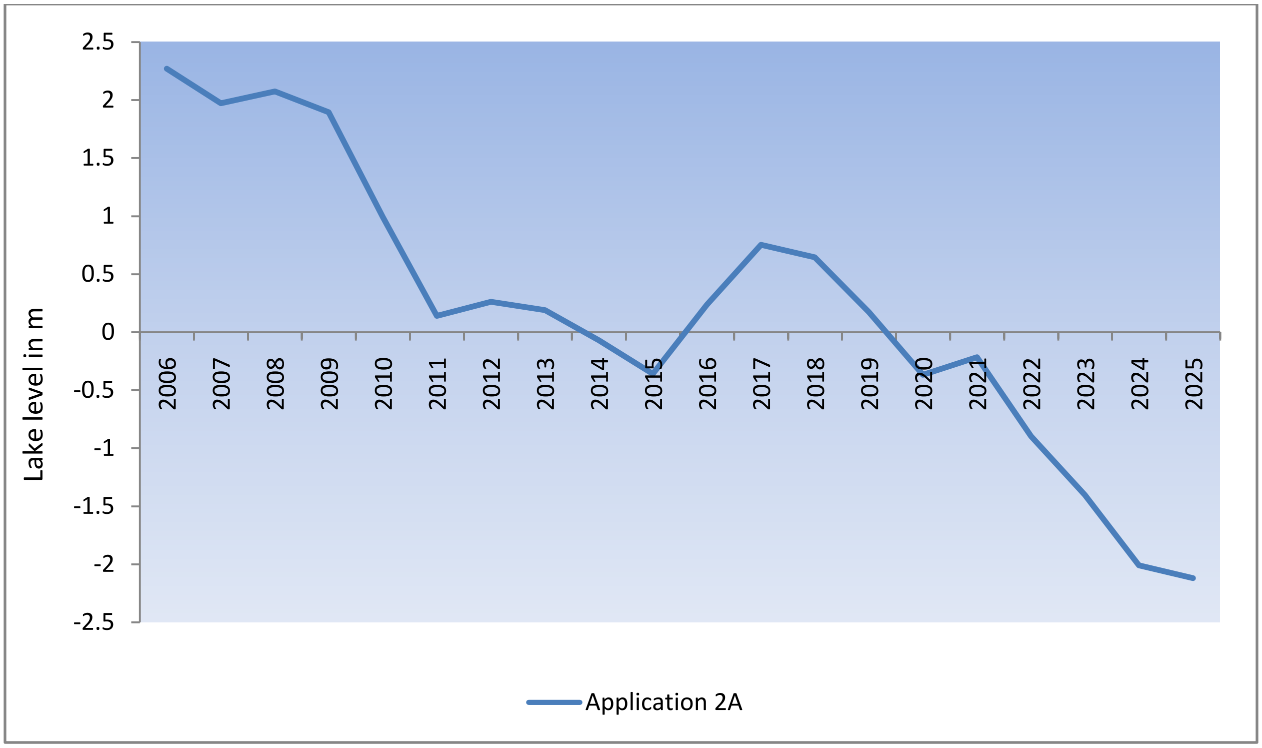


Figure 7 2 Forecasted lake levels based on Application Two

Result: The result of this assumption contradicts with application 1B, which tells us that the role of evaporation during the lake level fluctuation is significant if the decreasing trend of lake evaporation continues for a long time. This can be checked by looking at the figure 7.2, which shows a decreasing trend which is the cumulative effect of evaporation. But it shows an increase during 2016 and 2017 is assumed to have high value of runoff and precipitation.

7.1.3 Application Three

Future lake level using the 1987-2005 average hydro-climatic conditions in each year of the forecast is going to occur.

Application 3A: In this application the total runoff and rain fall on the surface of the lake are set equal to their base period average in each year of the forecast (the average total runoff, gauged and unguaged, and precipitation on the lake are 750.39mcm,690.9 and 979.76mcm, respectively from 1987-2005).

Application 3B: In this application the evaporation is set equal to the base period average in each year of the forecast (the average lake evaporation is 2009.28 mcm from 1987-2005).

Application 3C: In this application every components of the water balance are set equal to their base period average**.**

Plotting the results of 3A, 3B and 3C together gives a good picture how the lake level respond to average inflow and outflow component.

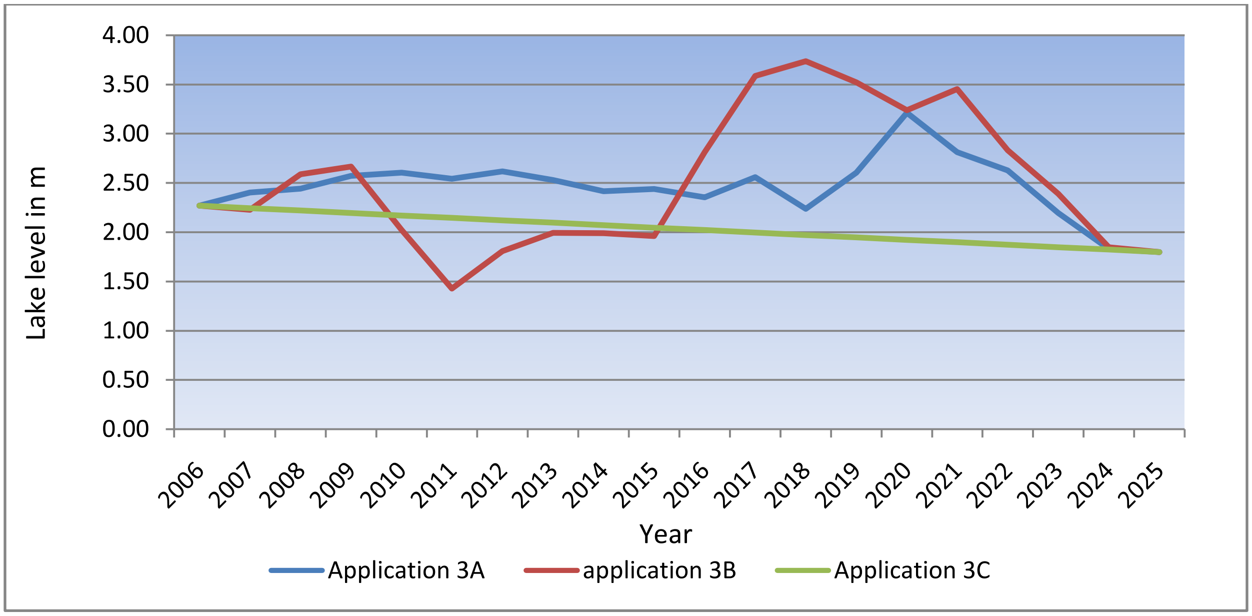


Figure 7 3 Forecasted lake levels using Application Three

Results: In application 3A, the level shows an increase of 0.94m up to 2020 in which it reaches 3.21m (figure 7.3). After 2020 the level decreases and reaches 1.8m by the end of 2025. This is because of lake evaporation increment in those years which causes the level to decrease. Based on the assumptions made in application 3B, the level shows a decreasing trend from 2006 to 2012 then starts to increase until 2019 and starts again declining. This situation is entirely the result of dry and wet periods and then dry periods respectively. The result of application 3C is purely deterministic, i.e. for the given input (as determined by the assumption) the lake will respond as calculated, if the average of all components continues in the future the lake level will have a decreasing trend.

7.1.4 Application Four

Future lake level using the sequence of 1987-2005 hydro-climatic data with the 1987-2005 average precipitation rates of the catchments for years that have low rain fall relatively to the others.

The purpose of the application is to show the response of the lake to annually varying precipitation rate in the catchment. The assumption here is that the low rain fall years (1987, 1990, 1991, 1993, 1994, 2000, 2002, 2003 and 2004) will be replaced by their base period average. Thus, the amount of precipitation on the surface of the lake and runoff from unguaged catchment will be changed since these components are calculated based on the amount of precipitation in the catchment.

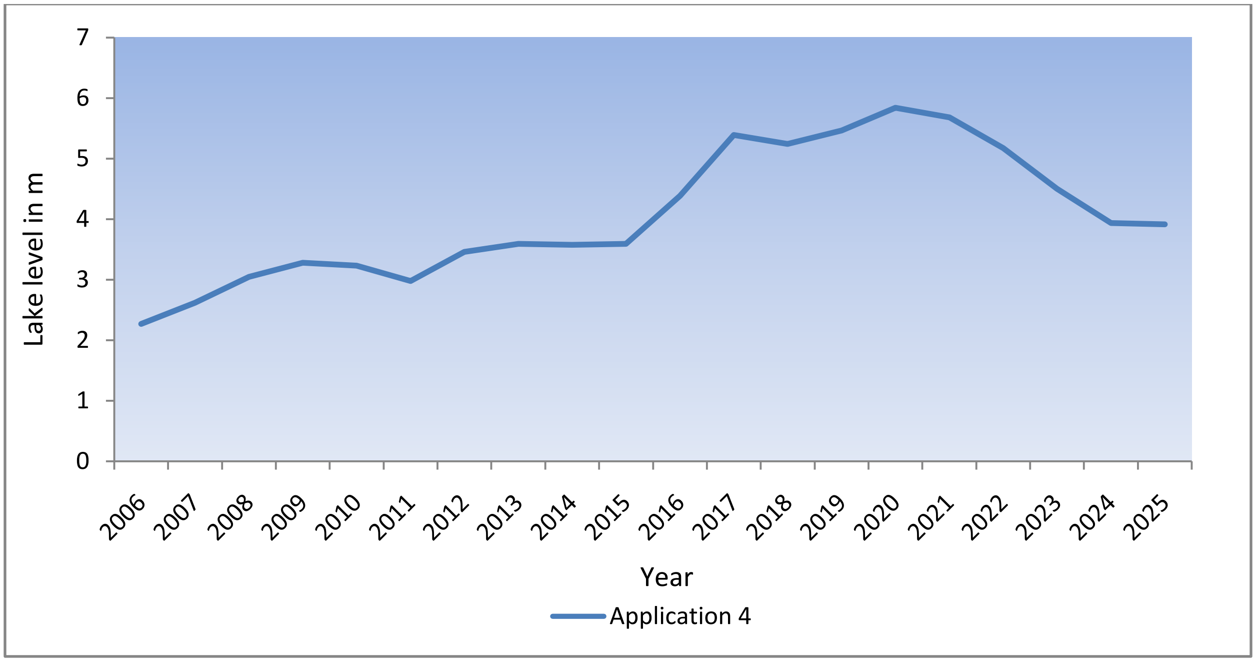


Figure 7 4 Forecasted lake levels using Application Four

Result: The output of application 4 shows lake level increment to 3.92m by 2025 since the change in the runoff and precipitation is high (figure 7.4).The effect of rainfall on the lake level increases because of large lake water surface area which is in average 1084.86km^2 and the perimeter of the lake which has a direct contact with unguaged catchment.

7.1.5 Application Five

Future lake level using the sequence of 1987-2005 hydro-climatic data with the increase of runoff by 50 % of the present amount.

The purpose of the application is to show the response of the lake to annually varying runoff in the catchment. The assumption here is that the runoff amount increases by 50% of the present due to land use/land cover change by deforestation and traditional farm surrounding of the lake. This condition decreases the infiltration capacity of the soil and the infiltrated water to the soil by plant roots and facilitates runoff to the lake.

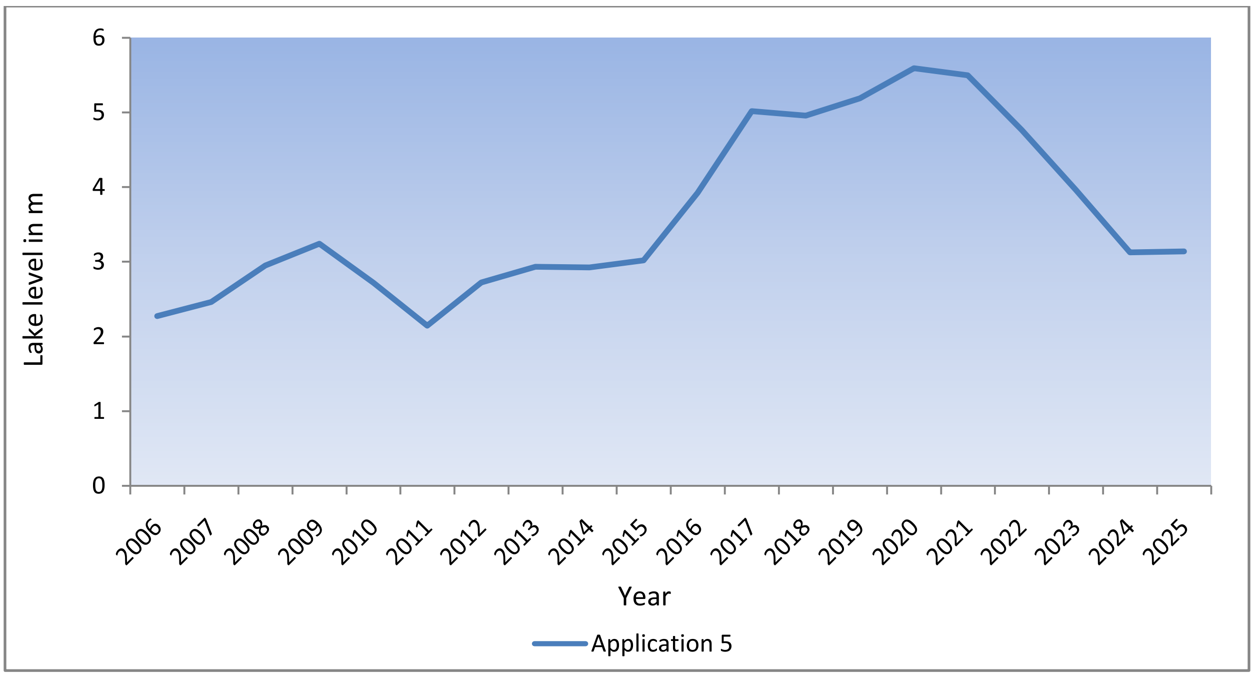


Figure 7 5 Forecasted lake levels using Application Five

Results: In application 5, the level shows an increase up to 2020 and reaches 5.59m (figure 7.5). After 2020 the level decreases and reaches 3.14m by the end of 2025, which is also high lake level compared to the past historic records of Abaya Lake level record.

7.2 Discussion on Model Results

Forecasting water level of a lake requires a scenario approach for taking a long wide view that controls futures with fundamentally different environmental assumptions. The assumptions made previous are useful in understanding the effect of different elements that affect the lake level. The results of the assumption are discussed below by taking R^2 as measure of good prediction of the regression model.

7.2.1 Discussion on Application 1

Application 1A: The result of the analysis revealed that replacing the runoff and rainfall amount on the lake surface of the initial sequences by the average wet years causes the lake level to reach 3.47 meter by 2025. One method for evaluating the result of the assumption is to compare the association of the observed and iterated rainfall amount on the lake surface with their corresponding lake level.

As shown in the figure 6.6, the iterated rainfall amount on the lake surface and projected lake level correlate positively with $R^2 = 0.37$. This is almost close to 0.4 which is in the same rang with the correlation value, $R^2 = 0.52$ made between the measured rainfall amount from the three stations in the catchment and observed lake level for the period of 1987-1994. The correlation can also be checked by regressing the observed lake level plus the forecasted lake level and also the simulated plus the forecasted lake level. The result shows the observed and simulated correlate positively with $R^2 = 0.57$ and $R^2=0.6$, respectively (figure 7.7 and figure 7.8).

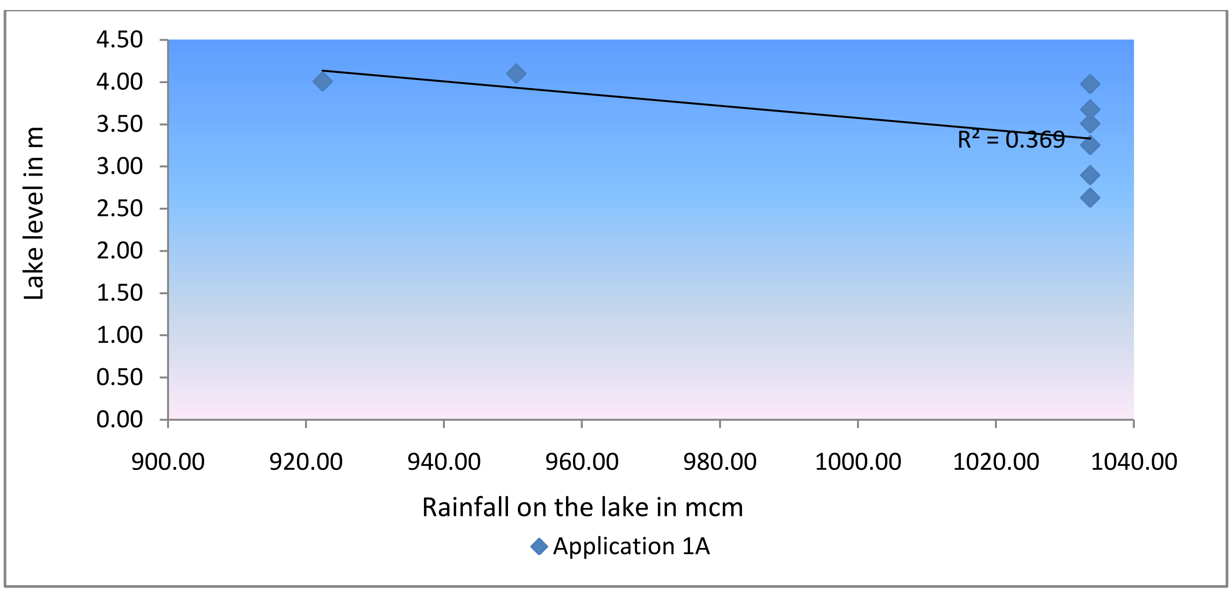


Figure 7 6 Correlation between the iterated Rainfall on the lake surface with forecasted Lake level (from 2007-2014)

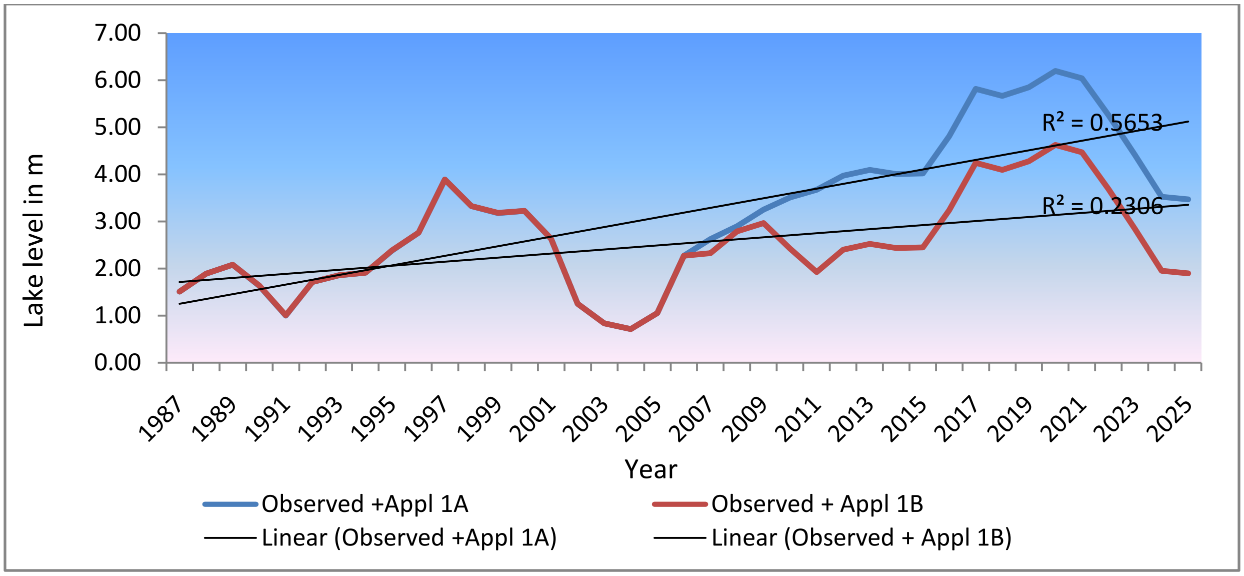


Figure 7 7 Observed and Forecasted lake level based on Application 1A and 1B

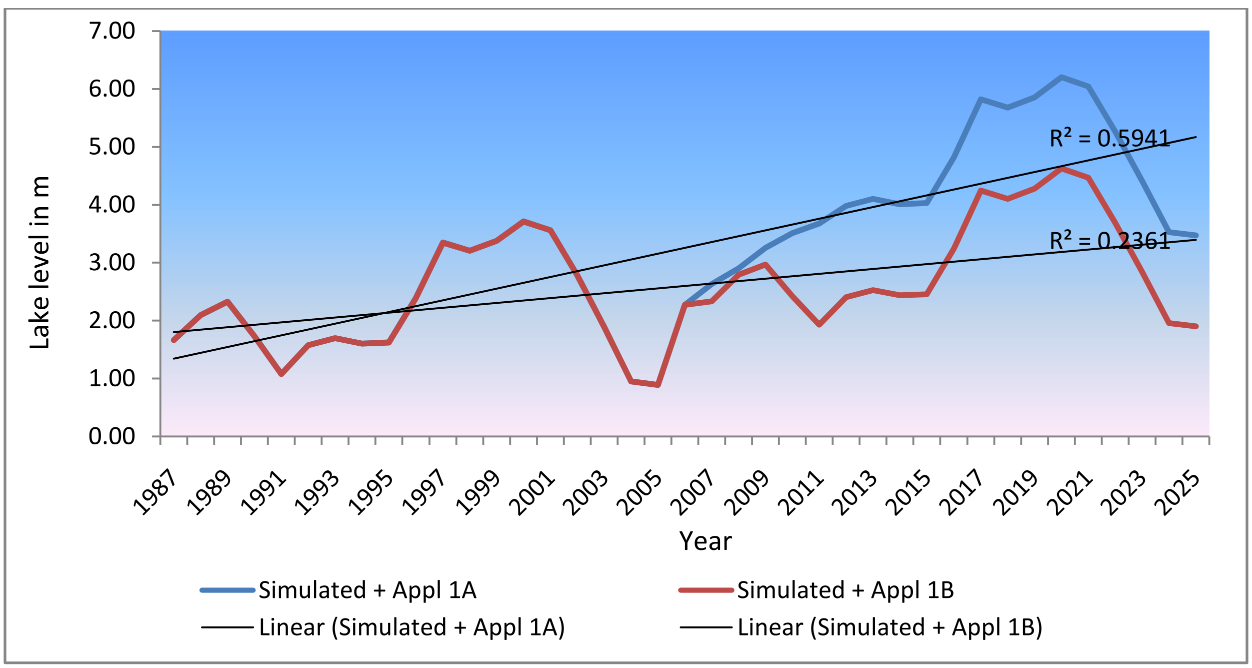


Figure 7 8 Simulated and Forecasted lake level based on Application 1A and 1B

Application 1B: The result of assumption 1B shows minor change in the forecasted lake level. As shown in the figure 7.7 and 7.8, the observed and forecasted lake level shows similar trend with R square 0.23 and 0.24 respectively. Generally the assumptions show the effect of rainfall and evaporation in lake level fluctuation. Thus application 1A could be taken as a good predicator of lake level.

7.2.2 Discussion on Application 2

The result of this application is different with that of application 1B because a decrease in evaporation rate is applied for a long period of time. The reason is to see the effect in the long term lake level when the evaporation values are continued until 2025. As shown in the figure by the end of 2025 the level will differ by1.28 m with those levels calculated based on application two and a 5.14 m with those levels calculated with the observed evaporation values (figure 7.9). This means if the current evaporation trend continues the level will reach -3.40 m by the end of 2025.

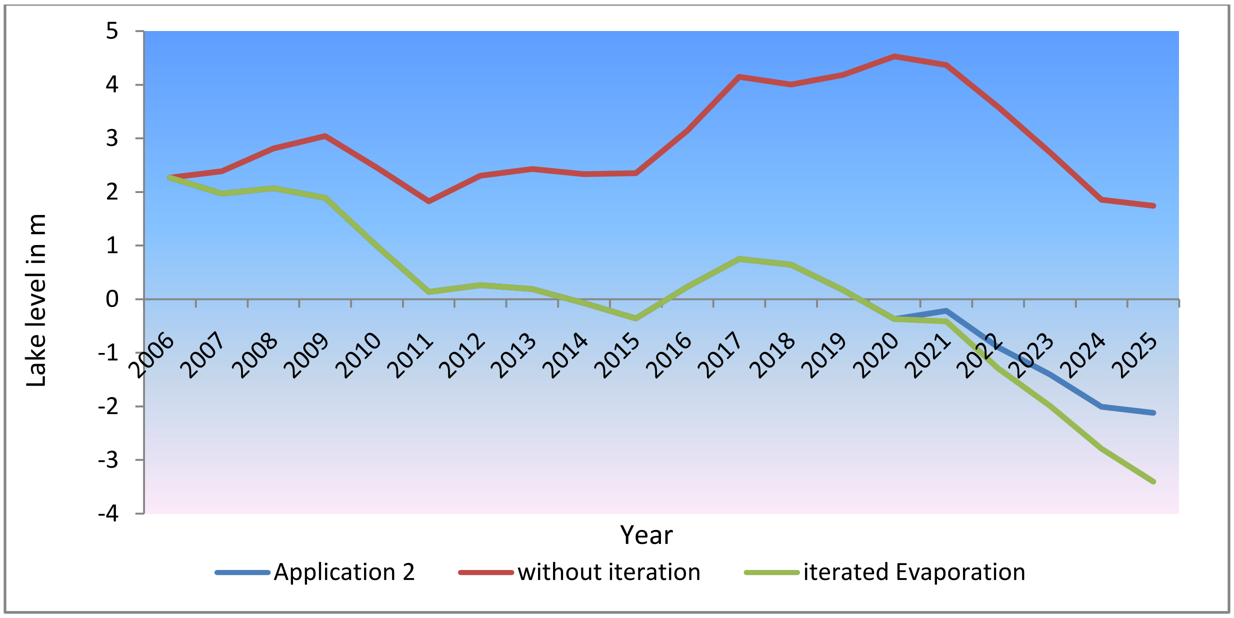


Figure 7 9 Forecasted lake levels based on Application 2 with different evaporation values

7.2.3 Discussion on Application 3

Plotting, application 3A, 3B and 3C, together with the observed and simulated lake levels give a good picture how this correlate with the projected one. However, the R^2 value is very small which means the correlation is very poor with the past lake level record. But they correlate almost the same (figure 7.10 and 7.11). This application answers what would happen if the average values of the components are projected into the future.

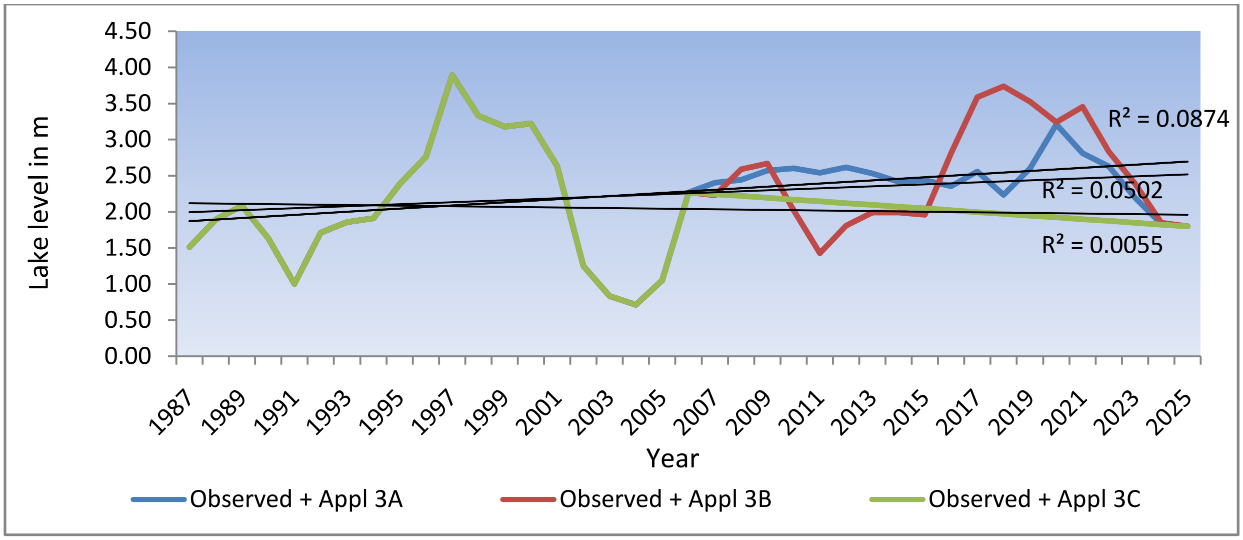


Figure 7 10 Observed and forecasted lake level based on Application 3

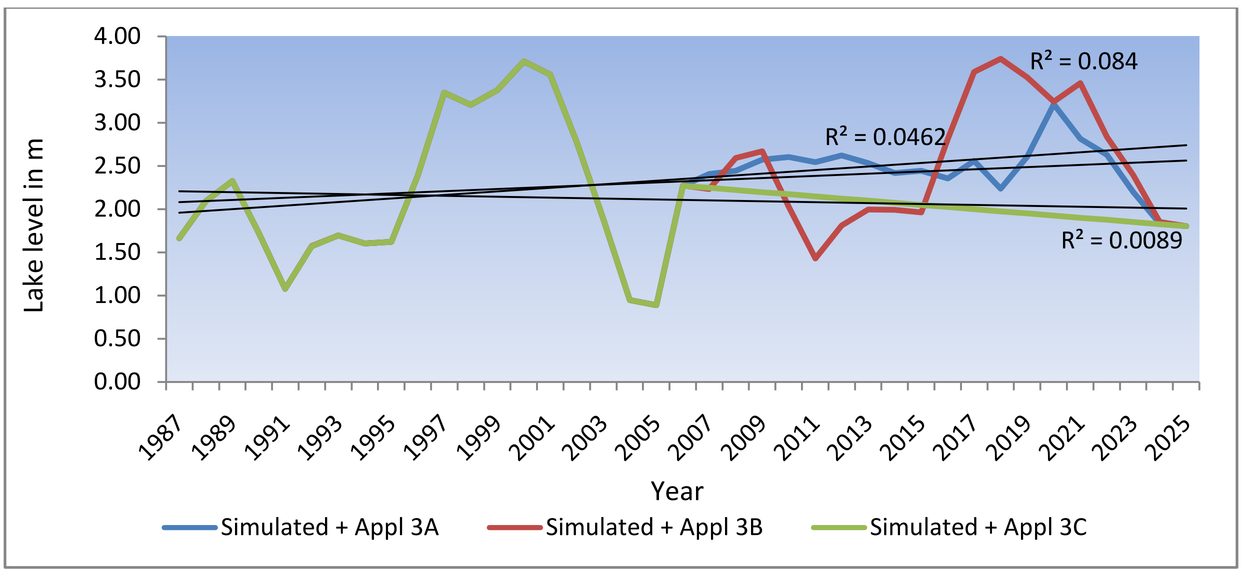


Figure 7 11 Simulated and forecasted lake level based on Application 3

7.2.4 Discussion on Application 4

A comparison has been made to see the effect of precipitation on lake level rise between the forecasted lake level of this application with forecasted level produced from original precipitation rate, i.e. without replacing the low rain fall years. As shown in the figure below by the end of 2025 the level calculated without the low rainfall period will differ by2.18 m with those levels calculated based on application four. Furthermore, the result shows a lake level difference of 1.34 m on average with those that are not replaced the corresponding low rain fall years (figure 7.12). This means annually a 0.12 m rise can happen if the annual rain fall of the catchment is around its base period average.

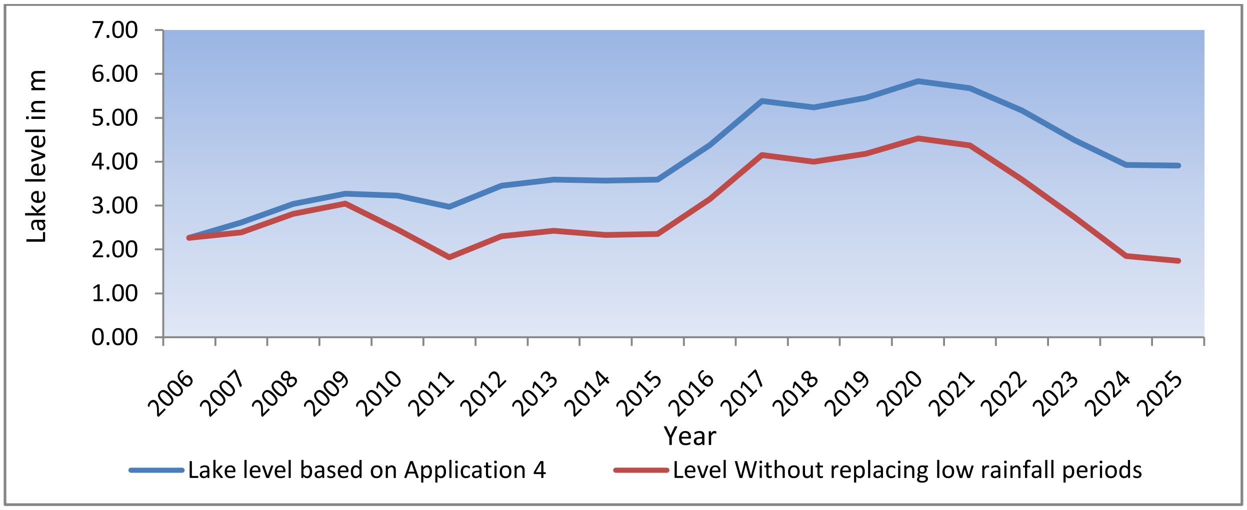


Figure 7 12 Forecasted lake levels based on Application 4 with level forecasted without replacing low rainfall periods

7.2.5 Discussion on Application 5

A comparison has been made here in application 5 also to see the effect of runoff amount in the catchment on lake level rise between the forecasted lake level of this application with forecasted level produced from original unguaged runoff amount, i.e. keeping the original unguaged runoff amount as it is. As shown in the figure below by the end of 2025 the level calculated without changing the runoff amount will differ by 1.4 m with the level calculated based on application five. This means an increase of the base period runoff amount in the area could make the lake level to increase more than the present lake level.

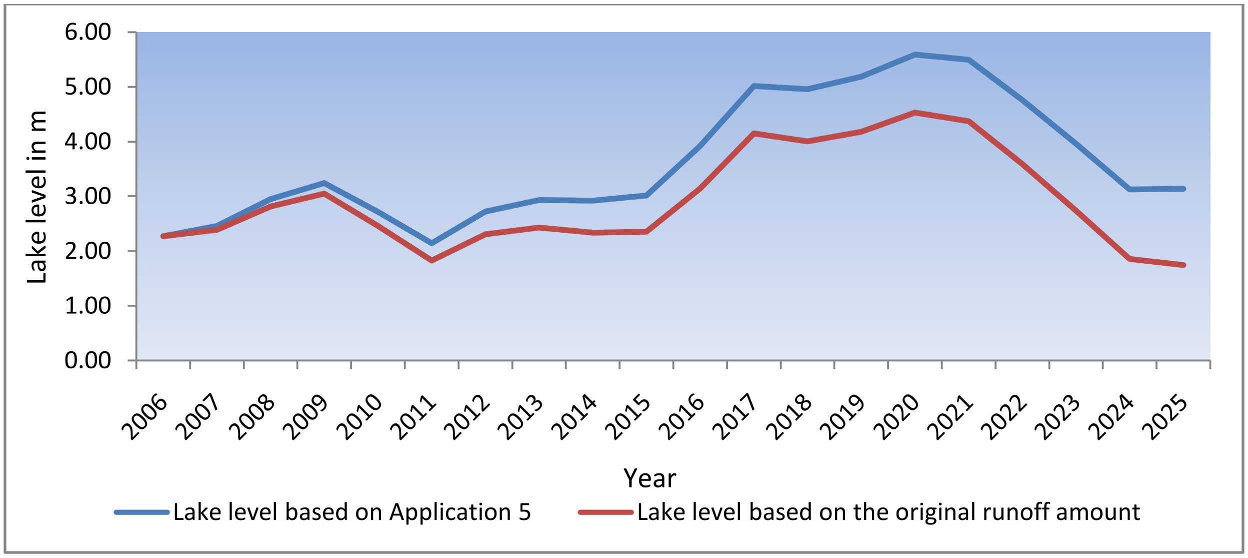


Figure 7 13 Forecasted lake levels based on Application 5 with level forecasted without changing the runoff amount

CHAPTER EIGHT

Conclusion and Recommendation

8.1 Conclusion

1. A lake level forecast model for Lake Abaya over the period 1987-2005, based on systematic analysis of annual changes of the water balance components (runoff, precipitation, evaporation and storage changes) shows the average yearly inflow from river discharge, unguaged runoff and precipitation are 750, 691 and 980 mcm, respectively, while the average outflow from evaporation is 2009mcm.
2. The lake level forecast model was used to ascertain the effect of the water balance components in the historic and future lake levels based on the sequence of 1987-2005 hydro-climatic conditions with different applications and assumptions, which are used to test the values of the observed hydro-climatic parameters in the future lake levels. Amongst the forecasted lake level models (plotted in figure 8.1), model application 1A, 2, 4 and 5 are considered to better predict Abaya lake level fluctuation, because the assumptions considered in the applications are from past hydro-climatic conditions observed and recorded as evidence and by inquiring questioners from the community living in this area. From the models we can conclude the following:

- Projections made based on application 1A, 4 and 5 forecast lake level increases in the near future (2015-2022). Even though future climatic conditions are not deterministic in nature, one could say the prediction is highly likely but with the current increase in runoff volume from effective catchment combined with land use and land cover changes confirms that the lake level rise could happen in the future.
- If the evaporation trend continues as it is in application 2 the lake level will reach -3.40 meter by the end of 2025.

3. The results of the lake level forecast model can be interpreted to indicate what amounts of inflow (given the calculated amounts of outflow) to the Lake are needed in order to maintain lake levels within a given elevation range.
4. The lake level fluctuation is mostly due to climatic factors and also man-made processes. Among these precipitation and evaporation causes the major changes but there is also

deforestation and agricultural expansion in the catchment, which could increase the evaporation rate and runoff amount in the area.

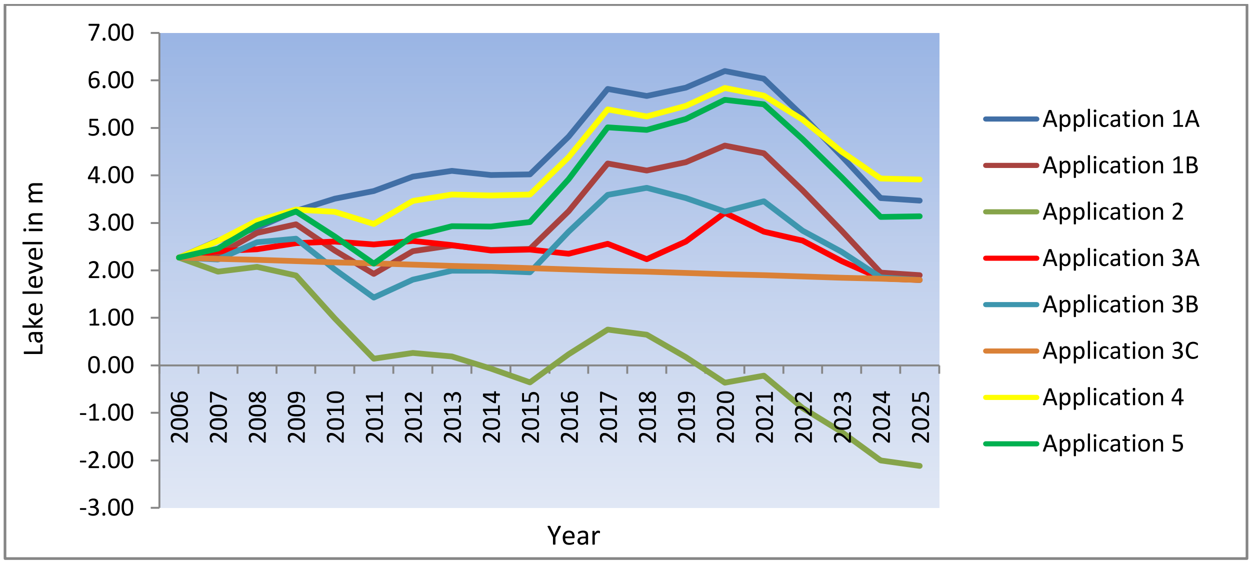


Figure 8 1 Forecasted lake levels based on the Five Applications.

5. The lake level fluctuation shows correlation with some specific climatic events (e.g. Lake Abaya had high lake level in the year 1997/1998 as a response to the exceptionally high precipitation of the El Ninõ event of 1997/1998). Furthermore, the interannual variations of lake level and highland precipitation correlate as, the rift lakes get substantial inflow in the form of river discharge from the adjacent highlands.

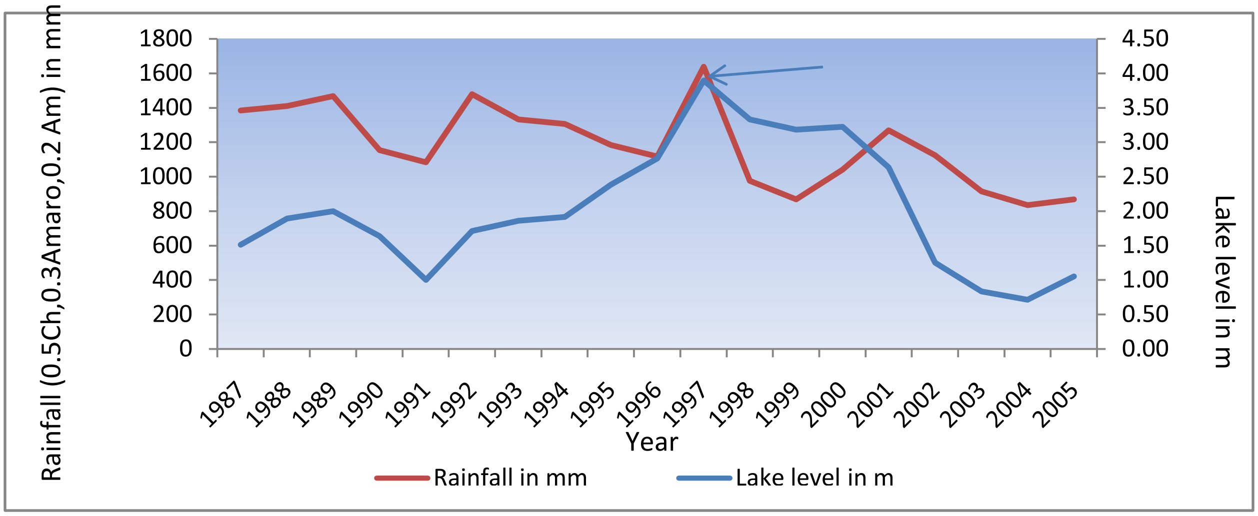


Figure 8 2 Comparison of Abaya lake level and precipitation amount in the catchment.

8.2 Recommendation

Utilization of water in Ethiopia has proceeded without basic understanding of the complexity of lacustrine environment. Unwise utilization of water becomes a major problem in water resources management in the Ethiopian Rift and adjacent highlands (Ayenew, 2007). Therefore, mitigation measures to protect the degrading lacustrine environment are the most vital thing to prevent Lake Abaya from threats. These mitigation measures can be achieved by:

- "Wise use" of the lake water and its tributary rivers for the expanding agricultural activities in the catchment.
- Controlling the deforestation in the area.
- Implementing integrated urbanization plan that could prevent the lake environment from dangerous human activities.
- Supporting the "Nech Sare "National Park by finance and personnel, which is working on the protection of the forest and aforestation program in the park.
- Developing monitoring stations and scientific information about the lake and the catchment.

Computing the water balance components and modeling the water balance of a lake is very important thing in understanding the natural and man-made processes. But the ability to model the water balance of the lake requires a full and accurate data base of the components. Additional data also would substantially improve the accuracy of the component estimates and allow a refinement of component variables into more realistic parameters. For the improvement of the model for future use the following recommendations are found to be appropriate:

- Install/upgrade lake stage recorders on opposite shores and river discharge measuring stations on the major rivers within the catchment and aware the recorders how this data are important to reduce measurement error on scientific studies.
- Develop more detailed bathymetric maps of the lake to improve stage/area/volume relationships
- Monitor evaporation from the pan, pan water temperature, wind speed, relative humidity to improve estimation of pan coefficients and to determine the spatial variation of evaporation

- Monitor and establish new precipitation stations in Bilate because Bilate River is the major tributary of Lake Abaya and this data can be used to understand the precipitation amount and lake level fluctuation relation and also on the islands to improve the accuracy of the data that is going to be used for precipitation amount on the lake.
- Drill and monitor wells around the lake for the purpose of estimating groundwater storage change and getting a visible relationship with lake level changes.
- Inform the authorized organizations about the type of data they are providing to users are not as good as they need to be, for research activity and the development activity the country is trying to achieve.

8.3 Future Studies

Detail study on hydro-climatic and lake sediments could give more accurate information about the climate change in the past.

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Appendix

Appendix I Raw Meteorological Data from NMSA

Appendix I A Mean Monthly Rainfall at Arba-Minch Station (mm)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1987	13.2	10.1	65.3	-	163.2	-	-	6.8	52.6	92.4	44.9	17.4
1988	38.7	29.5	32.7	217.9	134.1	68.1	97.5	98.7	116.8	167.4	38.4	24.3
1989	39.8	82.8	49.9	163.0	114.5	48.5	64.3	71.0	50.1	161.5	86.0	94.7
1990	24.6	107.3	64.5	106.6	104.0	25.5	30.6	52.5	28.6	27.6	25.0	25.4
1991	72.4	45.3	79.3	52.0	130.3	85.1	30.7	80.8	81.6	49.1	35.7	14.6
1992	12.8	18.1	27.1	164.8	140.2	131.9	32.0	42.8	132.2	172.7	59.6	29.3
1993	178.0	120.8	34.4	94.8	198.2	52.6	3.1	24.6	31.4	117.1	18.2	1.2
1994	0.3	-	36.4	183.9	164.6	59.9	72.1	82.9	29.7	70.3	59.6	18.8
1995	0.4	27.1	54.4	256.8	140.4	85.3	21.6	17.6	84.7	109.1	53.6	43.5
1996	0.4	-	52.9	283.3	123.9	90.4	23.4	20.1	100.6	117.4	58.3	29.0
1997	16.0	0.4	18.0	240.8	172.5	27.7	61.0	27.8	49.1	-	273.1	152.8
1998	66.6	90.1	24.3	-	96.5	41.2	30.4	28.2	42.0	148.5	58.5	0.8
1999	17.1	0.7	-	-	-	44.2	79.2	23.9	68.9	203.6	9.7	44.5
2000	1.3	0.0	19.3	92.4	236.1	40.7	61.7	39.1	70.4	185.8	56.0	65.8
2001	68.7	86.6	56.0	175.3	236.3	52.9	40.7	45.1	108.2	123.9	85.1	5.5
2002	42.9	22.4	93.9	112.4	56.5	52.2	55.1	12.4	87.9	87.7	18.1	167.2
2003	13.5	11.3	61.6	201.1	192.1	98.1	30.2	105.5	39.6	89.4	25.8	14.2
2004	41.7	31.2	17.5	164.8	-	34.8	22.2	-	81.6	55.6	143.0	32.0
2005	-	1.4	67.1	311.1	221.4	16.2	28.8	22.3	77.4	120.6	33.4	4.3
2006	12.8	83.9	137.4	115.4	129.7	126.2	24.4	75.2	42.8	158.7	103.3	118.6
2007	63.4	35.5	16.9	129.4	193.4	107.2	111.8	99.3	246.4	76.3	61.5	0.0

Appendix I B Average Annual Rainfall at the Surrounding Stations (mm)

Year	Arba-minch	Merab abaya	Amaro Kello	Bilate	Chencha
1987	795.6	701.9	1354.5	730.2	1735.2
1988	1064.1	528.4	1499.7	976.8	1650.9
1989	1026.1	633.3	1167.0	809.5	1819.5
1990	622.2	515.1	967.3	699.9	1482.3
1991	756.9	524.2	767.6	681.0	1412.1
1992	963.5	656.8	1019.6	982.1	1491.5
1993	874.4	811.0	577.8	796.2	1527.2
1994	848.0	659.6	749.4	821.6	1562.8
1995	894.5	707.8	984.6	617.2	1374.9
1996	948.0	816.6	1096.7	1085.8	1206.6
1997	1152.5	1217.2	1162.7	914.0	2112.8
1998	889.2	952.8	806.2	631.6	1134.1
1999	898.9	561.1	787.9	462.3	909.4
2000	868.6	779.4	769.6	616.4	1269.6
2001	1084.3	800.7	816.2	536.9	1615.3
2002	808.7	613.1	835.1	520.6	1423.0
2003	882.4	789.2	879.8	847.7	944.2
2004	807.7	826.3	913.7	801.3	758.3
2005	931.6	852.8	974.4	824.5	676.4
Mean	**900.9**	**734.1**	**954.2**	**755.6**	**1374.0**

Appendix I C Monthly Maximum Air Temperature at Arba-Minch Station (°C)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1987	31.8	32.6	32.5	30.6	28.7	28.05	26.25	30	31.1	30.4	30.6	32.3
1988	32.4	33.5	34.2	30.8	27.8	27.7	26	26.7	28.2	28.8	30.2	30.8
1989	30.3	31.8	32.3	29.2	28.8	28.4	26.5	29	29.1	29	29.8	29.8
1990	30.7	31.8	31.2	29.1	29	28.6	28.3	28.4	31	31.4	31.7	31.3
1991	31.8	32.7	32.6	31.8	30.2	28.4	26	28.5	29.8	31.2	31.8	31.7
1992	32.6	33.5	34.8	32	29.2	28.2	27.8	27.6	29.6	28.2	30.4	31.3
1993	30.2	29.8	32.7	31.8	29	27.2	28.1	29.6	30.55	29.75	30.6	31.55
1994	33.4	34.4	34.3	31.4	27.8	27.4	26.8	27.6	31.5	31.3	30.8	31.8
1995	33.2	33.6	32.4	29.9	28.9	28.3	27.5	28.9	29.2	29.6	30.6	32.3
1996	32.3	33.9	32.9	30.8	28.3	25.6	26.4	28.5	28.6	30.4	31.2	31.7
1997	32.8	33.9	35.1	29.1	28.1	29.2	27.8	29.8	32.6	29.9	29	29.3
1998	30.6	31.8	33	32.1	29.5	29.3	28	28.2	31.2	28.4	30.4	31.9
1999	33.1	35.3	32	31.4	30.5	30.1	27.3	29.9	31.2	28.4	30.6	31.1
2000	33.1	34.5	35.1	32.7	28.1	27.6	28	28.3	30.7	29.2	29.9	30.6
2001	31.2	32.4	32.2	30	28.6	27.6	27.9	28.3	30.2	30	30	31.7
2002	31.7	34	32.6	31.5	29.2	29.1	29.6	29.8	31.6	30.4	32.3	30.9
2003	31	34.4	34	31.1	28.1	27.2	27.5	27.6	30.6	31.1	32	31.4
2004	32.2	32.7	33.5	30.3	27.65	29	29.4	29.6	30.7	29.9	29.8	31.4
2005	32.6	34.5	33.1	31.6	27.2	27.2	27.3	29.3	29.3	29.8	30.7	31.9

Appendix I D Monthly Minimum Air Temperature at Arba-Minch Station (^oC)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1987	16.8	17.9	19.6	18.2	18.4	18.15	17.85	18.7	19	18.7	17.5	17
1988	19.3	20	20.5	19.6	19.2	18.6	18.1	17.8	17.9	17.6	15.1	14.5
1989	15.9	16.5	18.7	18.2	17.4	17.7	17.6	17.8	18.2	17.1	16.6	17.6
1990	15.5	18.5	18.3	18.5	18.5	18.5	18.3	18.9	18.3	17.7	17.7	16.8
1991	18.2	18.8	19.6	18.3	18.8	19.1	18	18.9	17.9	17.4	17	16
1992	17.6	20	20.9	19.2	18.4	18.4	18	18.5	17.7	17.1	14.8	16.2
1993	16.6	16	15	18.6	17.9	17.9	18.3	17.3	18.2	16.85	15.6	15.73
1994	15.2	17.4	19.3	18.2	18.5	18.1	17.8	18.1	18.7	16.6	16.4	15.25
1995	14.8	16.7	17.6	18.5	18	17.9	17.7	18.4	17.7	17.2	16.1	16.2
1996	17.1	18	17.6	18.2	17.8	17.6	16.8	17.4	17.2	16.2	15	14.3
1997	16.9	14.6	20	17.9	17.4	16.6	17.6	17.8	17.7	17.4	16.6	16.1
1998	16.2	16.6	16.8	18	18.3	17.2	18	17.6	18	17.6	14.7	11.7
1999	14.1	14.6	17.3	16.8	17.3	18	16.9	17.7	17.5	16.7	13.7	14.1
2000	13.8	15.5	18.2	18.6	17.3	17.6	17.5	17.6	17.2	17.4	15.1	14.3
2001	15.7	14.9	17.2	17.5	17.3	17.1	17.7	17.3	17.2	17.4	14.9	14.4
2002	16.1	15.5	17.9	17.6	18.6	18	18.2	18.2	17.4	17.4	15.9	17.1
2003	15.5	16.7	18.2	17.9	17.3	17.7	17.4	17.6	18.1	17	16.65	17.05
2004	15.9	16.1	17.5	18.7	17.7	18.5	18.2	18.7	18.4	17.2	17.4	17
2005	16.3	17.6	19.4	18.8	18.1	17.7	18.2	18.9	17.8	17.7	15.5	12.8

Year	Annual RH at 6:00	Annual RH at 12:00	Annual RH at 18:00
1987	829	509	476
1988	943	604	576
1989	807	656	571
1990	937	584	560
1991	979	588	560
1992	976	616	584
1993	690	451	436
1994	897	544	565
1995	691	498	495
1996	1043	503	500
1997	858	554	511
1998	1081	629	613
1999	962	548	531
2000	-	-	
2001	1054	608	616
2002	992	567	540
2003	983	579	566
2004	945	558	538
2005	947	562	561

Appendix I F Average Wind Speed at Arba-Minch Station (m/s)

Year	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
1987	1.3	1.2	1.2	-	1.3	-	-	-	-	-	-	-
1988	-	-	-	-	-	-	-	-	-	-	-	-
1989	-	-	-	-	1.1	1.3	1	1.4	1.1	0.8	0.6	0.6
1990	0.6	0.7	0.8	0.7	0.9	1.2	1.1	1	1.1	0.8	0.8	0.8
1991	0.8	0.9	0.8	0.9	0.9	1.1	0.9	1.1	0.9	0.7	0.7	0.7
1992	0.8	0.9	1.1	1.1	1	1.1	0.9	1	0.9	0.6	0.4	0.5
1993	0.5	0.4	0.4	0.6	0.5	0.6	0.7	0.7	0.7	0.5	0.4	0.4
1994	0.4	0.6	0.6	0.6	0.7	-	-	-	0.7	0.6	-	0.5
1995	0.5	0.6	0.6	0.5	0.5	0.7	0.6	0.7	0.6	0.5	0.4	0.6
1996	0.7	0.8	0.9	0.8	0.6	0.5	0.5	0.6	0.5	0.4	0.5	-
1997	0.7	0.7	0.8	0.6	0.6	0.7	0.6	0.7	0.7	0.3	0.2	0.4
1998	0.1	0.2	1.4	0.3	0.3	0.4	0.4	0.4	0.5	0.2	0.9	0.3
1999	0.4	0.4	0.4	0.4	0.6	0.7	0.5	0.7	0.6	0.4	0.3	0.3
2000	0.4	0.5	0.7	0.7	0.6	0.6	0.5	0.6	0.7	0.4	0.4	0.4
2001	0.4	0.4	0.5	0.5	0.6	0.5	0.6	0.5	0.5	0.4	0.4	0.5
2002	0.5	0.6	0.5	0.6	0.7	0.9	1	0.9	0.8	0.5	0.5	0.6
2003	0.5	0.8	0.7	0.5	0.6	0.7	0.8	0.8	0.8	0.6	0.6	0.8
2004	0.7	0.7	0.8	0.7	1	1.2	1.1	1	1	0.8	0.7	0.7
2005	0.93	0.7	0.8	0.8	0.62	0.84	0.85	1.01	0.76	0.58	0.51	0.54

Appendix I G Average Sun-Shin Hours at Arba-Minch Station

Year	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
1987	9.6	8.3	7.2	7.5	6.8		7	6.7	7.8	5	9.2	9.4
1988	8.9	8.8	9.1	6.8	9.7	7.4		6.1	6.7	7.8	10	9.6
1989	8.6	9.4	7.9	6.7	8.8	6.8	4.2	7.6	6.8	8	9.3	7.9
1990	9.4	7	8	8	7.4	7.6	5.1	4.7	7.5	9.1	9.1	9.5
1991	8.9	8.4	8.2	8.5	8	6.7	3.2	5.2	7.7	8.4	8.9	8.5
1992			9.3	8.1	9.3	7.4	5.7	4.1	6.9	6.9	9.4	9.1
1993	7.9	7.6	10.1	7.2	7.4	6.5	4.6	6.4	7.3	7.9	9.6	9.9
1994	10.1	9.6	8.2	7.9	7.9	5.5	3.8	5	7.4	8.5	8.5	10.1
1995	10.1	8.9	7.1	7.2	8.8	7.8	4.8	4.8	7	7.7	8.9	9.6
1996	8.9	9.6	8.4	7.9	8.1	4.2	4.2	6.1	7	8.8	9	10
1997	9	10.5	8.6	5.6	8.9	7.3	5.1	7.1	8.5	7.3		7.7
1998	7.4	7.1	8.2	8.2	7.1	5.9	3.2	3.1	5.8	4.7	9	6.9
1999	8.1	8.6	6.3	6.8		3.7	6.7	7.2	6.2	9.2		
2000	10.4	10.1	9.7	8.3	7.8	5.5	5.5	5	6.9	6.4	9.2	9.6
2001	8.6	9.8	6.8	8.5					7.6	7		
2002			7.2	8.2	7.4	5.7	6.1		7.6	7.8	9.4	7.5
2003		10.2	9	6.9	7.8	4.4	6.7	4.3	7.8	8.6	8.9	9.5
2004	8.2	8.81	7.5	6.2	8.1	5.2	6.6	6.1	6.8	8	8.6	9
2005	9.5	9.7	8.3	8.1	6.8	4.4	6.5	6.2	6.1	7.3	9.2	10.2

Appendix I H Class A Pan Evaporation at Arba-Minch Station (mm)

Year	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
1985	208.3	191.4	186.8	139.4	131.6	137.6	137.9	154.8	160	200.5	202.9	237.3
1986	265.1	238	255	155.5	165.1	97.4	162.8	194.2	164.4	167.8	157	141
1987	250.7	241.3	82.9	141.4	129.9	156.09	208.7	290.8	263.8	181.3	196.2	239
1988	259.9	301.1	314.8	184.5	142.8	156.9	121.4	119.6	121.5	121.7	163	217.4
1989	255.3	271.2	198.85	163	136.35	156.9	165.05	205.2	192.65	151.5	179.6	228.2
1990	257.6	286.15	256.83	173.7	139.58	156.9	143.23	162.4	157.08	136.6	171.3	222.8
1991	256.5	278.68	227.84	168.3	137.96	156.9	154.14	183.8	174.86	144.05	175.45	225.5
1992	257	282.41	242.33	171	138.77	156.9	148.68	173.1	165.97	140.33	173.38	224.15
1993	182.4	253.08	303.29	137.4	110.12	162.94	146.34	184.56	216.76	117.36	162.52	149.16
1994	175.9	241.45	292.53	140	111.06	161.63	145.91	180.89	216.58	115.69	161.26	159.18
1995	188.9	264.7	314.05	134.9	109.18	164.25	146.78	188.23	216.95	119.03	163.79	139.15
1996	162.9	218.2	271	145	112.95	159	145.05	173.55	216.2	112.35	158.73	179.2
1997	215	311.2	357.1	124.8	105.4	169.5	148.5	202.9	217.7	125.7	168.85	99.1
1998	110.7	125.2	184.9	165.2	120.5	148.5	141.6	144.2	214.7	99	148.6	259.3
1999	272.1	306.3	199.3	122.3	157.2	217.3	148.5	209.8	212.7	127.2	189.1	224.25
2000	342.2	334.7	372.5	253.8	148	167	178.7	179	178.4	111.1	133.3	166.2
2001	155.2	197.7	211.4	129.7	129	116.9	148.2	132.7	128.4	133.3	139.8	199.5
2002	188	316.5	231.4	156	129.69	156.09	154.94	182.63	186.75	137.35	165.06	197.16
2003	221.5	255.88	248.27	156	129.69	156.09	154.94	182.63	186.75	137.35	165.06	197.16
2004	198.6	193.6	231.4	114.3	151	179.4	179.1	173.3	167.3	165.4	119	174.7
2005	228.1	264.7	231.2	199.5	87.6	143.7	173.3	216.9	162.3	139.8	172.3	260.9

Appendix-II Summary of Raw Hydrological Data from MoW

Appendix-II A Monthly Flow of Bilate River at Bilate Tena (Mcm)

Year	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1987	5.4	2.8	7.1	41.2	55.6	127.3	122.4	50.9	42.4	99.3	36.3	-
1988	-	-	-	-	-	-	-	-	-	-	-	3.6
1989	2.2	24.1	-	-	-	-	-	-	-	-	-	-
1990	-	-	-	-	-	-	-	-	45.0	40.4	17.6	-
1991	8.1	12.6	38.1	16.2	43.7	50.0	44.2	50.3	49.9	16.7	18.9	14.2
1992	49.9	32.4	31.5	27.1	27.2	50.7	45.2	85.4	148.5	148.6	-	17.6
1993	-	-	-	-	-	-	-	-	-	-	-	-
1994	-	-	-	-	-	-	-	-	-	-	-	-
1995	-	-	-	-	-	-	-	-	-	-	-	-
1996	-	-	-	-	-	-	-	-	-	-	-	-
1997	-	-	-	-	-	-	-	-	-	-	-	-
1998	-	-	-	-	26.2	18.3	29.6	122.2	62.7	58.8	17.8	-
1999	6.3	4.1	10.6	7.4	10.7	16.2	38.2	39.7	57.4	122.5	25.2	8.2
2000	5.6	4.1	3.8	13.5	35.9	14.6	21.0	40.3	35.9	-	-	8.0
2001	-	6.8	23.5	14.2	26.4	26.3	-	-	-	-	-	-
2002	5.9	9.9	33.5	20.3	15.7	14.8	16.6	40.3	30.6	14.6	9.1	15.0
2003	18.1	12.0	12.7	30.4	16.0	21.3	23.2	34.3	46.2	-	-	-
2004	-	-	8.9	26.6	18.5	19.7	63.5	68.3	47.2	50.7	9.3	7.6
2005	9.0	7.3	13.8	39.1	68.9	20.9	51.6	65.4	50.4	33.3	17.8	8.3
2006	5.3	8.5	28.3	35.2	26.9	27.7	42.6	148.9	60.1	27.0	14.1	14.9

Appendix-II B Monthly Flow of Gelana River at the bridge near Tore (Mcm)

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1987	0.48	0.38	0.49	0.44	1.36	1.88	1.14	1.36	2.08	2.13	0.91	-
1988	0.46	0.38	0.36	0.53	0.57	0.71	3.27	6.59	3.95	5.32	1.84	0.57
1989	0.59	0.45	0.47	0.81	0.57	0.60	1.96	1.81	2.88	2.44	1.08	0.84
1990	0.53	0.68	0.81	0.95	0.63	0.66	0.85	2.18	2.62	7.23	5.07	0.81
1991	0.91	0.65	0.66	1.42	2.49	3.86	2.15	1.21	4.35	6.99	3.24	1.89
1992	0.34	0.36	0.31	1.83	8.32	7.12	3.35	2.04	4.40	14.30	4.78	0.86
1993	1.24	1.40	0.68	0.73	11.80	12.81	4.14	1.94	2.15	5.25	3.78	0.90
1994	1.08	0.47	0.32	2.12	14.17	8.14	6.13	7.42	3.20	3.68	3.86	1.45
1995	0.69	0.58	0.65	3.53	10.97	5.50	4.84	3.26	5.67	13.69	6.14	1.55
1996	1.48	0.77	1.32	6.83	14.16	14.60	7.66	7.28	14.77	12.27	6.25	2.24
1997	1.71	1.00	0.80	3.06	10.03	3.22	3.64	2.24	1.52	6.32	11.14	2.87
1998	6.16	3.64	2.39	3.68	11.61	9.10	4.40	4.20	2.87	8.04	5.93	6.20
1999	1.29	0.79	1.62	2.85	7.80	-	-	-	-	-	-	2.01
2000	0.87	0.58	0.53	0.91	7.12	2.78	1.98	3.03	2.81	-	-	-
2001	-	-	-	-	11.64	8.84	3.15	3.15	8.39	15.78	10.04	-
2002	1.73	0.87	1.22	1.99	7.18	4.82	2.10	1.76	1.80	-	-	3.02
2003	1.77	0.74	0.44	1.41	6.75	6.60	2.25	4.29	2.69	-	-	-
2004	-	-	-	-	-	3.54	1.52	1.53	2.97	6.59	5.88	2.72
2005	1.17	0.68	0.76	0.82	11.34	8.89	2.99	2.14	6.52	11.37	8.59	2.14

Appendix-II C Monthly Flow of Gidabo River at Aposto (Mcm)

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1987	2.1	1.8	3.0	4.8	15.1	10.5	5.0	4.4	6.9	12.6	-	-
1988	-	-	-	-	-	-	-	-	-	-	-	-
1989	2.9	2.3	2.2	5.3	4.5	6.2	6.3	4.0	11.8	13.0	4.9	4.7
1990	2.7	3.8	6.7	10.5	11.1	6.7	6.9	6.6	7.2	7.5	4.1	3.6
1991	3.6	3.5	4.2	4.9	5.1	3.6	5.3	4.8	10.6	6.0	2.3	1.9
1992	1.2	1.6	1.3	7.0	7.1	5.4	7.8	22.8	19.1	27.0	11.0	5.0
1993	3.3	4.3	2.6	5.8	16.8	16.4	8.4	6.0	9.6	16.8	7.8	3.0
1994	2.0	1.4	1.9	3.3	10.5	7.3	16.3	18.1	12.8	7.0	5.7	2.7
1995	1.8	1.6	2.0	9.6	9.7	4.5	5.3	7.1	16.9	13.1	4.1	3.3
1996	3.2	1.9	6.5	11.6	15.4	-	14.7	17.1	17.1	17.1	4.7	3.0
1997	2.4	1.4	1.6	5.9	8.8	6.4	10.4	12.2	8.6	18.6	15.6	6.5
1998	2.2	0.7	1.0	3.6	10.4	5.1	8.0	20.0	11.1	24.9	6.7	-
1999	-	-	2.1	2.0	4.3	2.7	2.8	3.6	4.4	7.6	3.3	3.2
2000	1.3	1.1	1.1	2.0	5.7	3.3	2.9	8.5	7.5	17.5	-	2.0
2001	2.3	1.7	2.0	2.8	5.8	8.4	4.1	9.1	9.9	10.2	4.1	2.6
2002	2.1	1.5	2.1	2.9	4.1	5.3	2.8	3.8	4.9	3.6	2.2	2.3
2003	1.9	1.4	1.8	4.0	3.1	2.4	3.1	6.8	4.8	-	-	-
2004	-	-	-	-	-	3.2	2.9	4.2	6.2	8.2	2.6	2.2
2005	1.8	1.3	1.8	2.8	10.9	6.8	5.7	6.2	8.8	6.5	3.7	2.1
2006	1.7	1.6	2.8	4.6	9.6	5.3	11.3	14.4	8.9	11.4	6.4	4.7

Appendix-II D Monthly Flow of Hare River (Mcm)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1987	3.2	2.3	4.6	10.6	12.8	7.8	4.9	6.6	5.1	7.4	4.8	3.4
1988	3.2	3.2	2.6	5.4	8.3	6.4	12.3	11.4	9.6	10.5	4.6	3.2
1989	2.7	4.0	3.9	7.2	8.5	5.5	8.0	6.4	8.8	9.9	3.5	5.3
1990	3.3	4.6	5.5	5.7	3.5	2.3	2.4	4.9	2.6	2.5	1.4	0.9
1991	1.1	0.6	1.4	1.3	5.5	3.3	4.6	2.5	4.3	2.3	1.4	1.0
1992	0.7	0.7	0.6	2.6	2.8	3.9	3.7	3.8	6.1	11.0	5.6	3.0
1993	6.0	7.8	3.4	5.2	11.7	6.7	1.4	0.3	13.1	12.1	8.3	6.6
1994	1.0	0.7	0.9	1.6	6.5	4.7	6.3	8.9	4.6	4.6	4.0	2.7
1995	2.2	1.9	2.5	5.2	5.5	5.0	5.2	5.9	-	-	3.8	2.6
1996	1.9	1.5	2.3	4.9	15.0	9.6	6.5	7.9	7.7	5.2	3.5	3.0
1997	2.7	2.0	2.2	4.2	5.0	4.2	8.6	7.1	4.4	11.2	7.4	4.0
1998	4.0	2.0	2.1	1.6	2.9	2.3	3.4	3.8	3.1	6.2	3.4	2.0
1999	1.5	1.1	1.4	1.7	2.0	2.0	2.9	3.8	3.5	6.8	3.1	2.2
2000	1.6	1.3	1.1	2.4	5.8	3.2	4.7	6.1	5.0	7.1	4.8	2.8
2001	1.9	1.4	2.8	5.1	6.0	5.2	3.4	6.7	4.6	8.2	7.2	5.2
2002	4.7	3.9	5.0	6.7	6.7	5.7	6.2	7.8	6.1	6.5	5.5	5.9
2003	7.4	4.9	5.2	6.5	7.8	7.8	9.3	11.2	7.3	-	-	-
2004	-	-	-	-	-	4.5	4.7	6.5	7.6	8.7	6.2	5.4
2005	4.7	3.7	5.0	5.7	10.9	5.7	7.0	6.5	7.3	6.7	5.9	4.4
2006	3.8	3.4	5.7	8.4	7.2	5.8	5.0	7.8	5.6	7.3	5.6	4.4

Appendix-II E Abaya Lake level (m.a.m.s.l)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1987	1.5	1.4	1.3	1.3	1.4	1.8	1.8	1.7	1.6	1.6	1.6	1.6
1988	1.4	1.3	1.2	1.1	1.2	1.1	1.1	1.5	1.8	2.1	2.2	2.2
1989	2.0	2.0	1.9	1.8	1.9	1.8	1.8	1.7	1.8	1.9	2.1	2.1
1990	2.0	2.0	2.0	2.1	2.1	2.1	2.1	2.2	2.2	2.1	2.1	2.0
1991	1.9	1.8	1.8	1.7	1.7	1.6	1.6	1.6	1.5	1.5	1.5	1.3
1992	1.3	1.2	1.1	1.0	1.0	0.9	0.6	0.7	0.8	1.0	1.2	1.2
1993	1.1	1.3	1.5	1.6	1.7	1.8	1.8	1.9	1.9	1.9	2.0	2.0
1994	2.0	1.7	1.5	1.5	1.6	1.7	1.7	1.9	2.2	2.2	2.2	2.1
1995	2.0	1.9	1.8	1.8	1.9	1.9	1.9	1.9	1.9	2.0	2.0	2.0
1996	1.9	1.8	1.6	1.6	1.6	2.1	2.5	2.8	3.1	3.3	3.2	3.2
1997	3.0	2.9	2.7	2.7	2.7	2.5	2.7	2.7	2.6	2.5	2.7	3.4
1998	3.9	4.0	4.1	4.0	3.9	3.8	3.6	3.6	3.7	3.9	4.1	4.0
1999	3.9	3.7	3.4	3.3	3.4	3.2	3.1	3.1	3.1	3.1	3.3	3.2
2000	3.1	3.0	3.2	3.3	3.3	3.2	3.2	3.2	3.2	3.2	3.2	3.2
2001	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.1	3.1	3.3	3.5	3.5
2002	3.3	3.2	3.1	3.1	3.1	3.1	2.9	2.5	2.2	1.9	1.6	1.5
2003	1.4	1.3	1.1	1.1	1.2	1.2	1.2	1.2	1.4	1.4	1.3	1.2
2004	1.2	1.1	1.0	0.9	0.9	0.7	0.5	0.7	0.7	0.8	0.8	0.8
2005	0.7	0.6	0.4	0.3	0.5	0.8	0.6	0.7	0.8	1.0	1.1	1.0
2006	0.9	0.7	0.6	0.5	0.7	0.8	0.9	1.0	1.2	1.4	1.7	2.2
2007	2.3	2.2	2.1	2.0	2.1	2.3	2.4	2.7	3.1	3.3	3.4	3.3
2008	3.1	3.0	2.8	2.6	2.4	2.3	2.2	2.2	2.3	2.5	2.8	2.9

Appendix-III Questioner

Appendix-III A. Questionnaire to be Filled by the Local Society to Assess Abaya Lake Level Fluctuation

Date: ______________________

Questionnaire No.:____________

Locality: ____________________

1. Personal Information
   Sex _______ Age ______
   Literacy Level:
   - Unable to read and write ________
   - Read and write _______
   - Some primary or secondary education ______
   - Above secondary education level _________
2. Working condition (you may have more than one answer)
   - Farmer ☐
   - Fisher ☐
   - Company worker ☐
   - Other (please specify) _____________
3. For how many years do you live in this area? ________
4. Do you know the existing condition of the lake in terms of size compared with the previous years?
   Yes ☐ No ☐
5. If your answer is yes for question no. 4, is the size of Lake Abaya
   Expanding? ☐ Shrinking? ☐ No Fluctuation? ☐
6. If you answer question no. 5, what do you think the cause for expansion or shrinkage of the lake in your opinion?
   ____
   ____
   ____
7. What was the land cover of this area in the previous years?
   ☐ All covered by forest (please specify the year) ______________
   ☐ Partially covered by forest (please specify the year) __________
   ☐ It was degraded land (please specify the year) ______________
   Other land cover (please specify the year) ________________
8. What was the land use of the area in the previous years?
   Agriculture ☐ Grazing Land ☐
9. Is there any water abstruction from the lake?
   Yes ☐ No ☐

10. If your answer is yes for question no. 9, please specify for what purpose is the water abstracted?

    ____

    ____

11. Is there any precipitation difference temporally and spatially from the existing condition compared with the previous years?

    Yes ☐ No ☐

12. If your answer for question no. 11 is yes, please specify the difference/shift?

    ____

    ____

    ____

Thank You!

CERTIFICATION

I, the undersigned, certify that I have read and hereby recommend for acceptance by the Addis Ababa University a Thesis entitled: **Climate Change Impact on Lake Abaya Water Level**, in fulfillment of the requirements of the degree of Masters of Earth Sciences in Geo-Environmental Systems Analysis. And the thesis has been submitted for examination with my approval as university advisor.

Asfawossen Asrat (PhD) ____________________________

Date: --------------------

DECLARATION

I, the undersigned, declare that this thesis is my original work and has not been presented for a degree on any other university and all sources of materials used for the thesis have duly acknowledged.

Azeb Belete

signature__________________________

Place and date of submission: School of Graduate Studies, Addis Ababa University, October, 2009