ADDIS ABABA UNIVERSITY

INSTITUTE OF TECHNOLOGY

SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

"ASSESSMENT OF WATER BALANCE AND LAKE LEVEL FLUCTUATION, LAKE ABAYA, ETHIOPIA"

THESIS SUBMITTED TO THE SCHOOL OF GRADUATE STUDIES IN PARTIAL FULFILLMENT OF THE REQUIREMENT FOR THE DEGREE OF MASTERS OF SCIENCE IN HYDRAULIC ENGINEERING

BY: HEYRU ABDO

ADVISOR: Dr. YENESEW MENGISTE

OCT, 2019

ADDIS ABABA, ETHIOPIA

ABSTRACT

Lake Abaya is a quasi-endorheic lake which is located 6º 26’ N Latitude and 37º 53’ E Longitude with surface area of 1095 km^2. It drains with five main rivers (Bilate, Gidabo, Gelana, Hamessa and Harie) and many other intermittent tributaries and covers a total catchment area of 14638.83km^2.

The objective of this study is to assess the water balance and lake level fluctuation of Lake Abaya. The lake level is gauged up to the year 2013, but the inflow from the four out of five tributaries is gauged up to the year 2005. As a result stream flow is predicted by using HEC-HMS to the year 2013. Inflow from the un-gauged catchment is estimated using area ratio method. Areal rainfall for the sub-basin and lake surface is estimated using Thiessen polygon method. Evaporation from the lake surface is estimated using Cropwat 8 software, Penman’s method and Pan Evaporation; pan evaporation is taken for the analysis. Water abstraction from tributary rivers and the lake for irrigation is determined by Cropwat 8 software.

After analysis of all components of water balance for the lake, a water balance model has developed using continuity equation. Summing up of all the components, lake surface rainfall 18.87 %, inflow 32.35 % (Gauged 19.18 %, un-gauged 13.16 %), lake surface evaporation 46.08 % and abstraction 2.71 % contributes for the lake water balance trend and no observed out flow from the lake. The lake level has a relation with climatic and human factors; rainfall and temperature of the area shows a slow increment and that of wind speed, sunshine hours and evaporation shows slow decrement. When comparing the land cover of 1996 to the land cover of 2006 that the area under intensive cultivation, grassland, urban area and riparian has increased by 84.59, 32.64, 1.08 and 0.11 km^2 respectively and that of shrub-land, unidentified area, marshland, forest, moderately cultivated and exposed surface has decreased by 69.20, 35.90, 8.00, 4.92, 0.40, 0.01 km^2 respectively and that of water body and woodland has not changed yet. These all is not in contradict with the increment of the lake level rather it agrees. To irrigate a total land of 9906 ha with common crops of Banana, Tobacco, Cotton, Vegetables and diversified crops 140.98 MCM of water is abstracted from the lake and all the tributary rivers. Two irrigation scenarios are conducted, scenario 1 with irrigation expansion of 10610 ha on the tributaries needs additional water of 84.10 MCM per year and reduces the lake level by 60 mm, and scenario 2 irrigation expansion of 30,831 ha, it requires additional water of 528.45 MCM per year and this will reduce the lake level by 420 mm. The simulation of lake level has been conducted by excel spread sheet model at monthly time stapes.

The causes for the increment of lake level are (1) the nature of the lake (which is quasi-endorheic) (2) Climatic factors (the increment of rain fall, decreasing of evaporation, etc.) (3) Anthropogenic factors (deforestation, intensive cultivation, etc.)

ACKNOWLEDGEMENT

I am grateful to express my sincere thanks to my advisor Dr. Yenesew Mengiste, from School of Civil and Environmental Engineering, Addis Ababa University, who devoted her time to guide and assist me in the process of the thesis work.

I would like to thank all staffs in the Ministry of Water Irrigation and electricity especially to those in the Department of Hydrology and National Metrological Service Agency for providing me with related data and materials.

I would also thank the staff members of Addis Ababa University Civil Engineering Department and my classmates for their material and moral support.

TABLE OF CONTENTS

TABLE OF CONTENTS

LIST OF FIGURE

LIST OF TABLE

CHAPTER ONE

1. INTRODUCTION

1.1. Background

Water is the prime requirements for the existence of life and thus it has been man's endeavor to utilize the available water resources. The total amount water available to the earth is finite and conserved. Although the total volume of water in the global hydrologic cycle remains constant, the distribution of this water is continually changing on continents, in regions and local catchments (K. Subramanya).

The World's total water resources are estimated at 1.36×10^8 M ha-m. Of these global water resources, about 97.2% is salt water mainly in oceans, and only 2.8% is available as fresh water at any time on the planet earth. Out of this 2.8% of fresh water, about 2.2% is available as surface water and 0.6% as ground water. Even out of this 2.2% of surface water, 2.15% is fresh water in glaciers and icecaps and only of the order of 0.01% is available in Lakes and Streams, the remaining 0.04% being in other forms. Out of 0.6% of stored ground water, only about 0.25% can be economically extracted with the present drilling technology (the remaining being at greater depths) (H.m. Raghunath, 2006).

The Encyclopedia of Lakes defines lakes as follows: "Lakes are formed when depressions are filled with water. Lakes are used for many purposes such as for domestic and industrial water supplies, flood control, hydroelectricity generation, irrigation, recreation, navigation, fishing, atmospheric cooling, leaching of saline water intrusion, dilution of polluted water and provisional services to coastal ecosystems. Lakes have a key function in storing excess water from periods of high rainfall to provide water during dry spells. The water stored in lakes play a vital role in the economic development and many services that contribute to the well-being of communities up to kilometers downstream (even across administrative borders) and in close proximity to lakes (Zhung Duan, 2014).

There are about nine million lakes in the world, and they cover a total surface area of around 1600,000 km^2. The total water storage in these lakes is about 230,000 km^3 (Zhung Duan, 2014). Africa is endowed with hundreds of lakes; both natural and artificial. According to the world lake database, there are 677 lakes in Africa. Although Lakes are a source of livelihoods for many African communities, it is important to note that Africa's lakes are undergoing significant changes due to a combination of human activities and climate change, with potentially serious implications for people's livelihoods and aquatic biodiversity (UNEP, 2006).

In the Southern part of Rift Valley Region of Ethiopia there are two natural Lakes, namely Abaya and Chamo Lakes. These Lakes are important shallow Lakes and among others importance, to inhabit a number of aquatic animals, as a source of fish and to locally modify the climate of the area. Although, not much is known about the two lakes, yet there are evidences that they are heavily influenced by human activities. They are endangered Lakes unless proper precautionary measures are undertaken through studying the impact of various activities (Seleshi B., 2006). In order to investigate the available water resources quantity in the Lakes as well as impacts and influences of natural and man-induced factors a water balance assessment will be conducted. In this study a water balance assessment of Lake Abaya will be conducted.

1.2. Statement of the Problem

Because of its shallow depth, lake level of Lake Abaya reacts quite sensitive to changes of water and sediment input and, thus, is an ideal subject-matter to analyze complex pattern of natural and human impacts on lake level changes. These problems require proper hydro-meteorological studies, assessing water resources potential of the lake and the extent to which it is to be utilized, so that there will be no serious consequences on the rift valley environment (for future sustainable utilization of the water resources of the lake).

Despite its importance on the lives of millions of people in the region the water balance of Lake Abaya and its catchment is poorly understood, like many other Ethiopian rift valley lakes.

1.3. Research Questions

i. What are the dominant components of the hydrological cycle controlling the hydrological behavior of Lake Abaya and its catchment at large?
ii. Does the Lake volume increase or decrease? If it is so can it be explained in terms of climatic or anthropogenic factors?
iii. What is the futurity of the Lake Abaya with the development of the human activities?

1.4. Objective of the Study

1.4.1. Main Objective

The main objective of the study is to quantify the water balance components of Lake Abaya and asses if the lake level fluctuation could attribute to natural or anthropogenic factors:

1.4.2. Specific Objectives

- Estimate the various water balance components of the lake, such us precipitation, surface runoff, evaporation, net ground water flow and abstraction.
- Assess the relation of lake levels with catchment factors (climate, land use, etc.)

- Assess the water abstraction and future scenario

1.5. Significance of the Study

The Lake and its tributaries Rivers water would potentially be used in the past and planned to be used in the future extensively for agricultural, transportation, fishery purposes and the like. For utilizing the lake water or any water from the catchments (springs, wells or rivers) requires base line survey so that there will be no grave consequences on the fragile rift valley environment and will lead:-

- To restrict the over utilization of the lake to the optimum level of the lake capacity of the base line survey.
- To protect the environmental degradation by restricting the over utilization of Lake/tributary Water for irrigation, domestic needs and decreasing sedimentation by changing the land use practice in the catchment area etc.
- To improve sustainability of the water resources of the lake by utilizing proper irrigation practice.
- To understand the combined effect of climatic, land and lake use change during the past year and in the future.

1.6. Organization of the Thesis

This thesis contains seven chapters organized as follows: Chapter one gives a general introduction to the study with emphasis on global water budget, relevance and objective of the study. In chapter two different literatures have been reviewed. Chapter three gives a brief description of the study area and materials and methodology. Chapter four deals with hydro meteorological data analysis and results of water balance components from observed data such as lake areal rainfall, open water evaporation, inflow from gauged and un-gauged catchments. In chapter five discussions about lake water balance simulation is presented. Chapter six deals with climatic and anthropogenic factors which affect the lake level of Lake Abaya. Chapter seven ends with conclusion and recommendations.

CHAPTER TWO

2. LITERATURE REVIEW

2.1. Lake Ecosystem

Lake ecosystems are vital resources for aquatic wildlife and human needs, and any alteration of their environmental quality and water renewal rates has wide-ranging ecological and societal implications. The increasing accumulation of greenhouse gases in the atmosphere as a result of human activities has begun to affect the structure, functioning, and stability of lake ecosystems throughout the world, and much greater impacts are likely in the future (W. F. Vincent, 2009).

2.1.1. Effects of Climate Change on Lakes

Lakes have always been subject to the impacts of climate change, and natural climate variations in the past have been one of the main reasons that lakes are ephemeral (short-lived) features of the landscape. Most of today's lakes are the result of climate amelioration (improve) and the retreat of the Pleistocene glaciers some 10 000 years ago, and so most present-day lakes are relatively young (W. F. Vincent, 2009).

Some of the immediate impacts of climate change on high-latitude lakes include loss of perennial ice cover, increasing duration of open water conditions, increasing water temperatures, stronger water column stratification and shifts in water balance, in some cases leading to complete drainage or drying up of the water bodies(W. F. Vincent, 2009).

Changes in air temperature and precipitation have direct effects on the physical, chemical, and biological characteristics of lakes, and they also operate on lakes indirectly via modifications in the surrounding watershed, e.g., through shifts in hydrological flow pathways, landscape weathering, catchment erosion, soil properties, and vegetation(W. F. Vincent, 2009).

2.1.2. Effects of Topography and Elevation on Lakes

The daily lake surface water temperatures (LSWTs) were governed primarily by altitude and topographic shading represented by lake-specific total duration of direct solar radiation (TDDSR). Lakes at higher elevation are likely to be cooler than lakes at lower elevations. Topographic shading appeared to play an important role in the development and duration of ice-cover. Lakes with low TDDSR retained ice-cover longer than well insulated ones (Milan et al., 2013).

2.1.3. Effects of Land Use Land Cover on Lakes

Land use and land cover change leads to changes in water distribution in hydrological processes such as evaporation, runoff, lateral flow, infiltration, and groundwater response of the area (Pengcheng et al., 2018) subsequently affects water resources. A study have reported the drying of Lake Cheleleka as a result of long term land use changes and subsequent reduction stream flow related to deforestation and water extraction for irrigation from streams feeding the lake, sediment deposition in the lake (Yemane Gebreegziabher, 2004). A similar case has been found in the eastern Ethiopian highlands where Lake Haramaya reportedly disappeared, due to water abstraction, deforestation and clearing of land for farming on its watershed, resulting in increased siltation of the lake that decreased the lake’s volume and surface albedo, which in turn increased the rate of evaporation (Tamiru et al., 2007).

2.2. Related Studies

A number of related studies have been carried out in country and in the outside world. These studies have been focusing on assessment of water balance, using water balance models to approximate the effects of climatic or anthropogenic factors, on spring catchment discharge, estimating water balance components of lakes and reservoirs using various open access satellite databases, which directly or indirectly related to the current study. Some of the works are briefly described as follows:

(Seleshi, 2006), in the work entitled “Investigation of physical and bathymetric characteristics of Lakes Abaya and Chamo, Ethiopia, and their management implications”, physical characteristics such as depth, water resources capacity, hydrology, water balances, and impacts of water use and degradation of their watersheds: and the bathymetric survey(utilizing a combination of global positioning system (GPS) and echo sounder) were conducted. To calculate the morphometric characteristics, the background lake map was digitized, and the surveyed primary data were developed as digital values. The digital values were interpolated, generating grids of the elevation surface. The elevation area and elevation volume curves (capacity curves) of the two lakes were developed from the digital values, describing the water resources capacity of the lake water basins.

(Mulugeta, 2015), in the title “Characterization of Water Level Variability of the Main Ethiopian Rift Valley Lakes”, the water level fluctuations of eight Ethiopian Rift Valley lakes were analyzed for their hydrological stability in terms of water level dynamics and their controlling factors. Long-term water balances and morphological nature of the lakes were used as bases for the analyses. Pettit’s homogeneity test and Mann–Kendall trend analysis were applied to test temporal variations of the lake levels. It is found that the hydrological stability of most of the Ethiopian Rift Valley lakes is sensitive to climate variability. In terms of monotonic trends, Lake Ziway, Hawassa, Abaya and Beseka experienced significant increasing trend, while Ziway, Langano and Chamo do not. In addition, homogeneity test revealed that Lake Hawassa and Abaya showed significant upward shift around 1991/1992, which was likely caused by climate anomalies such as the El Niño / Southern Oscillation (ENSO) phenomena. Lake Abiyata is depicted by its significant decreasing monotonic trend and downward regime shift around 1984/1985, which is likely related to the extended water abstraction for industrial consumption.

(Azeb Belete, 2009), in her master's thesis entitled "Climate Change Impact on Lake Abaya Water Level" climate change impact on Lake Abaya water level is assessed and the future lake level is forecasted based on scenario analysis conducted by changing the lake water balance parameters. 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. The forecast result shows 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.

(Amare, 2008), in the work entitled "Assessment of Lake Ziway Water Balance", estimation of the various water balance components of the Lake Ziway which includes, Surface runoff (Inflow and Out flow estimation for gauged and Un-gauged catchment to the Lake Ziway), Evaporation and precipitation over the surface of Lake Ziway, water abstraction and future scenario, impact of Lake Ziway on Lake Abiyata were conducted. Two major irrigation development scenarios are considered in his study to evaluate, how irrigation activities affect the Ziway lake level and the outflow to downstream of the lakes. The abstraction scenarios in the Ziway-Abijata Lake watershed affect not only the Abijata Lake but also the domestic water users along the river since it is the only fresh water available in between the two lakes.

Another study was conducted in Tanzania by (Randall E., 2011) with title "Using Water Balance Models to Approximate the Effects of Climate Change on Spring Catchment Discharge" to conceptually characterize the aquifer system using basic water quality parameters and recession analysis, to create a water balance model that is conceptually sound and accurately reproduces the mean dry-season discharge of the project catchment and to use the water balance model to assess the relative effects of changes in temperature and precipitation on aquifer storage, offering some insight about how future climate conditions may impact spring flows. Geochemical analysis, recession flow analysis, and water balance models were applied to characterize the system. The geochemistry shows a meteorically-recharged, shallow aquifer system with quickly circulating groundwater. Recession flow varied from year to year, but an average monthly constant of 0.151/mo was calculated for the 2004-2009 discharge dataset. Two models were developed from the Thornthwaite Mather Water Balance model that accurately reproduced observed dry-season discharges. The study confirms that climate change will significantly impact hydrologic systems, and that water balance models, modified to local conditions and calibrated to historic data, are tools that offer a simple and accurate method of assessing hydrologic conditions and outputs.

(Zhung Duan, 2014) in the work entitled "Estimating Water Balance Components of Lakes and Reservoirs Using Various Open Access Satellite Databases" to explores the use of satellite measurements to estimate the various key water balance components of lakes and reservoirs, ultimately leading to predictions of releases from reservoirs. This study demonstrated the feasibility of estimating water volume variations using only freely available satellite data for lakes and reservoirs where reasonable accurate water levels can be obtained from satellite altimetry.

As S. M. Onywere et al., (2013), in Kenya the increasing of lake level of Lake Naivasha, Lake Nakuru, Lake Bogoria, and Lake Baringo in the years 2010 to 2013 has detrimental effects on the ecosystem, the settlements, the infrastructure, the tourism and the biodiversity.

According to Berihu Abadi (2007) the surface area of Lake Beseka was increasing from 3 km^2 in 1960's to 27.5 km^2 in 1976 and to 41 km^2 in 2006. At the same time the gauge height was about 0.71m in 1976 and 5.6 m in 2006 which almost increased by about 5 m in the last 30 years. The extension of Lake Beseka resulted in flooding and salinization of Abadir farm land and endangering of the routes (road and railway) from Addis Ababa to Djibouti.

Studies carried out in the Lake District areas of Poland show progressive reduction of the surface area of the Lakes, which leads to their eventual disappearance. This occurs due to natural factors and human activity. Among natural factors the most important role play: climate fluctuations, water inflow and the associated sedimentation of clastic debris, depth of lake basins, biomass growth, chemical precipitation, deforestation caused by pests, and also local factors influencing the incorporation of lakes into the hydrographic network. In turn, the most important anthropogenic factors are: deforestation, hydro-technical works (including drainage), intensity of agriculture, and wastewater discharges within the lake catchment that affect the lake eutrophy (Adam et al., 2011).

In Ethiopia Lake Harumaya is already disappeared (Siraj Jawar, 2013), and many other lakes are also in a treat of disappearing such as, Lake Abe, Lake Ziway, Lake langano, Lake Abijata and Lake Shala due to natural factors and human activities (Teklu et al., 2017).

CHAPTER THREE

3. MATERIAL AND METHODS

3.1. Descriptions of the Study Area

3.1.1. Location and Accessibility

Lake Abaya (Abaya Hayk in Amharic) is a quasi-endorheic lake which is found/located in the Southern Nations Nationalities and Peoples Region of Ethiopia, in the Main Ethiopian Rift, East of the Guge Mountains, with coordinate 6° 26’ N Latitude and 37° 53’ East Longitude. It is fed on its Northern shore by the Bilate River which rises on the Southern slopes of Mount Gurage, Gidabo River on its North Eastern, Gelana River on its South Eastern, Harie River on its South Western, Hamessa River on its North Western, and other intermittent rivers. The town of Arba Minch lies on its southwestern shore, and the southern shores are part of the Nechisar National Park. Just to the south is Lake Chamo. The total catchment area including the islands is 14638.83km^2 (Halcrow, 2012).

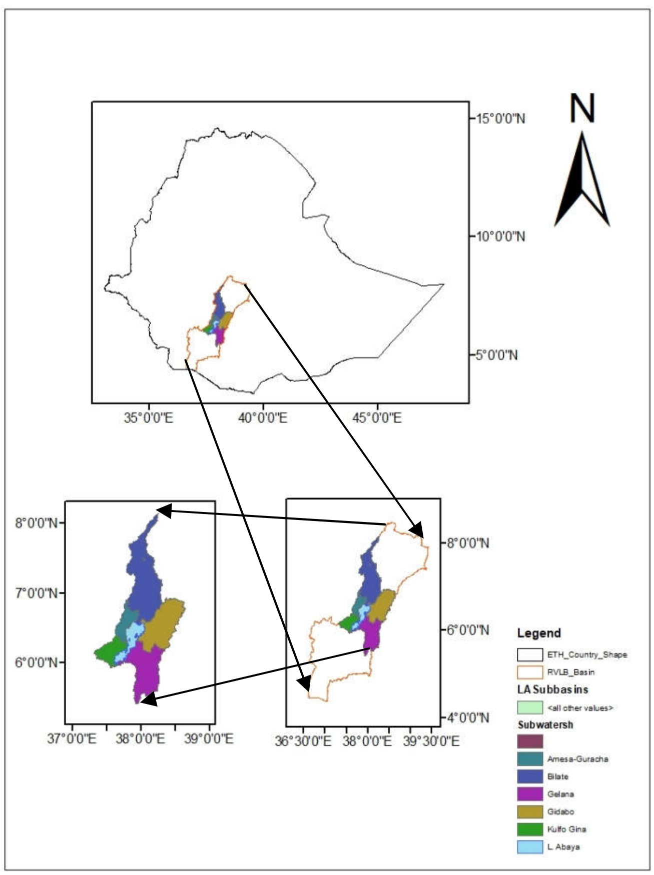


Figure 1 Location Map of Lake Abaya Sub-basin

3.1.2. Population

According to the assumptions made for the high variant, the population of the Rift Valley Basin, which was 8.894 million in the year 2005, will add nearly 4.2 million people to become 13.1 million by the year 2015. This population increase is driven by the inherent growth rate, which starts with 4% for the first five years and declines to 3.2% per annum in the last five years. The crude population density of the basin is 167 persons per km^2; nearly three times the density of the nation (65 persons per km^2) in the year 2005, now a day it becomes more than 246 persons per km^2 (Halcrow, 2012).

3.1.3. Physiography and Drainage

The principal feature of the RVLB is that it is a graben, a block fault geological structure in which the floor of the valley has become vertically displaced with respect to the valley sides. As in all areas, the temperature and rainfall of the RVLB tend to vary as a function of elevation and, in consequence, so do relative humidity and potential evapotranspiration. The top of the rift valley on the east and west sides is therefore cooler, wetter and with lower evapotranspiration rates, and hotter, drier and with higher evapotranspiration in the central lowlands (Halcrow, 2012).

Generally, Lake Abaya sub basin is divided into three physiographic areas: the high plateau on either side of the rift, the transitional escarpment and the rift floor. There is an elevation difference of about 2000m between the rift floor and mountains. Lake Abaya is fed principally by Bilate, Gidabo, Gelana, Hamesa and Hare rivers; from its Northern, North-Eastern, South-Eastern, North-Western, and South-Western, sides respectively. Most parts of plateau area are sources for perennial rivers while the tributaries in the escarpments are intermittent sources. Rift floor sources are disappearing before reaching the lake. In addition, the highland is characterized by higher drainage density than the escarpment due differences in rock permeability, climate and slope.

3.1.4. Climate and Rainfall

In the Lake Abaya catchment mean annual rainfall varies from 792 mm in the valley (weather stations at Abaya) to 1718.19 on the plateau (weather stations at Teferi Kela). Highlands flanking the Lake Abaya in both directions intercept most of the rainfall in the basin.

Two principal patterns of rainfall season are apparent in the Lake Abaya Sub Basin. The seasonal structure of the rainfall is characterized by a single wet season from April to September in the northern Part of Lake Abaya and a bi-modal pattern in the Eastern and Western escarpments and towards the South. North of Lake Abaya, the main rains occur July through September, with a secondary peak in March or April. South of Lake Abaya, the main rains occur earlier in the year, between March and May.

On the average at Arba Minch 50 % of the annual rainfall has fallen by the end of May. This switch in the arrival rate of rainfall within the first and second halves of the wet season is caused by a characteristically dry July and August which becomes increasingly apparent to the south of Abaya.

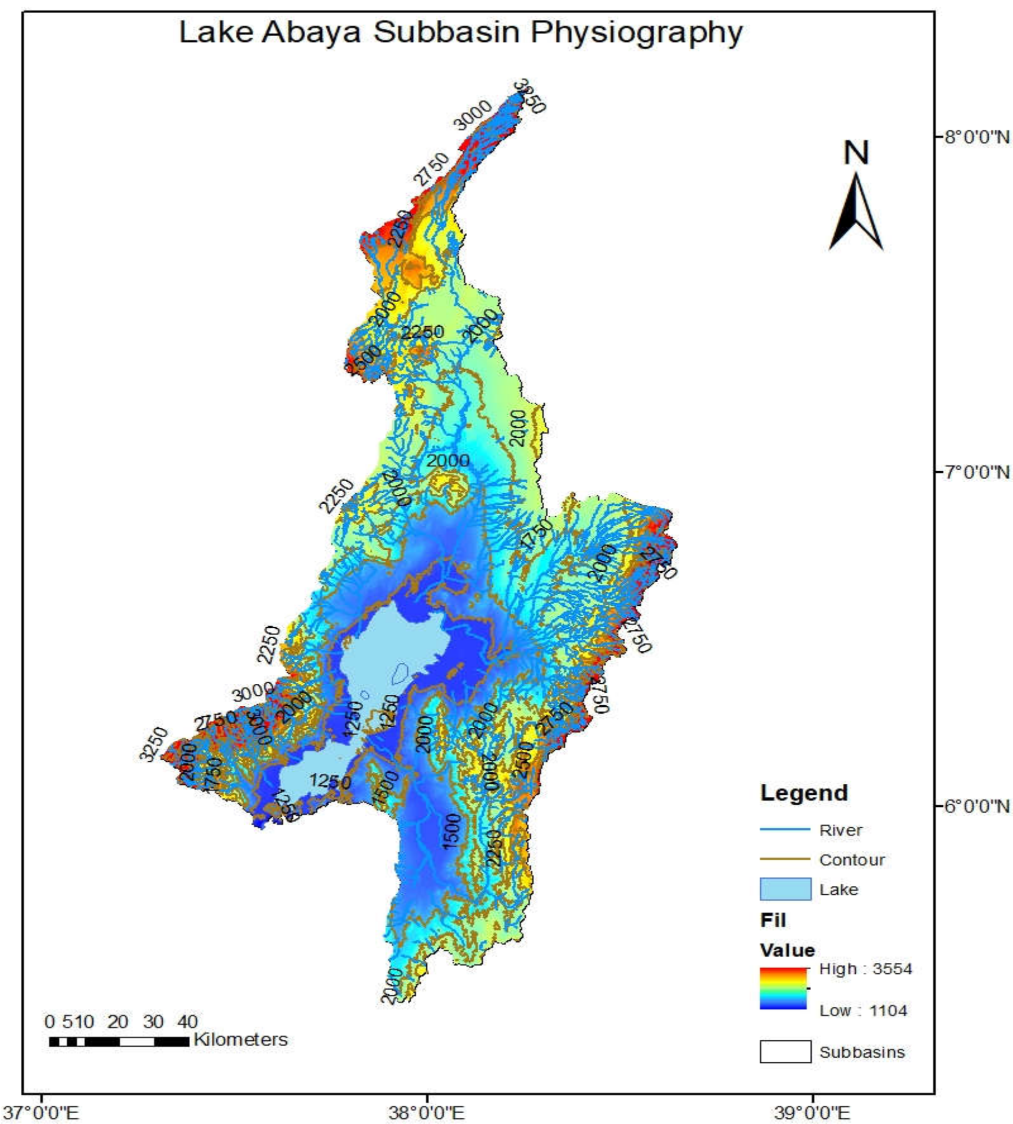


Figure 2 Physiographic Map of Lake Abaya Sub-basin

Annual average temperatures vary from approximately 24°C on the valley floor near Arba Minch to a low of approximately 13°C at higher elevations, particularly in Hagere Selam.

Open water evaporation (lake evaporation) is in the order of 111.38- 164.15 MCM/Month. This shows the total evaporation is greater than rainfall on the Lake surface which is in the range of 28.4-145.46 MCM/Month (Halcrow, 2012).

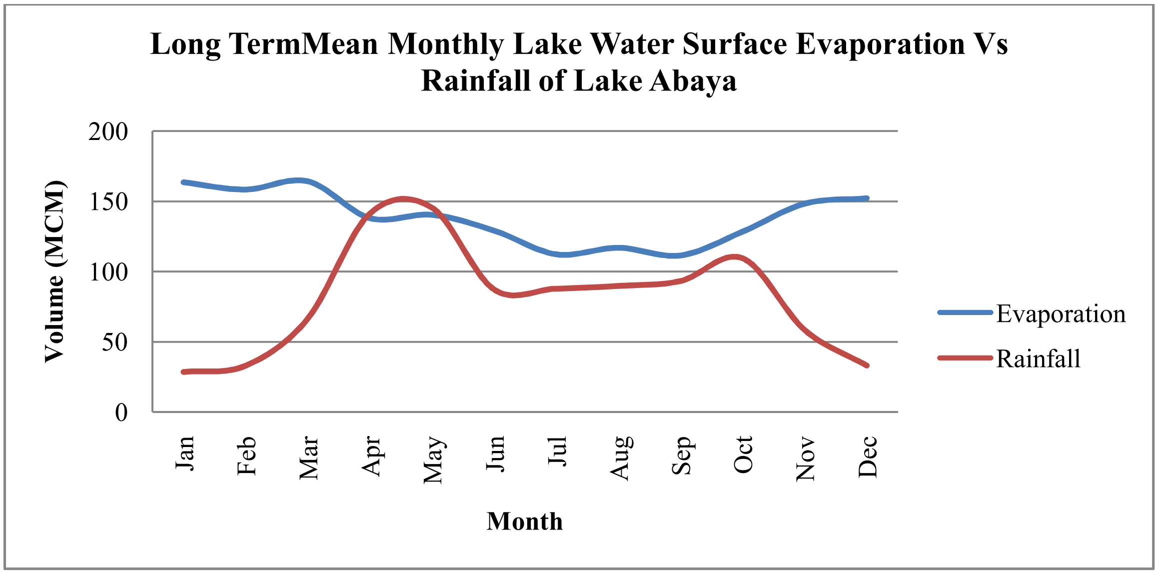


Figure 3 Long term Mean Monthly Lake Water Surface Evaporation and Rainfall of Lake Abaya

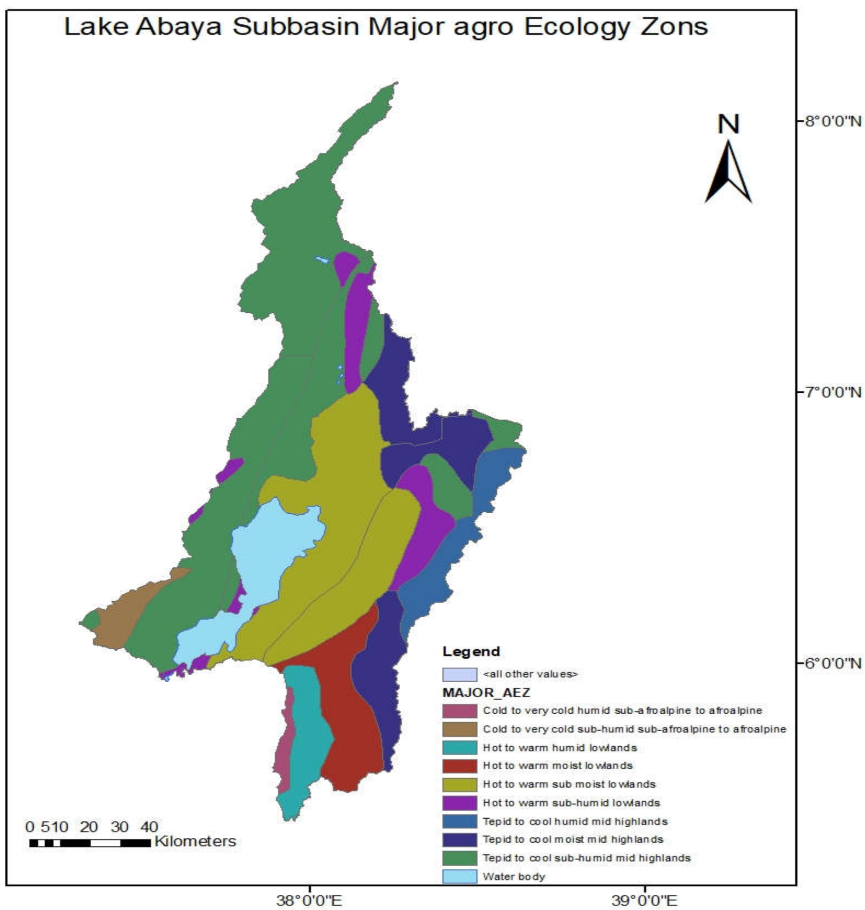


Figure 4 Agro-Ecology Climatic Zone of Lake Abaya Sub-basins

In Lake Abaya Sub-basin, there are ten agro ecologic climate zones can be distinguished, ranging from afro-alpine to hot low lands. Lake Abaya is located in hot to warm sub moist low lands agro-ecologic climatic zone. The prevailing temperature largely depends on the altitude.

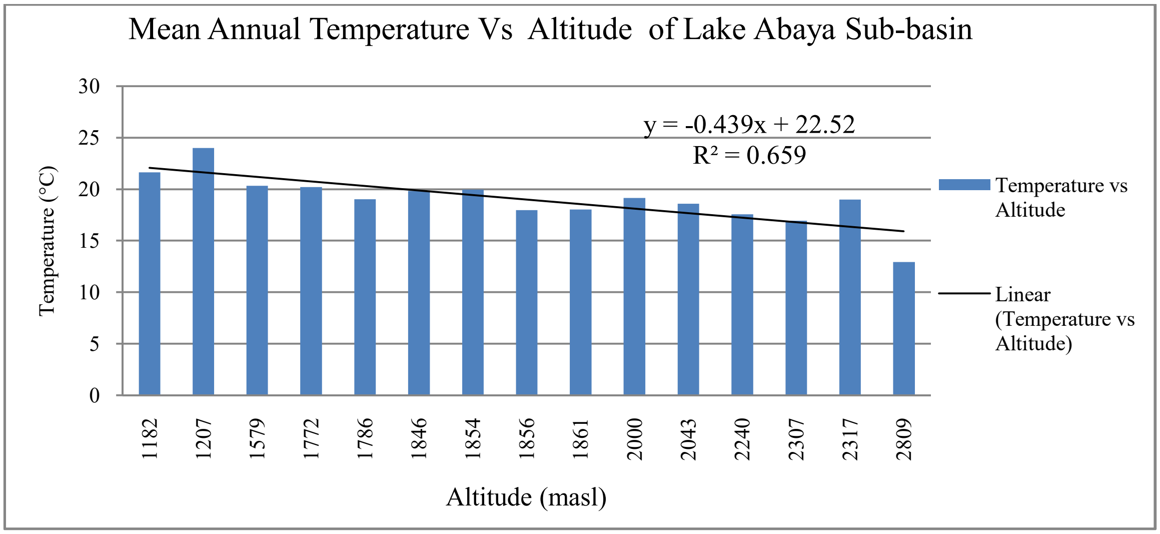


Figure 5 Mean Annual Temperature Vs Altitude of Lake Abaya Sub-basin

The number of daily sunshine hours varies from 4.7 hours per day in July to 9.1 hours in December and January with average 7.6 hours per day.

3.1.5. Water Resources

Naturally Lake Abaya drains in a broad, swampy overflow of approximately 300m width and over a length of 1km in to Kulfo River, which is flowing in to adjacent Lake Chamo in the south. Overflow is active only during high water level of the lake (Brigitta S. et al., 2006). The Lake Abaya can be characterized as a quasi-endorheic basin, with drainage to the southern Lake Chamo only in on sequence of overflow.

The inflow into the lake has been estimated using the run-off gauging at Bilate Tena for Bilate River, at Wajifo for Hamasa River, Nr. at Arba Minch for Harie River, Nr. at Aposto for Gidabo, and Nr. Tore for Gelana River.

3.2. Necessary Data and Procedures

For the analysis, relevant secondary data have been collected from all sources i.e. hydro meteorological data (rainfall, evaporation, temperature, wind speed, relative humidity, river discharge, lake level, and water abstractions from National Meteorological Agency main office, National Meteorological Agency Hawassa Branch Office and Ministry of Water Irrigation and Electricity). ARC-GIS software have been used to obtain hydrological and physical parameters and spatial information of the catchments of the study area, and DEM data is used as an input data for ARC-GIS software for catchment delineation and estimation of catchment characteristic. HEC-HMS software is used to predict runoff for the time when the rivers are un-gauged; precipitation and river discharge (stream flow) are used as inputs for HEC-HMS software. Pan evaporation data is obtained from National Meteorological Agency Hawassa Branch Office. Cropwat 8 software is used for the determination of water abstraction for irrigation from the lake and the tributary rivers. Finally, spread sheet lake water balance model has been applied and the water balance component of the lake has been estimated.

3.3. Methodology

3.1. The Hydrologic Cycle

The physical processes controlling the distribution and movement of water are best understood in terms of the hydrologic cycle. Although there is no real beginning or ending point of the hydrologic cycle, we can begin the discussion with precipitation. For the purposes of this discussion, we will assume that precipitation consists of rainfall and snowfall. A schematic of the hydrologic cycle for a natural environment is shown in Figure 1 below. Rain falling on Earth may enter a water body directly, travel over the land surface from the point of impact to a watercourse, or infiltrate into the ground. Some rain is intercepted by vegetation; the intercepted water is temporarily stored on the vegetation until it evaporates back to the atmosphere. Some rain is stored in surface depressions, with almost all of the depression storage infiltrating into the ground. Water stored in depressions, water intercepted by vegetation, and water that infiltrates into the soil during the early part of a storm represent the initial losses (Richard H. McCuen, 1998).

The loss is water that does not appear as runoff during or immediately following a rainfall event. Water entering the upland streams travels to increasingly larger rivers and then to the seas and oceans. The water that infiltrates into the ground may percolate to the water table or travel in the unsaturated zone until it reappears as surface flow. The amount of water stored in the soil determines, in part, the amount of rain that will infiltrate during the next storm event. Water stored in lakes, seas, and oceans evaporates back to the atmosphere, where it completes the cycle and is available for rainfall. Water also evaporates from soil devoid of vegetation. Rain that falls on vegetated surfaces may be intercepted; however, after the storage that is available for interception is filled, the water will immediately fall from the plant surfaces to the ground and infiltrate into the soil in a similar manner as the water falling on bare ground infiltrates. Some of the water stored in the soil near plants is taken up by the roots of the vegetation, and subsequently passed back to the atmosphere from the leaves of the plants; this process is called transpiration (Richard H. McCuen, 1998).

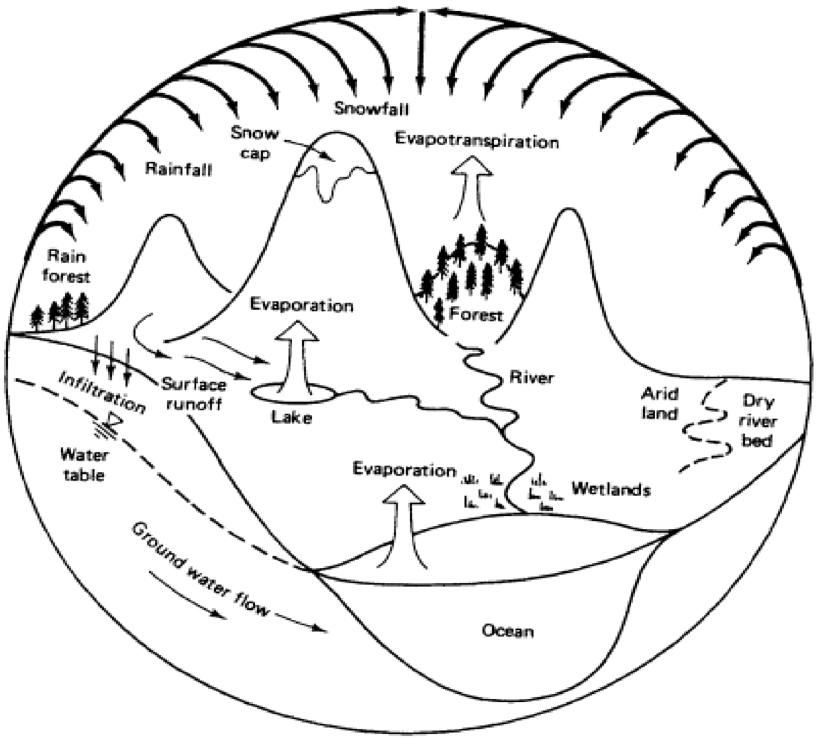


Figure 6 Hydrologic Cycle of a Natural Environment (Adopted from Richard H. McCuen, Hydrologic Analysis and Design Book)

3.1.1. Un-gauged Catchment

Area ratio method is used to estimate runoff from the au-gauged catchment.

$$Q_{ug} = \frac{Q_g * A_{ug}}{A_g} \qquad \textbf{(3.1)}$$

Where:

Qg = Discharge from gauged catchment

Qug = Discharge from un-gauged catchment

Ag = Area of gauged catchment and

Aug = Area of un-gauged catchment

3.1.2. Point Rainfall Data Analysis

3.1.2.1. Homogeneity Test

The objective of this treatment is to preliminary classify the basin in to sub-basin which helps various studies such as filling missing values, rainfall elevation and runoff correlation, as well as categorizing streams in to this regions. In order to find similar regions monthly rainfall values were non-dimensionalzed and plotted to compare the stations with each other.

The non-dimensionalzing of the monthly values where carried as

$P_i = \frac{P_{vi}}{p}$……… …………………………………………….…………………………………..... **(3.2)**

Where:

$Pi =$ Non dimensional value of precipitation for month i

$Pvi =$ Over years averaged monthly precipitation of the station i

$P =$ The over years average yearly precipitation of the station

3.1.2.2. Estimating Missing Data

Sometimes, the rainfall amounts at a certain rain gauges for a certain months may be missing due to the absence of some observer or instrumental failures. In such causes, it is needed to estimate the missing rainfall amount by approximating the value from the data of the nearby rain gauge and homogenous rain gauge stations**.** The precipitation value missing at a site can be estimated from concurrent observations at three or more neighboring stations and homogenous stations, known as index stations, located as close to and evenly spaced from the missing data stations as possible. The method adopted for computing the missing rainfall data is the Normal Ratio method which is recommended to estimate missing data in regions where annual rainfall among stations differ by more than 10%. This method is used to fill in missing data on rainfall station in the study area since the difference in annual rainfall between most of the station exceeds 10% due to large elevation difference between the stations that is from the high mountains at Chencha about 3250masl to the floor of the rift valley 1250masl at Abaya stations. This approach enables to estimate missing data by weighing the observation at n gauges by their respective annual average rainfall values as expressed by the equations;

$\frac{P_x}{N_x} = \frac{1}{n}(\frac{P_1}{N_1} + \frac{P_2}{N_2} + \frac{P_3}{N_3} + \cdots + \frac{P_n}{N_n}$ (Dimensionless)………..……….. **(3.3)**

Where:

$Px =$ Missing precipitation values for station x

$P1, P2, P3 \ldots\ Pn$:-are precipitation values at the neighboring stations for the concurrent period

Nx: - is Normal long term mean precipitation at station x

$N1, N2 \ldots\ Nn$: - are Normal long term precipitations for neighboring stations

N: - is Number of index neighboring stations.

3.1.3. Checking Consistency of Data: Double Mass Analysis

The double–mass analysis is a consistency check used to detect whether the data at a site have been subjected to a significant change in magnitude due to external factors such as tempering with the instrument, change in the recording conditions or shift in the observation practices. If the data are consistent, the plot will be a straight line. On the other hand, inconsistent data will exhibit a change in slope or break at the point where the inconsistency occurred.

$$Pa = \frac{ba}{bo} * Po \quad \textbf{(3.4)}$$

Where

Pa = Adjusted precipitation

Po = Observed precipitation

ba = Slope of graph to which records are adjusted

bo = Slope of graph at time Po was observed

3.1.4. Estimation of Areal Rainfall

The representative precipitation over a defined area is required in any water Resource Development and Management applications, whereas the gauged observation pertains to the point precipitation. The areal precipitation is computed from the record of rain gages with in the area by the following methods.

3.1.4.1. Arithmetic Average Method

This simple method consists of computing the arithmetic average of the values of the precipitations for all stations within and in proximity to the area. It assigns equal weight to all stations irrespective of their relative spacing and other factors. If the stations are uniform over the area, and the rainfall rate does not differ much at various stations, then this method is quite satisfactory. If P is the mean rainfall on the basin, then

$$P = \frac{P1+P2+,\ldots,+Nn}{N} \quad \textbf{(3.5)}$$

Where:

$P1, P2, P3, \ldots, Pn$: are precipitation values at the respective stations

N: is number of stations

However, Lake Abaya catchment has different rainfall patterns, highlands with high mean annual point rainfall, lowland (rift floor) with low mean yearly point rainfall and escarpments having in between of the two rain fall. Then due to the rainfall intensity vary considerably in the catchment this method may lead to errors.

3.1.4.2. Weighted Average Method

Thiessen Polygon Method

In this method, the weight is assigned to each station in proportion to its representative area defined by a polygon. It is assumed that the entire area within a polygon is nearer to the rainfall station that is included in the polygon than to any other rainfall station. The rainfall recorded at that station is, therefore, assigned to that polygon. If P is the mean rainfall on the basin, and area of the basin is A, then

$$P = \frac{(A1*P1 + A2*P2 + A3*P3 + \dots + An*Pn)}{A} \quad \textbf{(3.6)}$$

Where:

$P1, P2, P3, \dots, Pn$: - are precipitation values at the respective stations

$A1, A2, A3 \dots\ An$: -are surrounding polygons areas

Accordingly Abaya sub-basin divided into 28 polygons, the monthly and annual rainfall areal distributions are computed for the total catchment, Bilate River watershed, Gidabo River watershed, Gelana River Watershed, Hamesa River Watershed, Harie River Watershed and Lake Surface.

Isohyetal method

Isohyets are the contours of equal rainfall. They are drawn on the map by common sense, after the rainfall at each station is plotted. The area between adjacent isohyets is either estimated on the graph paper or measured by planimeter. Let them be $A1, A2, A3, \dots, An$; let the average precipitation for the areas be $P1, P2, P3, \dots, Pn$; then the mean precipitation P on the basin is given by

$$P = \frac{(A_1P_1+A_2P_2+A_3P_3+\cdots+A_nP_n)}{(A_1+A_2+A_3+\cdots+A_n)} \quad \textbf{(3.7)}$$

Since the area between the two adjacent isohyets is assumed to be having a rainfall equal to the arithmetic average of rainfall values represented by the two isohyets, the method evidently assumes uniform areal distribution of rainfall in between two isohyets. Such an assumption may not always be true, as geological consideration of the ground below might affect this assumption.

3.1.5. Methods of Determining Evaporation from Open Water Surface

3.1.5.1. Pan Evaporation

Pans have been used to estimate evaporation for over two hundred years. They have an intuitive appeal of apparent simplicity but it is difficult to reliably use data from pans except in specific circumstances.

Pans that have found wide use around the world are the US Class A pan and the USSR GGI 3000 pan. Measurements of pan evaporation can rarely be used directly as estimates of evaporation from a water body because of the differences in size between the pan and the water body and, possibly, differences in the overlying air. The two main approaches to estimating the evaporation of a water body from pan measurements are the use of pan coefficients and pan conversions. Pan coefficients are simply the ratio of the water body evaporation to pan evaporation. The coefficients are generally specific to the pan type, its location and the nature of the water body and they may, in addition, vary with time.

Pan conversions are achieved by taking the ratio of the bulk mass transfer equations of the lake and the pan:

$$\bar{E} = K \frac{(\bar{e}_s{}^* - \bar{e})}{(\bar{e}_p - \bar{e})} \bar{E}_p \quad \text{(3.8)}$$

Where: $\overline{E}$ is the mean evaporation rate from the water body, $\bar{E}_p$ is the mean evaporation rate of the pan, K is an empirical constant, $\bar{e}_s{}^*$ is the mean saturated vapour pressure of the air at the water surface temperature, $\bar{e}_p$ mean saturation vapour pressure at pan surface temperature and $\bar{e}$ is the mean vapour pressure of the air at reference height. This method is, however, dependent on knowing the surface temperatures of the lake and the pan, which is rarely practical. In addition, an empirical coefficient is still required which has to be determined for the specific situation.

Despite their apparent simplicity, all pans need to be carefully maintained. The water level must be kept close to the prescribed level and regular cleaning and periodic repainting are necessary.

3.1.5.2. Mass Balance

The mass balance method of measuring open water evaporation is simple in principle, evaporation being calculated as the change in volume of water stored and the difference between inflow and outflow, i.e.

$$E = P + \frac{(Q_{ri}+Q_{gi})-(Q_{ro}+Q_{go})-\frac{dV}{dt}}{A_s} \quad \text{(3.9)}$$

Where: E is the evaporation rate from the water body, P is the mean rate of precipitation over the sampling period, Q_{ri} is the surface inflow rate, Q_{ro} is the surface outflow rate, Q_{gi} is the groundwater and seepage inflow rate, Q_{go} is the groundwater and seepage outflow rate, V is the water stored and A_s is the surface area.

The relative importance of the terms depends on the hydrological and physiographical setting. The feasibility of determining evaporation depends primarily on the relative magnitudes of the terms: it is difficult to obtain a reliable estimate whenever the evaporation is of the same order of magnitude as the errors inherent in the measurements. The method is therefore unsuited to water bodies with large flow rates.

3.1.5.3. Energy Budget

In this approach evaporation from water body is estimated as the energy component required to close the energy budget when all the remaining components of the budget of the water body are known, that is, it is the residual component. The energy associated with evaporation is of two categories; first, the heat required to convert liquid water into water vapour (vaporization), second, the energy of the water vapour molecules carried from the water body (advection). The latent heat of vaporization ranges between 2.5 and 2.4 MJ kg-1 for liquid water between 0°C and 40°C. The energy budget of a water body is given by

$$N = S(1-\alpha_s) + L_{\downarrow}(1-\alpha_L) - L_{\uparrow} - \lambda E - c(T_s - T_b)E - H + F_{in} - F_{out} + F_p - G \quad \textbf{(3.10)}$$

where N is the change in the energy storage in the water, S and $L_{\downarrow}$ are the incident short and long-wave radiation respectively, and α_s and α_L are the albedos (reflectivities) for short and long-wave radiation, $L_{\uparrow}$ is the long-wave radiative loss from the water, λE is the flux of latent heat (evaporation rate in energy flux units; λ is the latent heat of vaporisation and E is the evaporation rate in mass units), c is the specific heat of water, T_s and T_b are the temperature of the evaporated water and an arbitrary base temperature respectively, H is the flux of sensible heat (the energy used in warming the atmosphere in contact with the water which is then convected upwards), F_{in} and F_{out} are the heat fluxes associated with water flows in and out of the water body, F_p is the heat inflow associated with precipitation, and G is the heat conduction occurring between the water and its substrate. All the energy components are in units of energy per unit surface area of the water.

The three radiation terms together give the net radiation, *Rn* such that rewriting equation the above equation gives

$$\lambda E + c(T_s - T_b)E = R_n - H + N + F_{in} - F_{out} + F_p - G \quad \textbf{(3.11)}$$

Usually the sensible heat term (the amount of energy directly warming the air) cannot be readily determined and it is eliminated from equation (3.10) through use of the Bowen ratio, β which is defined as the ratio between the sensible and latent heat fluxes. It can be expressed thus

$$\beta = \frac{H}{\lambda E} = \frac{c_p \phi (T_s - T_a)}{\varepsilon_m \lambda (e_s^* - e)} \quad \textbf{(3.12)}$$

Where: c_p is the specific heat of air at constant pressure, Φ is the atmospheric pressure, T_s and T_a are the temperatures of the water surface and the air at a reference height, ε_m is the ratio of the molecular weight of water to that of dry air, and e_s* and e are the saturated vapour pressure of the air at the water surface temperature and the vapour pressure of the air at the reference height. The ratio $c_p \phi / \varepsilon\lambda = \gamma$ is also known as the psychometric coefficient.

From the above Equation, $H = \beta\lambda E$ which, when substituted into equation (3.10), gives the evaporation rate,

$$E = \frac{R_n + N + F_{in} - F_{out} + F_p - G}{\lambda(1+\beta) + c(T_s - T_b)} \quad \textbf{(3.13)}$$

The second term in the denominator represents a correction term for the difference between the temperature of the evaporated water and an arbitrary base temperature.

By suitable selection of averaging period it is sometimes possible to neglect the F_{in}, F_{out} and G terms. Indeed, it is usually the case that the energy content of a water body is chiefly governed by the exchange of energy through the surface, rather than the inflows, including precipitation, and outflows and the water-substrate interface. This would certainly be the case if the volumes of water flowing in and out of the water body are small compared to the overall volume, or the temperatures are close to the temperature of the water body. Therefore, the last four terms in the numerator of the above equation can often be neglected if $T_b = T_s$ and the energy budget is then given by

$$E = \frac{R_n + N}{\lambda(1+\beta)} \quad \textbf{(3.14)}$$

Disadvantages of the energy balance method are the large number of measurements needed, the frequency of the measurements, and the difficulties inherent in making some of them. Consequently it is expensive and has not often been used in the more complete form of equation (Jon et al., 2008).

3.1.5.4. Penman's Equation (Combination Models)

Penman (combination approaches) is an approach which does not require surface water temperature and is recommended for estimating free water evaporation. The Penman equation reads as:

$$PET = ((Hn * \Delta) + (Ea * \gamma))/(\Delta + \gamma) \quad \textbf{(3.15)}$$

Where:

PET = Potential evaporation that occurs from free water evaporation [mm/day]

Hn = Net radiation in mm of evaporable water per day

The net Radiation, Hn,

$$Hn = Ha * (1 - r) * \left(a + b * \frac{n}{N}\right) - \delta * T_a{}^4 * \left(0.56 - 0.092 * \sqrt{e_a}\right) * (0.10 + 0.9 * \frac{n}{N}) \text{………….. } \mathbf{(3.16)}$$

Where:

Ha = Incident solar radiation outside the atmosphere on a horizontal surface, expressed in mm of evaporable water per day (it is a function of the latitude and period of the year, from table)

r = Reflection coefficient (albedo) 0.05 for water surface

a = A constant depending up on the latitude Φ and is given by

$a = 0.29 cos\Phi$

Φ = 6° (in our case)

b = A constant with an average value of 0.52

n = Actual duration of bright sunshine in hours

N = Maximum possible hours of bright sunshine (it is a function of latitude)

δ = Steven–Boltzman Constant = $2.01*10^{-9}$ mm/day

Ta = Mean air temperature in degrees Kelvin = 273 + °C

e_a = Actual mean vapour pressure in the air in mm of mercury

Δ = Slop of the saturation vapour pressure Vs temperature curve at the mean air temperature, in mm of mercury per ° C

$\Delta = (4098 * es) / 〚(T + 273.3)〛\text{^}2$

es = Saturation vapour pressure

$es = 611 exp((17.27 * T)/(T + 237.3))$

T ° C, es in Pa (N/m^2)

$RH = ea/es$

RH is relative humidity

Ea = Parameter including wind velocity and saturation deficit

The parameter Ea is estimated as

$$Ea = 0.35(1 + \frac{U2}{160})(es - ea)$$

$U2$ = Wind speed at two meter height

γ = Psychometric constant = 0.49 mm of mercury/ ^{o} C

$$\gamma = \frac{Cp * P}{0.622 * lv}$$

Cp = Specific heat of air (1005J/KG ^{o} C)

$$P = 101.3 * (\frac{293 - 0.0065 * Z}{293})^{5.26}, \qquad P\ in\ KPa$$

$Z\ in\ meter\ (Elevation)$

$Z = 1207m\ Arba\ Minch\ Met\ Station$

$P = 87.823KPa = 87823Pa$

$lv = latent\ heat\ of\ water$

$lv = 2.5 * 10^6 - 2370 * T(J/kg)$

T^oC

3.1.6. Water Balance

The study of the water balance is the application in hydrology of the principle of conservation of mass, often referred to as the continuity equation. This states that, for any arbitrary volume and during any period of time, the difference between total input and output will be balanced by the change of water storage within the volume. In general, therefore, use of a water-balance technique implies measurements of both storages and fluxes (rates of flow) of Water, though by appropriate selection of the volume and period of time for which the balance will be applied, some measurements may be eliminated (Unesco 1974).

The water balance equation for any natural area (such as a river basin) or water body indicates the relative values of inflow, outflow and change in water storage for the area or body.

$$P + Q_{SI} + Q_{UI} - E - Q_{SO} - Q_{UO} - \Delta S - \eta = 0 \quad \textbf{(3.17)}$$

Where:

P = Lake Area rainfall

Q_{SI} = Surface water inflow (from gauged as well as ungagged catchment in to the lake) Q_{UI} = Subsurface water inflow in to the lake

E = Open water evaporation from the lake surface

Q_{SO} = Surface outflow from the lake

Q_{UO} = Subsurface outflow from the lake

ΔS = Total water storage in the lake (it may be either negative or positive)

η =Discrepancy term (All the water-balance components are subject to errors of measurement or estimation and the water-balance equation should therefore include a discrepancy term)

As quantification of Q_{UI} and Q_{UO} is difficult with the available data, the net ground water flux (Q_{UI} - Q_{UO}) is estimated as residual to the model output.

3.1.6.1. Water Balance Recursive Formula

Equation 3.17 is the general water balance equation formulated for the lake. After rearranging using equation 3.17 and knowing the initial storage (at some reference time) and assuming ground water inflow is equal with outflow from the lake, the recursive continuity equation is formulated as:

$$S_t = S_{t-1} + Q_{SI} + P_{LAKE} - E_{LAKE} - Q_{SO} - Q_{ABS} \quad \textbf{(3.18)}$$

Where

S_t = Storage at the current month (MCM),

S_{t-1} = Storage at the end of the preceding month (MCM),

Q_{SI} = Inflow to the lake at the current month (Bilate, Gidabo, Gelana, Hamesa, and Harie Rivers in MCM),

P_{LAKE} = Is the mean areal precipitation on the lake at the current month (MCM),

Q_{S0} = Outflow discharge at the current month (Outflow from the Lake in MCM),

Q_{ABS} = Is the abstraction of water at the current month (MCM), and

E_{LAKE} = Evaporation loss from lake at the current month (MCM)

As it can be seen from the recursive formula, the components of the water balance for Lake Abaya are:

Reservoir storage, Surface Runoff, Lake Evaporation, Areal Precipitation for Lake Region, and Abstraction from the lake.

CHAPTER FOUR

4. HYDRO METROLOGICAL DATA ANALYSIS

4.1. Hydrological Data

Surface flow to Lake Abaya comes from gauged and un-gauged catchments. There are five perennial rivers which inters to Lake Abaya. These are Bilate, Gidabo, Hamessa, Gelana, and Harie Rivers. Among them Hamessa and Hare rivers are gauged at the inlet to the lake: the others gauged at the middle or at the upstream point of the river. The total drainage area of Lake Abaya sub-basin covers 14243.78 km^2 excluding the lake and islands area.

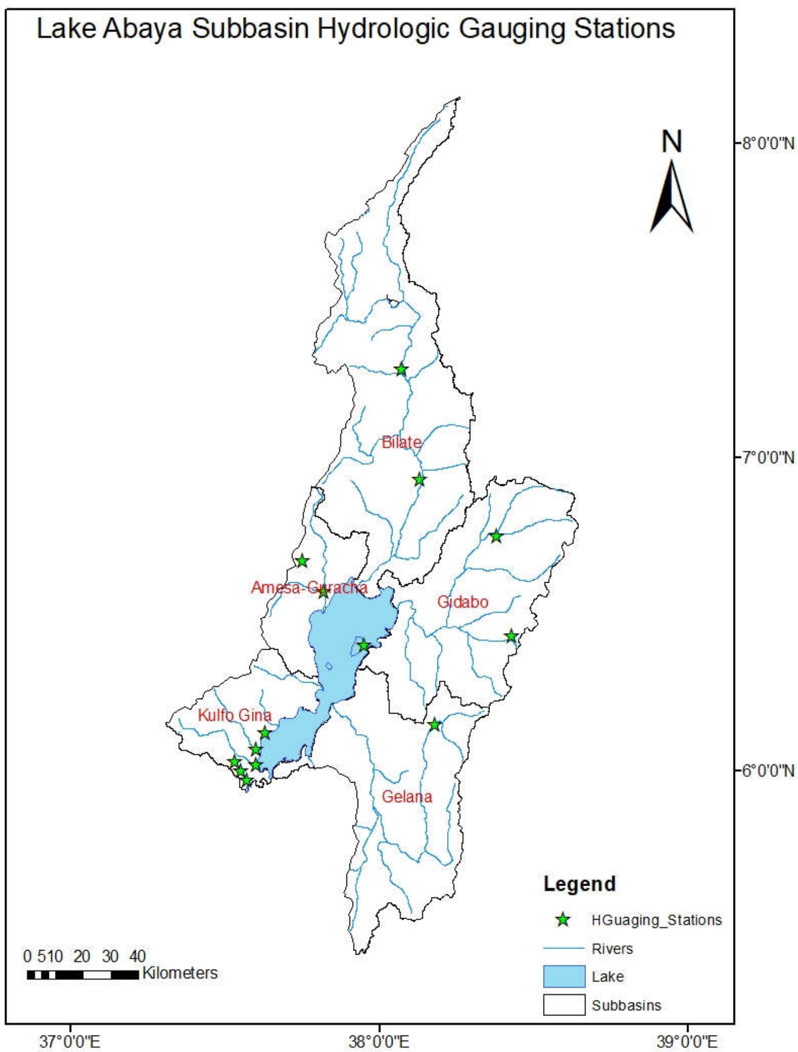


Figure 7 Hydrologic Gauging Stations on Lake Abaya Sub-basin Rivers and on Lake Abaya

4.1.1. Gauged River Runoff

4.1.1.1. Bilate River

Bilate River watershed is in the Abaya-Chamo sub-basin of the southern Ethiopian Rift Valley, situated between 37° 48’ 45’’ and 38° 18’ 22’’ Eastern longitudes and 6° 32’ 58’’ and 8° 08’ 59’’ Northern latitudes. It rise on the south western slopes of Mount Gurage, flowing south along the western side of the Great Rift Valley, and drains a land area of 5324.30 km^2 into Lake Abaya. The altitude of the watershed ranges from 1176masl at Lake Abaya to 3318masl at the Northern end of the watershed. Mean annual rainfall varies 1037mm to 1416mm at the lowland and highland respectively. The mean annual flow of Bilate River Nr. Bilate Tena and Nr. Alaba Kulito is 17.54 and 12.01 m^3 Sec-1 respectively. Discharge of Bilate River @Bilate Tena and Nr. Alaba Kulito is 568.86 and 379.37 MCM/Year with a drainage area of 3489.02 and 1734.02 km^2 respectively (Halcrow, 2012).

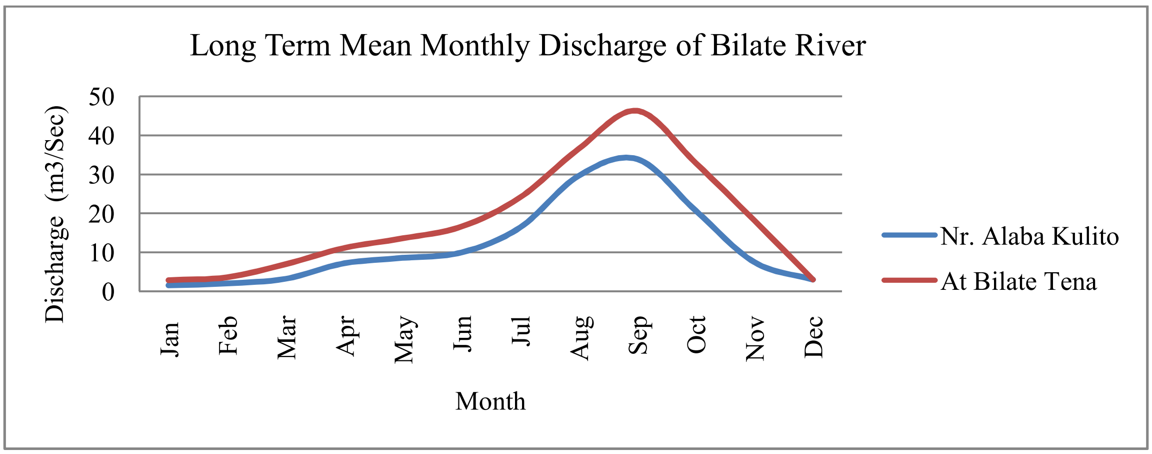


Figure 8 Long Term Mean Monthly Discharge of Bilate River

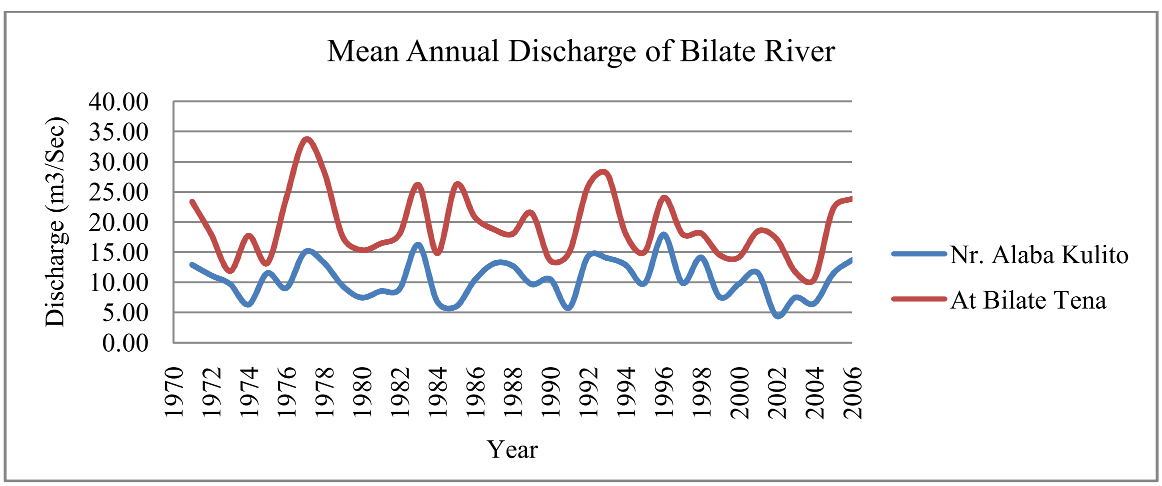


Figure 9 Mean Annual Discharge of Bilate River

4.1.1.2. Gidabo River

Gidabo River watershed is in the Abaya-Chamo sub-basin of the southern Ethiopian Rift Valley, situated between 37° 55’ 35’’ to 38° 38’ 35’’ Eastern longitude and 6° 09’ 04’’ to 6° 56’ 22’’ Northern latitude and drains a land area of 3549.42 km^2 into Lake Abaya. It is mainly covered by steep mountains characterized through abrupt faults and rises from 1176masl to 3112masl. Mean annual rainfall varies from 805mm to 1454mm at the lowland and highland respectively. Precipitation is characterized by a bimodal pattern with a subordinate peak in April, May and June (small rain season) and a maximum peak during in September and October (heavy rain season). The mean annual flow of Gidabo River Nr. Aposto is 6.51 m^3 Sec-1.Total discharge of Gidabo River Nr. Aposto is 204.57 MCM/year which covers a drainage area of 679.5 km^2 (Halcrow, 2012).

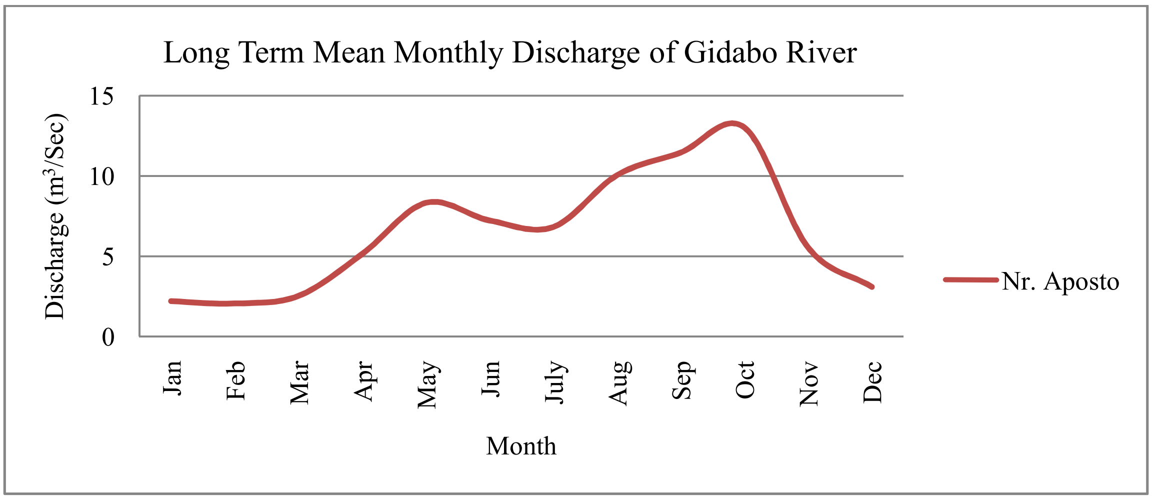


Figure 10 Long Term Mean Monthly Discharge of Gidabo River

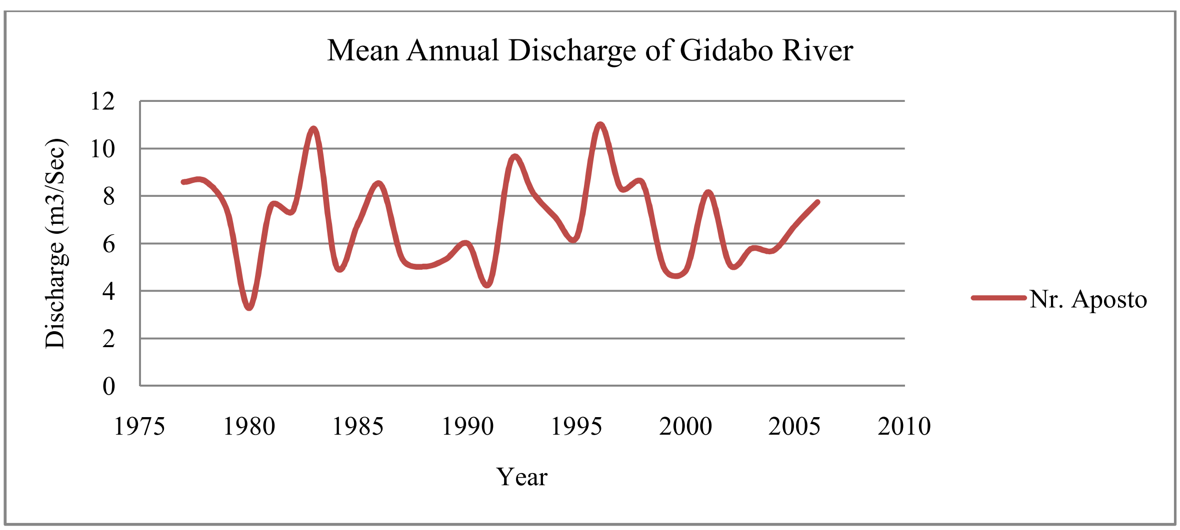


Figure 11 Mean Annual Discharge of Gidabo River

4.1.1.3. Gelana River

Gelana River watershed is in the Abaya-Chamo sub-basin of the southern Ethiopian Rift Valley, situated between 37° 40' 01'' and 38° 22' 13'' Eastern longitude and 5° 24' 57'' and 6° 20' 06'' Northern latitude and drains a land area of 3416.91 km^2 into Lake Abaya. It is mainly covered by steep mountains characterized through abrupt faults and rises from 1176masl to 2921masl. Mean annual rainfall varies from 911mm to 1309mm at the lowland and highland respectively. The mean annual flow of Gelana River below the bridge Nr. Tore is 4.66 m^3 Sec-1. Total discharge of Gelana River Nr. Tore is 146.74 MCM/Year, which covers a drainage area of 1647 km^2 (Halcrow, 2012).

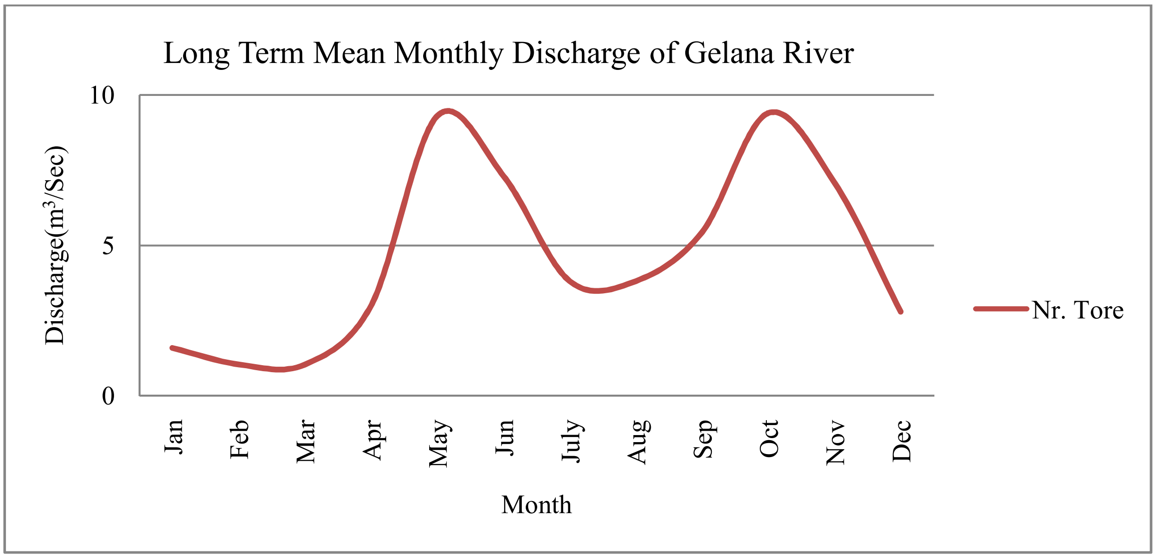


Figure 12 Long Term Mean Monthly Discharge of Gelana River

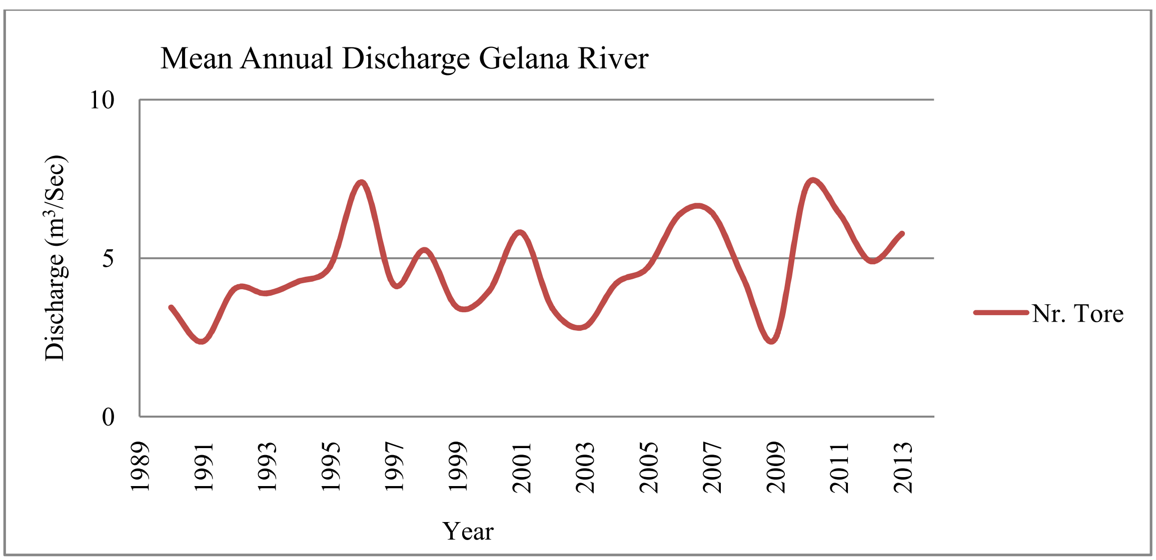


Figure 13 Mean Annual Discharge of Gelana River

4.1.1.4. Hamessa River

Hamessa River watershed is in the Abaya-Chamo sub-basin of the southern Ethiopian Rift Valley, situated between 37° 36’ 43’’ and 37° 57’ 46’’ Eastern longitude and 6° 17’ 43’’ and 6° 54’ 19’’ Northern latitude and drains a land area of 516.67 km^2 into Lake Abaya. It is mainly covered by steep mountains characterized through abrupt faults and rises from 1178masl to 2821masl. Mean annual rainfall varies from 1198mm to 1566mm at the lowland and highland respectively. The mean annual flow of Hamesa River Nr. Wajifo is 1.61 m^3 Sec-1. Total discharge of Hamessa River Nr. Wajifo is 53.77 MCM/year which covers a drainage area of 478.55 km^2 (Halcrow, 2012).

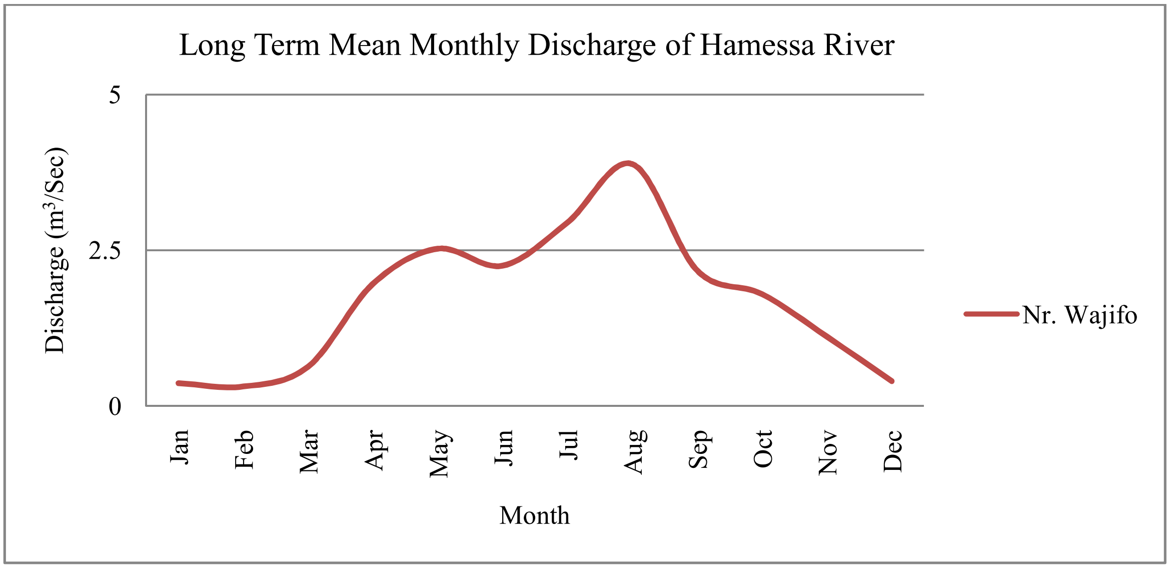


Figure 14 Long Term Mean Monthly Discharge of Hamessa River

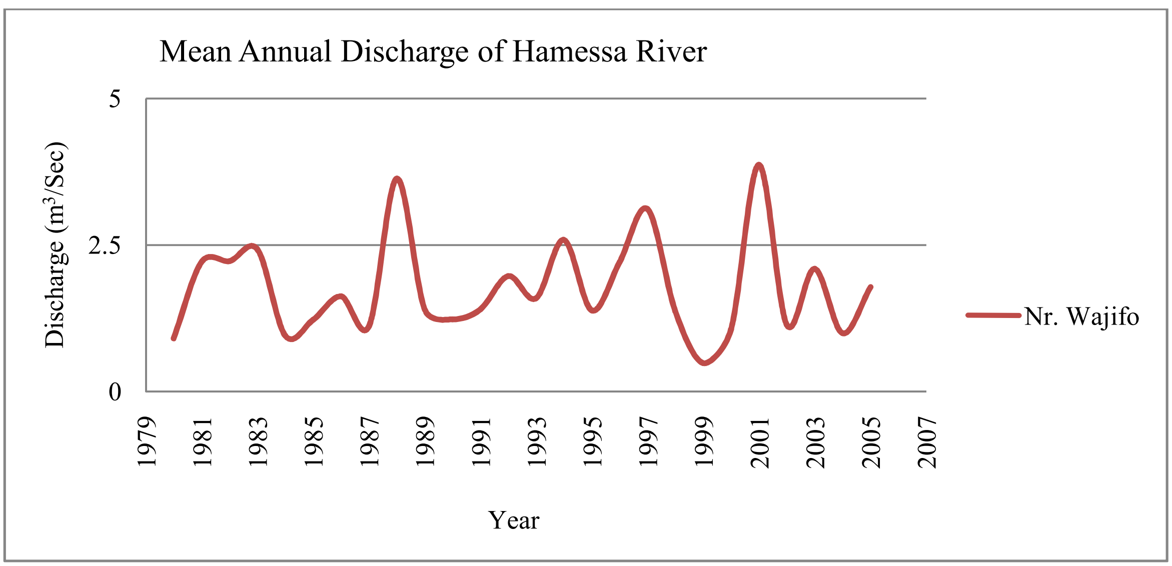


Figure 15 Mean Annual Discharge of Hamessa River

4.1.1.5. Hare River

Hare River watershed is found in the Abaya-Chamo sub-basin of the southern Ethiopian Rift Valley, situated between 37° 27’ 43’’ and 37° 37’ 44’’ Eastern longitude and 6° 03’ 21’’ and 6° 15’ 26’’ Northern latitude and drains a land area of 176 km^2 into Lake Abaya. It is mainly covered by steep mountains characterized through abrupt faults and rises from 1187masl to 3317masl. Mean annual rainfall varies from 1450mm to 911mm at the highland and lowland respectively. The mean annual flow of Hare is 1.91 m^3 Sec-1. Total discharge of Hare River Nr. Arba Minch is 60.14 MCM/Year (Halcrow, 2012).

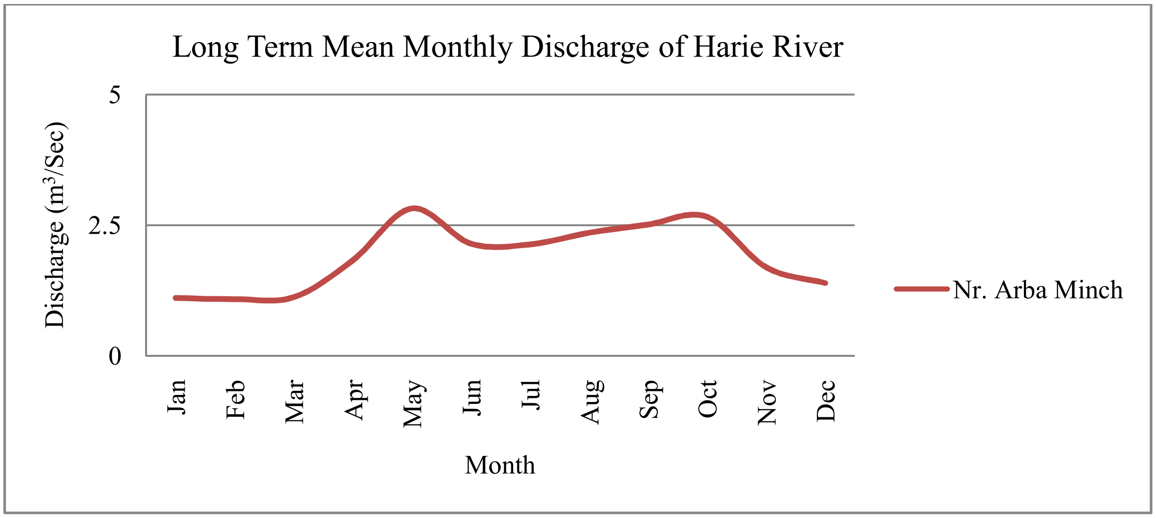


Figure 16 Long Term Mean Monthly Discharge of Harie River

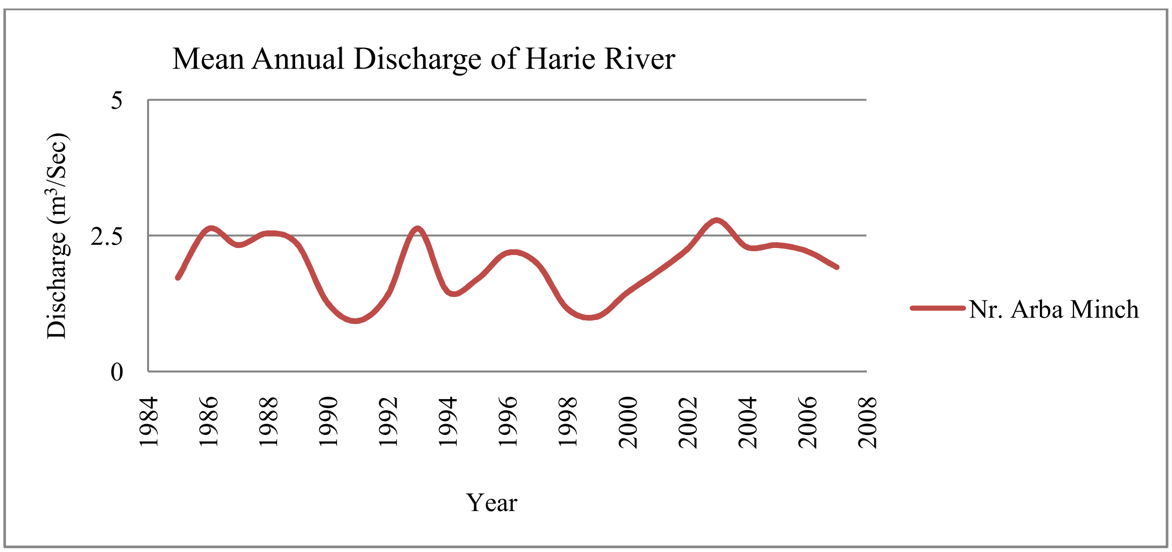


Figure 17 Mean Annual Discharge of Harie River

The total gauged area is 6470.12 Km^2 and the total inflow to Lake Abaya from this gauged catchment is **1034.07** MCM/Year.

4.1.2. Un-gauged Sub-Catchments Runoff

Apart from the Bilate, Gidabo, Gelana, Hamesa, and Harie, Lake Abaya has its own catchment covering about 7773.66 km^2 (54.6% of the total catchment area) part of the lake catchments referred to as un-gauged. The un-gauged area covers a sub-catchment adjoined to Lake Abaya almost on Eastern sides of the lake except small part to the north which is the sub catchment of the Bilate River. The gauged Bilate, Gidabo, Gelana, Hamesa and Harie sub-river basin which their runoff is directly entered to the Lake Abaya are used to estimate the runoff from the un-gauged sub-catchments using the Area Ratio Method.

Since the un-gauged catchment contributes runoff only during rainy season, the runoff from the un-gauged catchments considered in this study is only in the wet seasons (Under the Köppen climate classification, for tropical climates, a wet season month is defined as a month where average precipitation is 60 millimeters (2.4 in) or more.) and the amount is 685.45MCM.

4.1.3. Bathymetry Survey of the Lake

4.1.3.1. Lake Volume-Area-Elevation Curves

The Volume-Area-Elevation relationships of Lake Abaya reservoir were estimated and associated curves were established. The measuring staff gauge (zero water levels) of the Lake Abaya is located at 1171masl. The dead storage of the Lake Abaya is the volume below the elevation 1171 m. Then area–Volume-Elevation above this point's is used in this study for estimation of evaporation from the lake and at the same time precipitations on the lake. The Volume-Area-Elevation relationships are established for bathymetry survey by the curve fitting techniques (Seleshi B., 2006). Then area–Volume-Elevation above this point's is used in this study for estimation of evaporation from the lake and at the same time precipitations on the lake.

The dead storage of the Lake Abaya is the volume below the elevation 1171 m. Then area–Volume-Elevation above this point's is used in this study for estimation of evaporation from the lake and at the same time precipitations on the lake. The Volume-Area-Elevation relationships are established for bathymetry survey by the curve fitting techniques (Seleshi B., 2006)

The elevation-area-curve and elevation-capacity-curves are described by the following equations.

$V = -1 * 10^{-5} * d^5 + 0.0005 * d^4 - 0.0057 * d^3 + 0.0516 * d^2 - 1.2242 * d + 9.842$: $R^2 = 1$, **(4.1)**

$A = 0.0198 * d^5 - 0.06662 * d^4 + 7.7116 * d^3 - 39.766 * d^2 + 31.023 * d + 1133.4$: R^2=0.99, **(4.2)**

Where: d is depth of water (m) measured from zero lake level 1171masl, positive downwards, V is volume of water km^3, and A is Lake surface area km^2.

Table 1 Lake Abaya Capacity Curve Data

Depth(m)	Level(masl)	Area(km^2)	Volume(km^3)	Depth(m)	Level(masl)	Area(km^2)	Volume(km^3)
0	1171	1139.79	9.82	8	1163	699.6	2.14
0.5	1170.5	1133.25	9.25	8.5	1162.5	654.61	1.80
1	1170	1126.45	8.69	9	1162	605.16	1.49
1.5	1169.5	1119.07	8.12	9.5	1161.5	551.68	1.20
2	1169	1087.46	7.57	10	1161	498.81	0.94
2.5	1168.5	1059.01	7.03	10.5	1160.5	446.62	0.70
3	1168	1023.68	6.51	11	1160	385.17	0.49
3.5	1167.5	994.22	6.00	11.5	1159.5	310.46	0.32
4	1167	966.12	5.51	12	1159	230.26	0.18
4.5	1166.5	937.44	5.04	12.5	1158.5	134.96	0.09
5	1166	907.98	4.58	13	1158	67.58	0.04
5.5	1165.5	878.89	4.13	13.5	1157.5	41.86	0.02
6	1165	847.18	3.70	14	1157	8.22	0.00
6.5	1164.5	814.92	3.28	14.5	1156.5	2.39	0.00
7	1164	779.62	2.88	15	1156	0.70	0.00
7.5	1163.5	741.23	2.50				

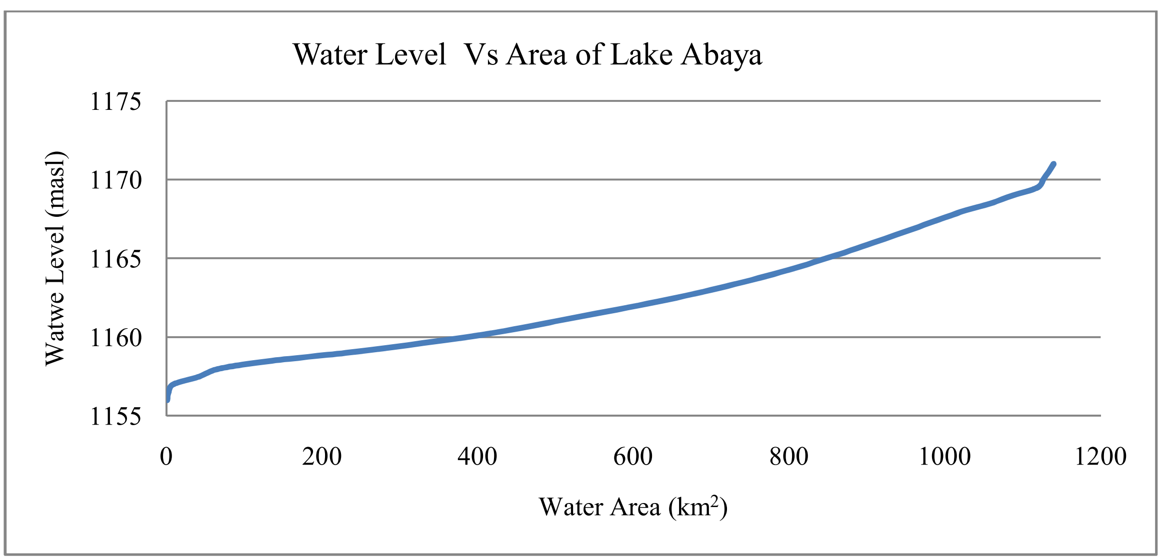


Figure 18 Area Curve of Lake Abaya (Seleshi B. 2006)

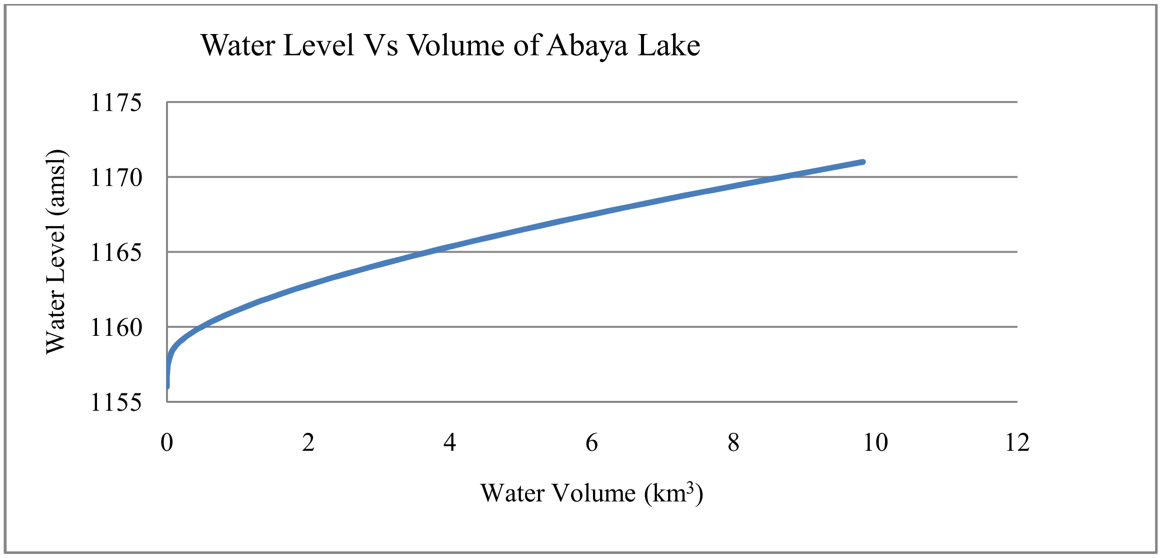


Figure 19 Volume Curve of Lake Abaya (Seleshi B. 2006)

4.1.4. Lake Level

The main water source for the lake is the inflows of the Bilate, Gidabo, Gelana, Hamesa and Harie Rivers. The mean annual inflows of these rivers are 568.87 MCM, 204.55 MCM, 146.75 MCM, 53.75 MCM, and 60.15 MCM respectively. The total catchment area of Lake Abaya is 14243.78 km^2.

The total annual average inflow in to the lake can be calculated by the sum of the Bilate, Gidabo, Gelana, Hamesa, and Harie Rivers and runoff water from the un-gauged Sub-catchment. The lake mean monthly as well as mean annual water level time series of Lake Abaya shows an increasing trend.

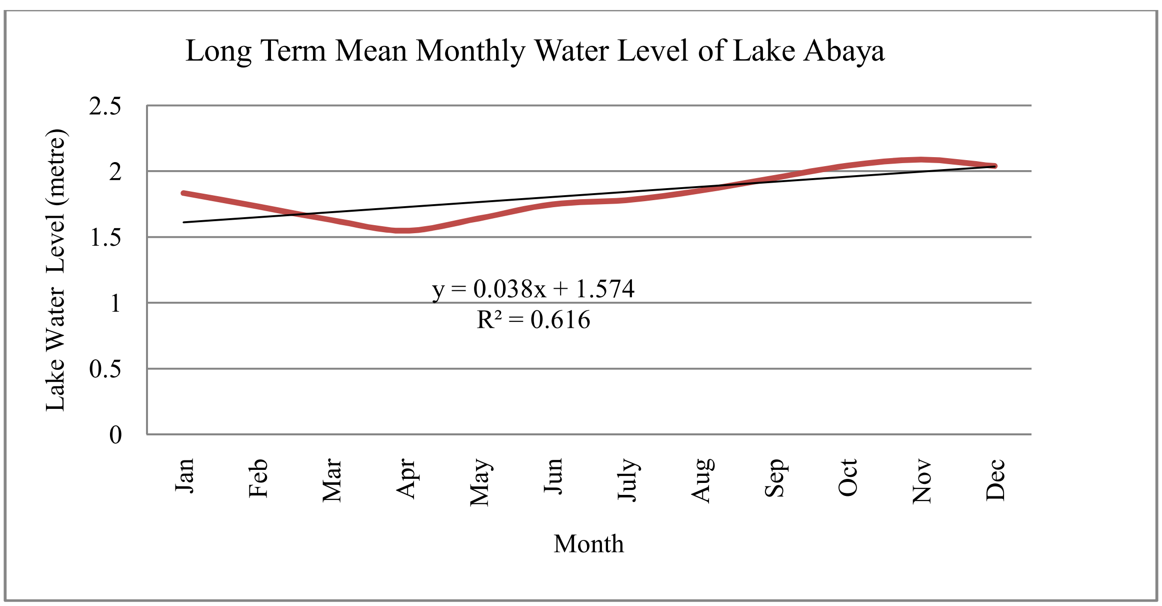


Figure 20 Long Term Mean Monthly Water Level of Lake Abaya (Reference Level 1171masl)

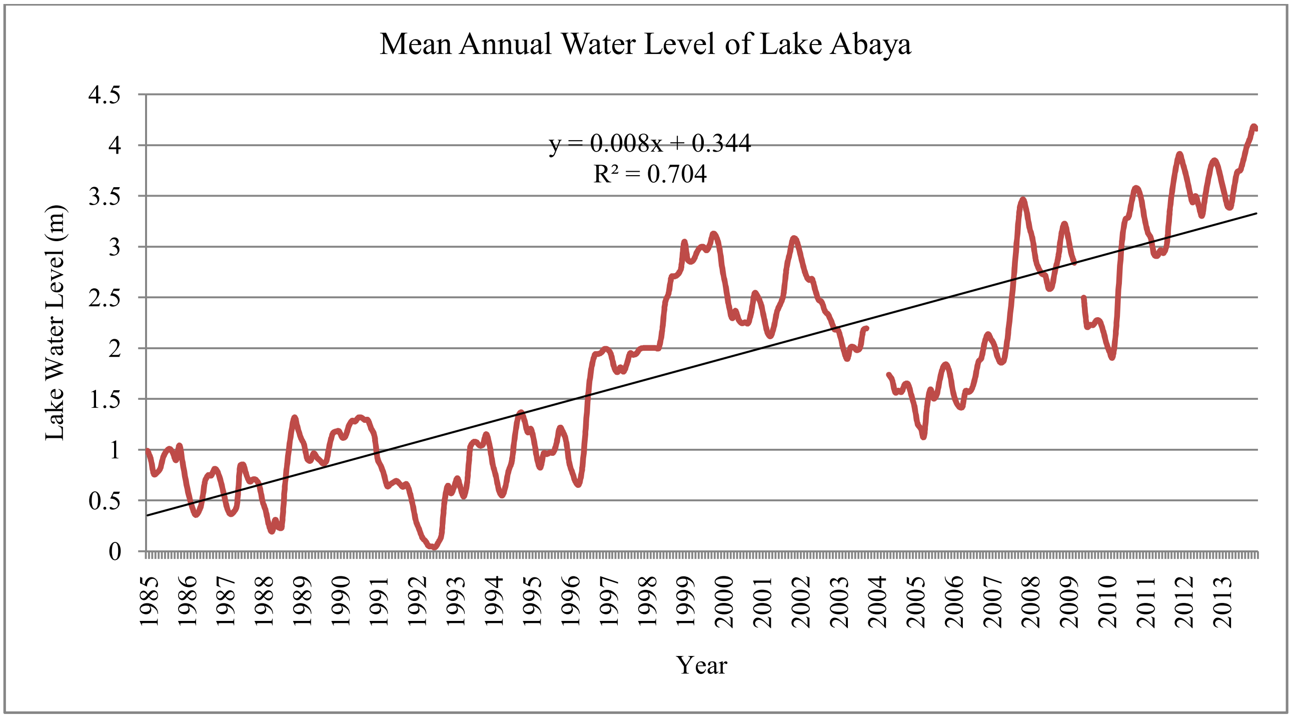


Figure 21 Mean Annual Water Level of Lake Abaya (Reference Level 1171masl)

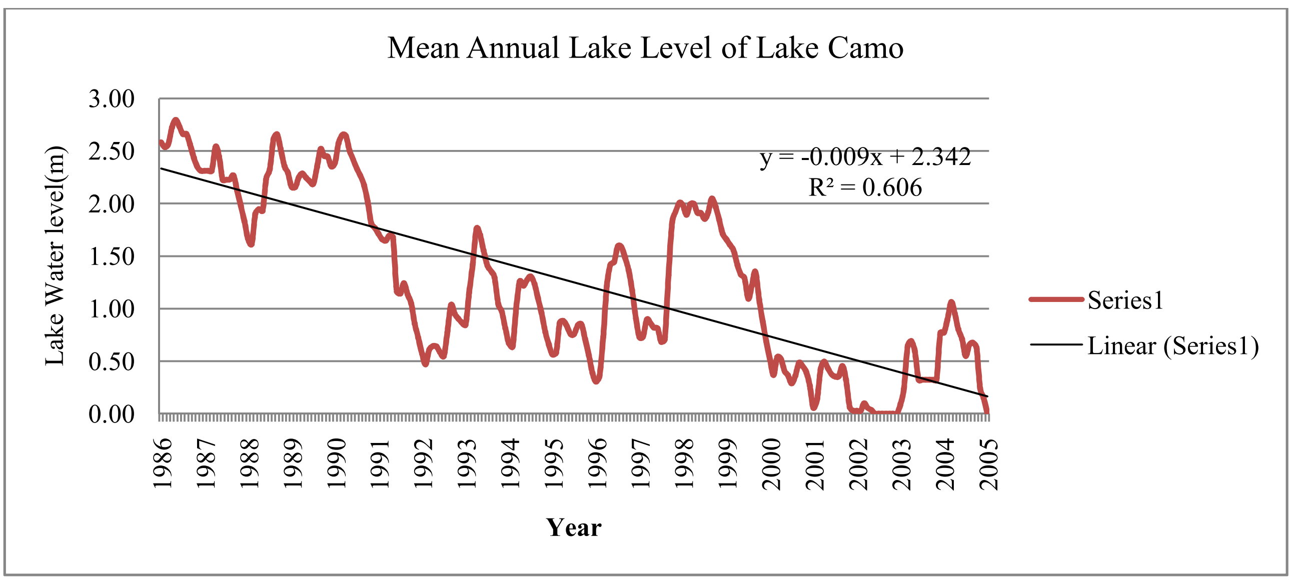


Figure 22 Mean Annual Lake Level of Lake Chamo (Reference level 111masl)

4.1.5. Stream flow and Lake Level

To analyze the relation of the inflow and Lake Level, 35 years data of Bilate, 30 years data of Gidabo, 24 years data of Gelana, 22 years data of Hamesa, 23 years data of Harie and 29 years data of Abaya Lake level are used.

Table 2 Long Term Mean Monthly Discharge of Main Rivers to Lake Abaya (MCM) (Ministry of Water, Irrigation and Electricity)

Watershed	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Bilate (@Bilate Tena)	7.65	8.8	18.69	28.85	36.39	42.99	64.45	97.85	119.96	88.09	47.04	8.11	568.87
Gidabo (Nr. Aposto)	5.92	5.05	6.79	13.34	22.3	18.75	18.28	26.91	29.69	34.85	14.38	8.29	204.55
Gelana (Nr. Tore)	4.26	2.55	2.78	7.76	24.92	18.94	10.21	10.22	14.1	25.17	18.36	7.48	146.75
Hamessa (Nr. Wajifo)	0.97	0.75	1.68	5.08	6.76	5.84	7.89	10.4	5.63	4.81	2.88	1.06	53.75
Harie (@Arba Minch)	2.95	2.64	2.99	4.73	7.54	5.56	5.7	6.3	6.51	7.12	4.39	3.72	60.15
Monthly Total	21.75	19.79	32.93	59.76	97.91	92.08	106.53	151.68	175.89	160.04	87.05	28.66	1034.07

Table 3 Long Term Mean Monthly Lake Level (m) of Lake Abaya (Reference Point 1171masl)

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Lante	1.83	1.73	1.63	1.55	1.64	1.75	1.78	1.85	1.95	2.04	2.09	2.04

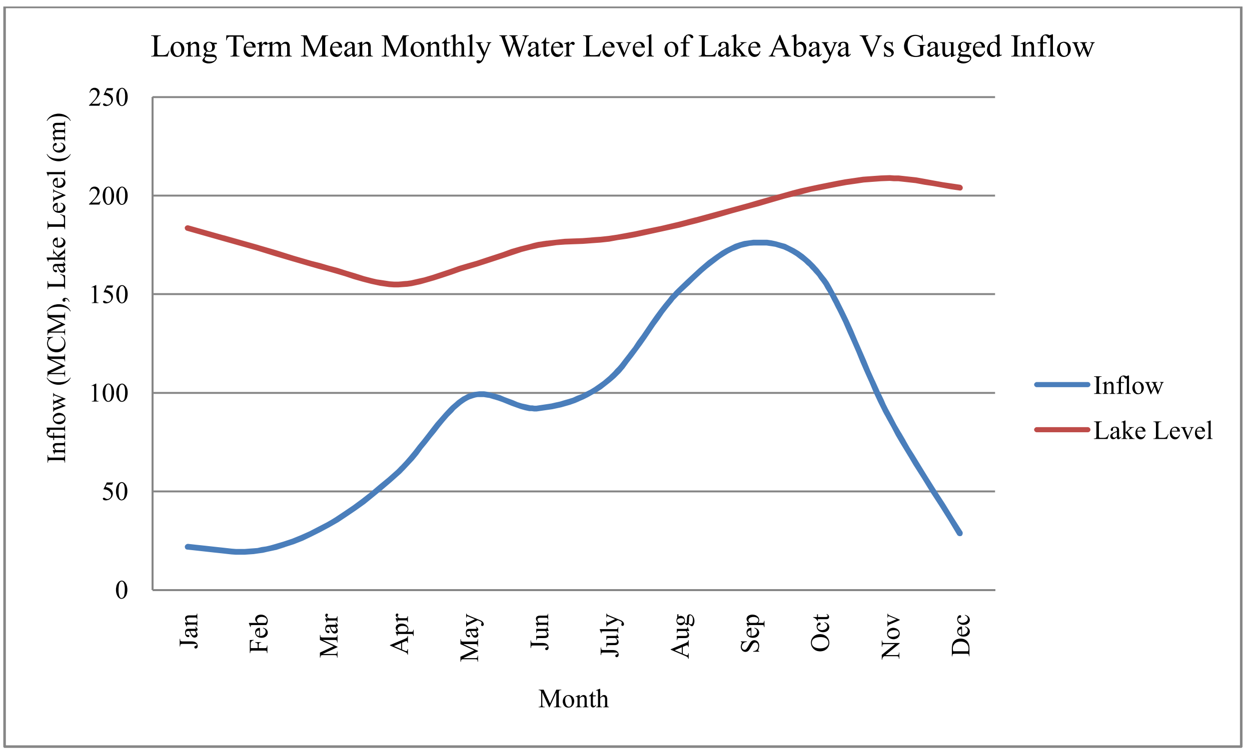


Figure 23 Long Term Mean Monthly Lake Water Level of Lake Abaya Vs Gauged Inflow

As it can be observed from Table 3 and 4, and figure 23 peaks of lake level and peak discharges of rivers inflow to the lake do not coincide. There is about 60 days (two month) lag time between peak of inflow and that of lake level; this is due to lake routing. Lake level is more dependent on Bilate, Gidabo and Gelana Rivers than Hamesa and Harie Rivers runoff.

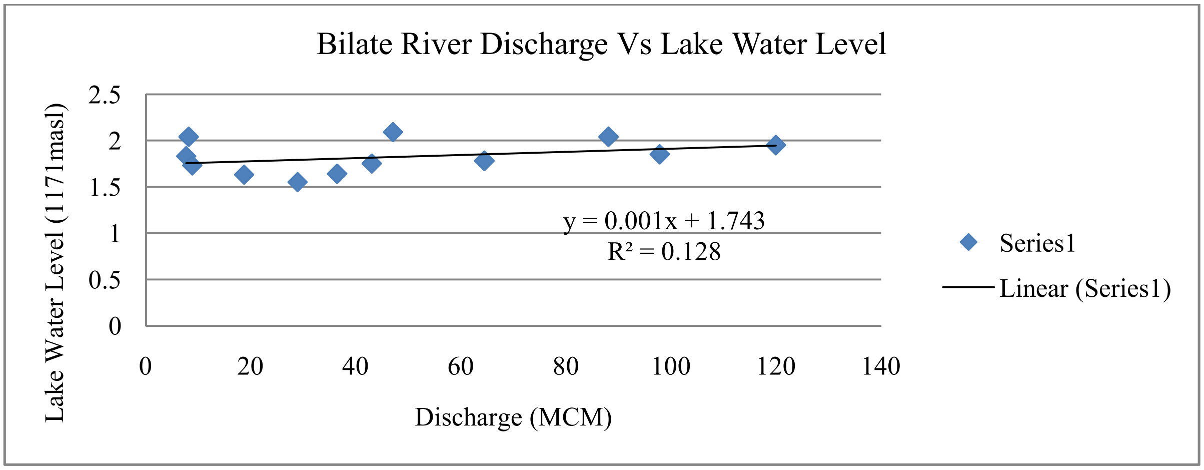


Figure 24 Scatter Plot between Long Term Mean Monthly Discharge of Bilate River and Lake Abaya Water Level (Lagged by Two Months)

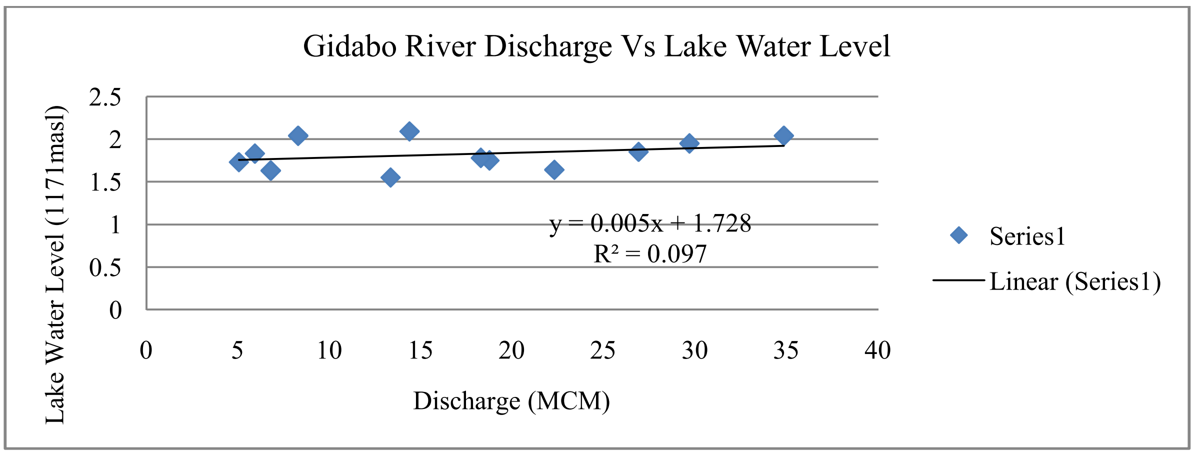


Figure 25 Scatter Plot between Long Term Mean Monthly Discharge of Gidabo River and Lake Abaya Water Level (Lagged by One Month)

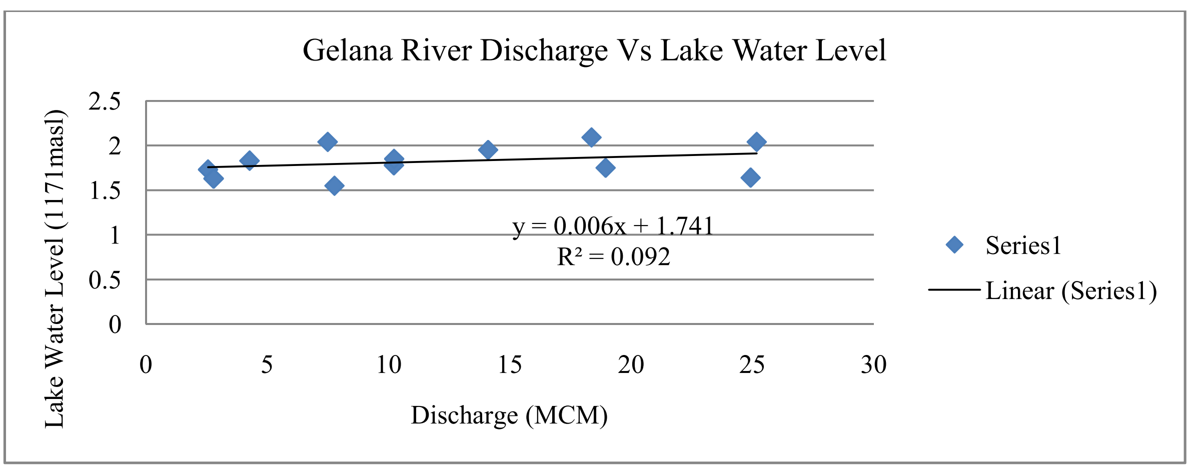


Figure 26 Scatter Plot between Long Term Mean Monthly Discharge of Gelana River and Lake Abaya Water Level (Lagged by One Month)

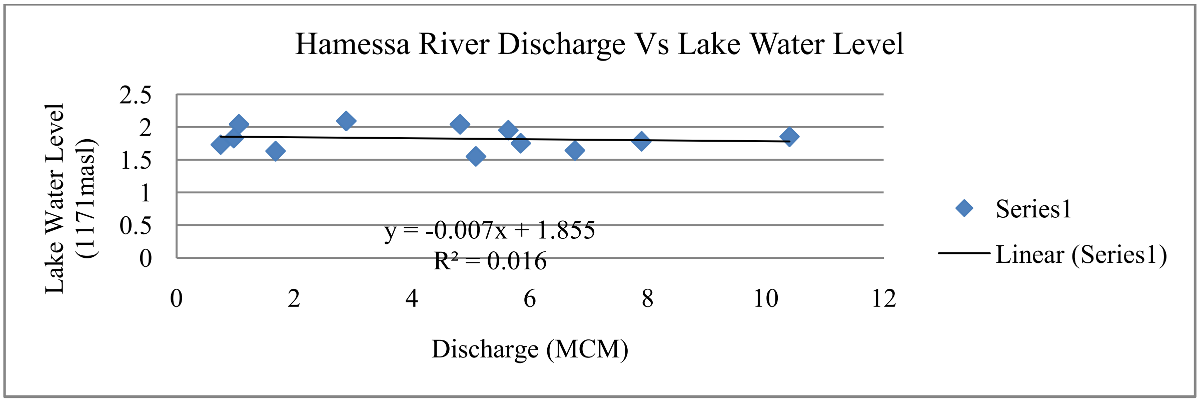


Figure 27 Scatter Plot between Long Term Mean Monthly Discharge of Hamessa River and Lake Abaya Water Level (Lagged by Three Months)

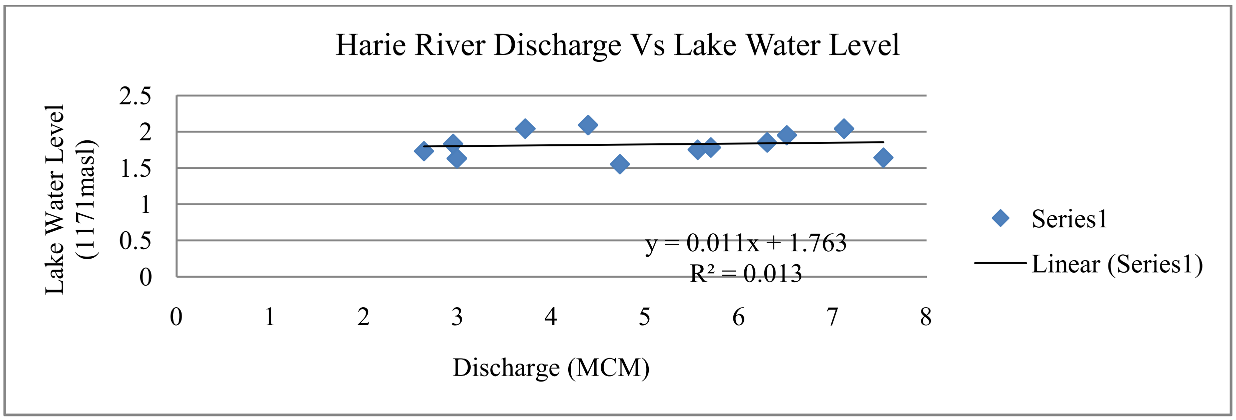


Figure 28 Scatter Plot between Long Term Mean Monthly Discharge of Harie River and Lake Abaya Water Level (Lagged by Six Months)

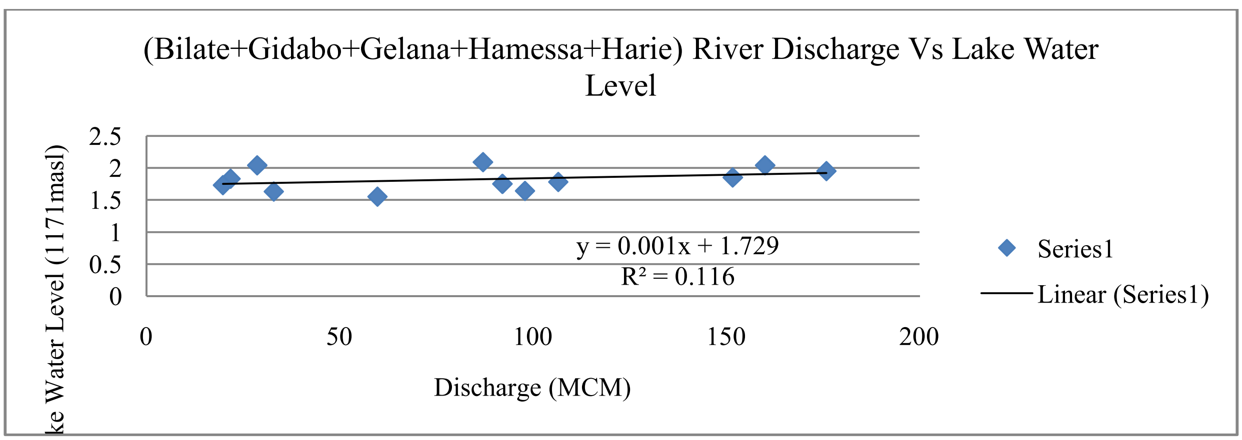


Figure 29 Scatter Plot between Long Term Sum of Mean Monthly Discharge of all Rivers and Lake Abaya Water Level (Lagged by Two Months)

The Lake Level of Lake Abaya shows a marked variations or amplifying change in hydro-meteorological conditions.

4.2. Rainfall Data Analysis

4.2.1. Analysis of Point Rainfall Data

The data from a precipitation gauge are subject to two regular problems. A gauge site (station) may have a short break in the record of instrument failure or absence of the observer. It is often necessary to estimate the missing record. Another problem is that the recording conditions at a gauge site may have changed significantly some time during the period of the record, due to relocation or up grading of the station in the same vicinity, difference in observational procedure, or any other reason. The problem is resolved in both cases by comparisons with the neighboring gauge site. Table 4 shows the distribution of the mean annual rainfall in the study area.

Rainfall is the lowest in the vicinity of the lakes, on the valley flanks and on hill masses, rainfall rises steadily with elevation to a maximum of 1675mm at around 1836masl.

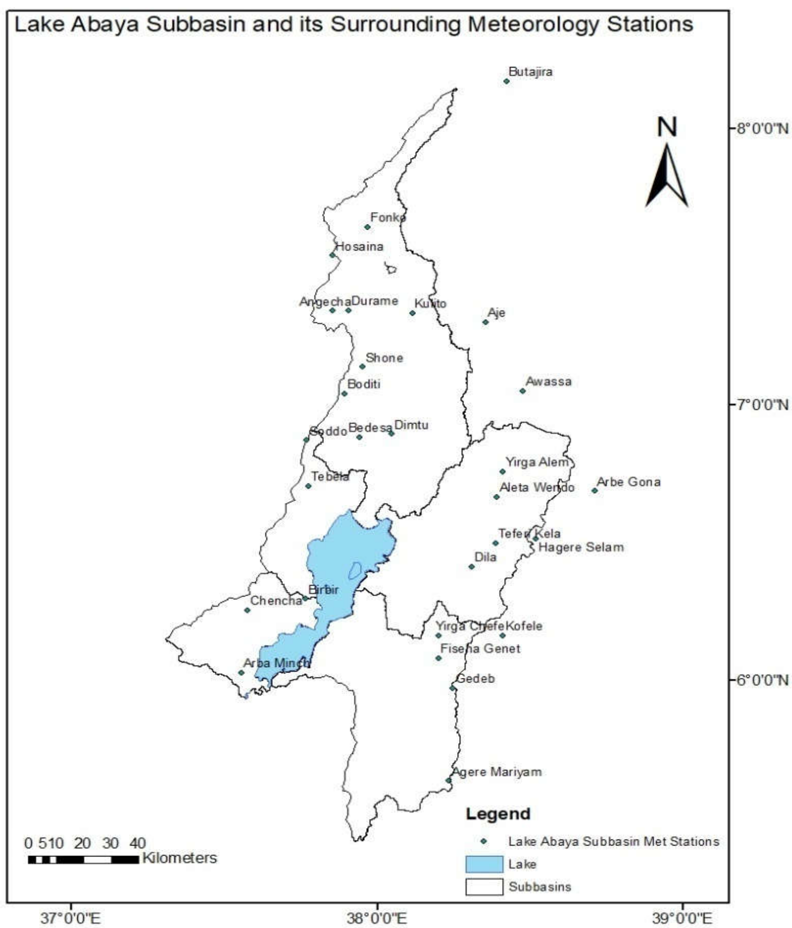


Figure 30 Meteorological Stations of Lake Abaya Sub-basin and its Surrounding

Table 4 Mean Annual Rainfall Distribution of Lake Abaya Sub-basin

Station	Year	Elevation (mamsl)	Mean Annual Rain Fall (mm)	Station	Year	Elevation (mamsl)	Mean Annual Rain Fall (mm)
Arba Minch	1987-2017	1266.2	905	Dilla	1988-2017	1511.47	1416
Chencha	1989-2011	2705.84	1359	Fiseha Genet	1986-2017	2219.08	1371
Aje	1986-2017	1846.28	664	Hagere Mariam	1986-2017	1823.65	878
Alaba Kulito	1986-2017	1801.77	1067	Humbo	1988-2017	1592.49	1117
Angecha	1987-2017	2265.34	1455	Wolaita	1986-2017	2097.41	1256
Butajira	1986-2017	2028.4	1089	Yirga Alem	1991-2017	1735.16	1221
Durame	1986-2005	2231.77	1175	Hagere Selam	1986-2016	2670.64	1298
Hosaina	1986-2017	2235.56	1186	Yirga Chefe	1986-2016	1895.56	1368
Shone	1986-2017	1949.5	1430	Arbe Gona	1986-2016	2539.61	856
Mirab Abaya	2008-2017	1248.04	777	Awassa	1986-2016	1768.72	968
Aleta Wendo	1986-2017	1802.53	1570	Fonko	1986-2016	2271.4	1240
Bedessa	1987-2012	1598.08	1114	Gedeb	1986-2016	2625.87	1436
Bilate Tena	1986-2015	1550.5	897	Kofele	1986-2016	2668.59	1212
Bodite	1986-2017	1832.15	1216	Teferi Kella	1986-2016	1836.58	1675

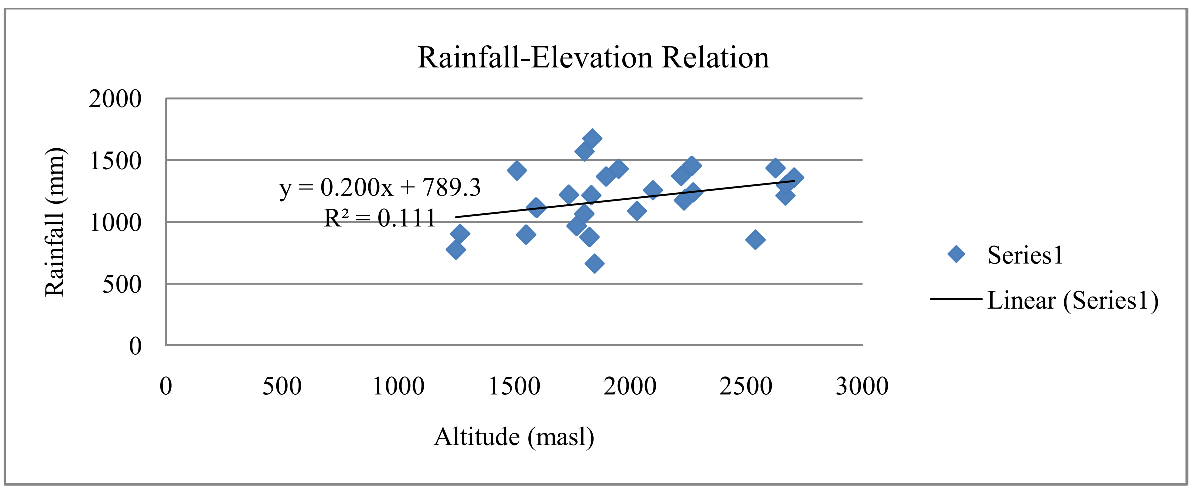


Figure 31 Scatter Plot of Mean Annual Rainfall Vs Elevation of Lake Abaya Sub-basin

Precipitation in the catchment varies with altitude. High altitude areas receive mean annual rainfall of over 1200 mm while the lake area gets average depth of about 775 mm. However, the correlation coefficient between precipitation and altitude is not very strong due orographic effect and is found to be 0.1118.

There is significant orographic effect on the spatial distribution of precipitation over the area. Areas close to mountains of eastern highland get higher mean annual precipitation than areas found far away from the mountainous region even if the later ones are in higher altitudes. One good example of this effect is the difference between Dilla and Yrga Alem; where the mean annual precipitation and altitude of Dila is 1416 mm and 1511.47masl respectively, while that of Yirga Alem, is 1221mm and 1735.16masl. In addition, western half of the area gets higher spring (March to May) rainfall than the eastern half.

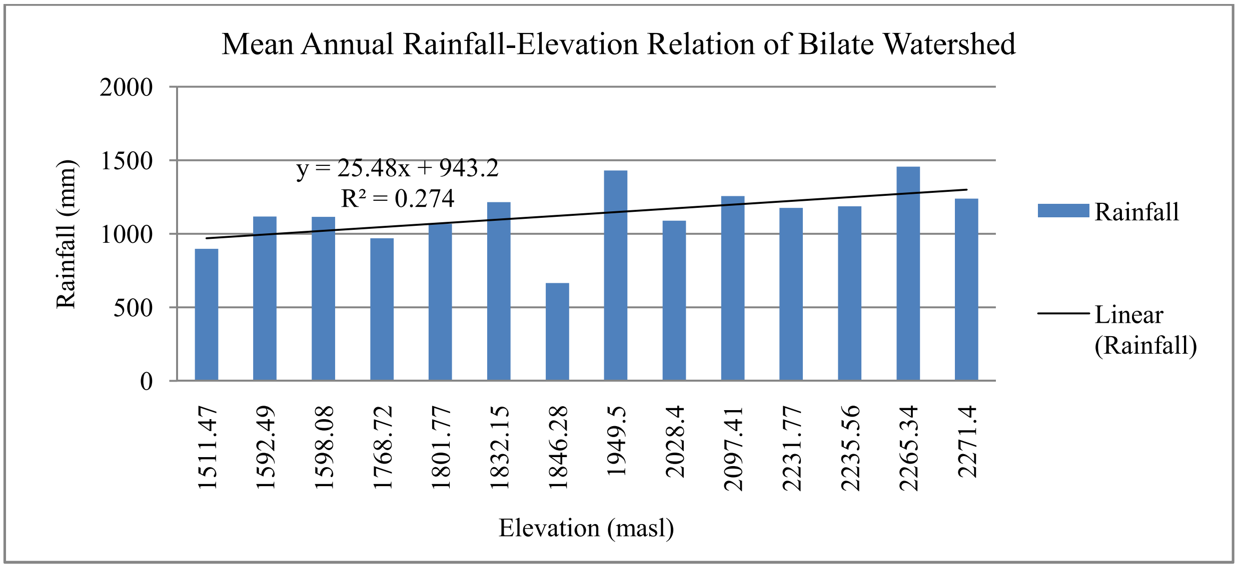


Figure 32 Mean Annual Rainfall-Elevation Relation of Bilate River Watershed

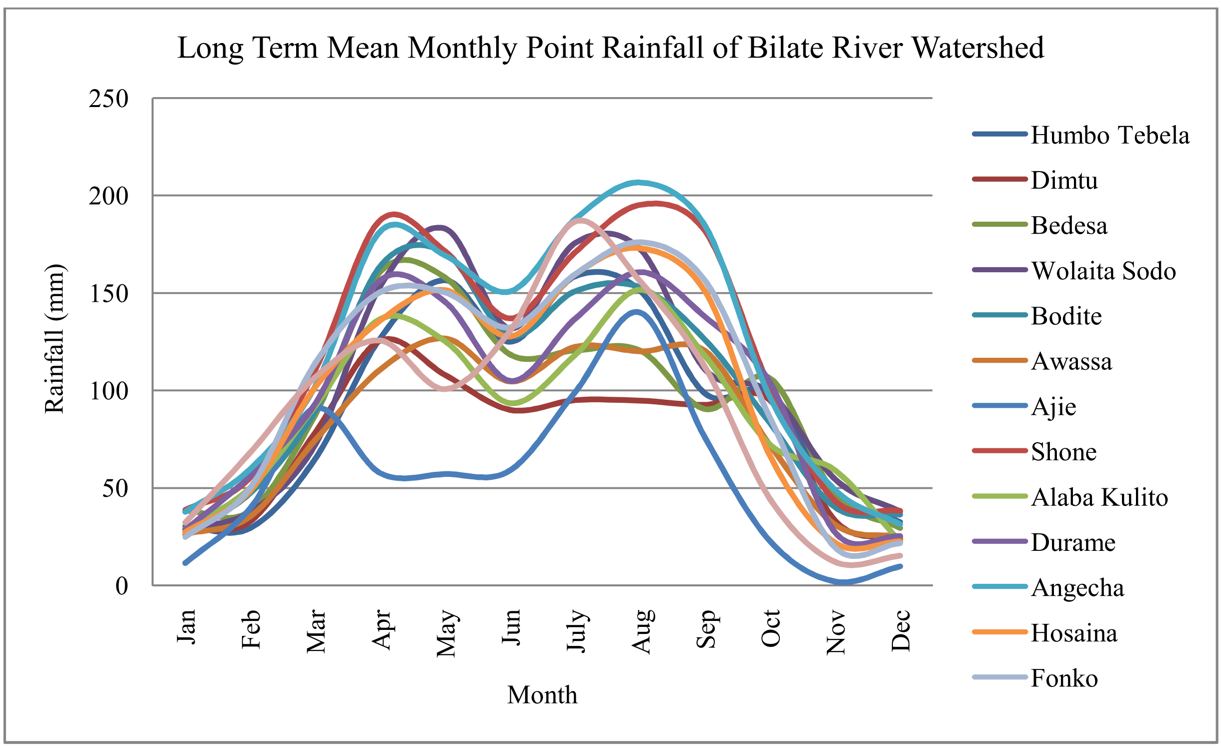


Figure 33 Long Term Mean Monthly Point Rainfall of Bilate River Watershed

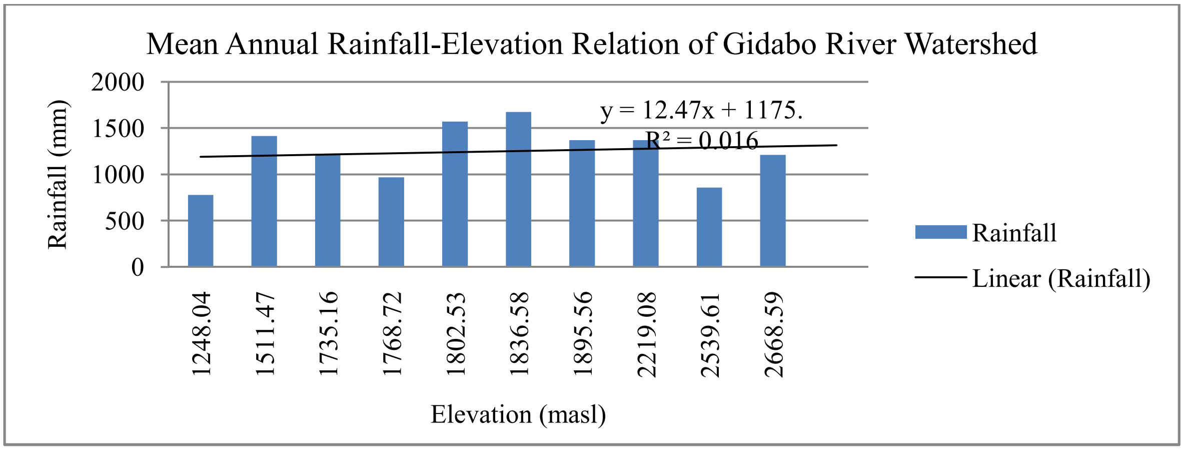


Figure 34 Mean Annual Rainfall- Elevation Relation of Gidabo River Watershed

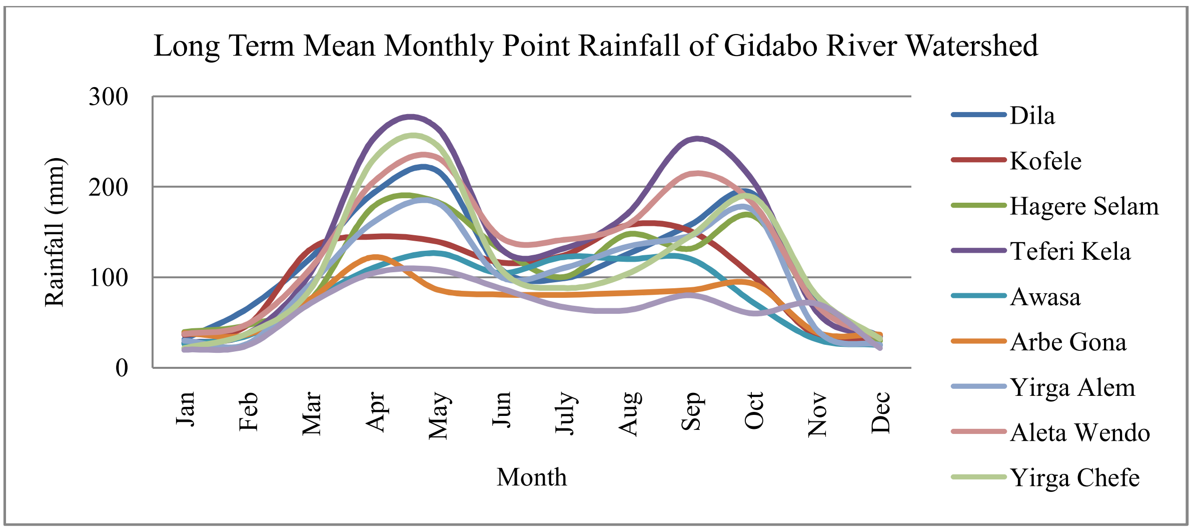


Figure 35 Long Term Mean Monthly Point Rainfall of Gidabo River Watershed

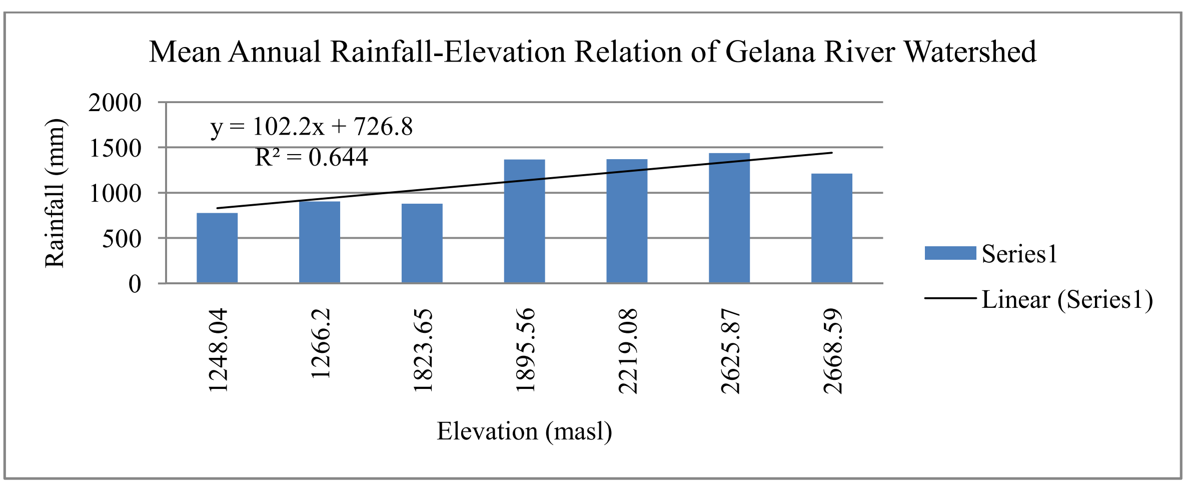


Figure 36 Mean Annual Rainfall-Elevation Relation of Gelana River Watershed

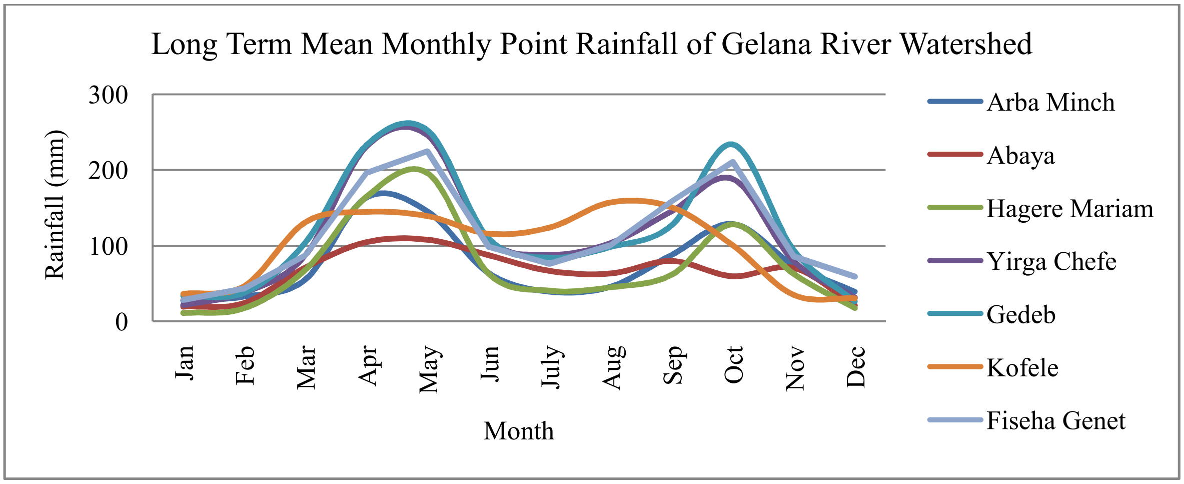


Figure 37 Long Term Mean Monthly Point Rainfall of Gelana River Watershed

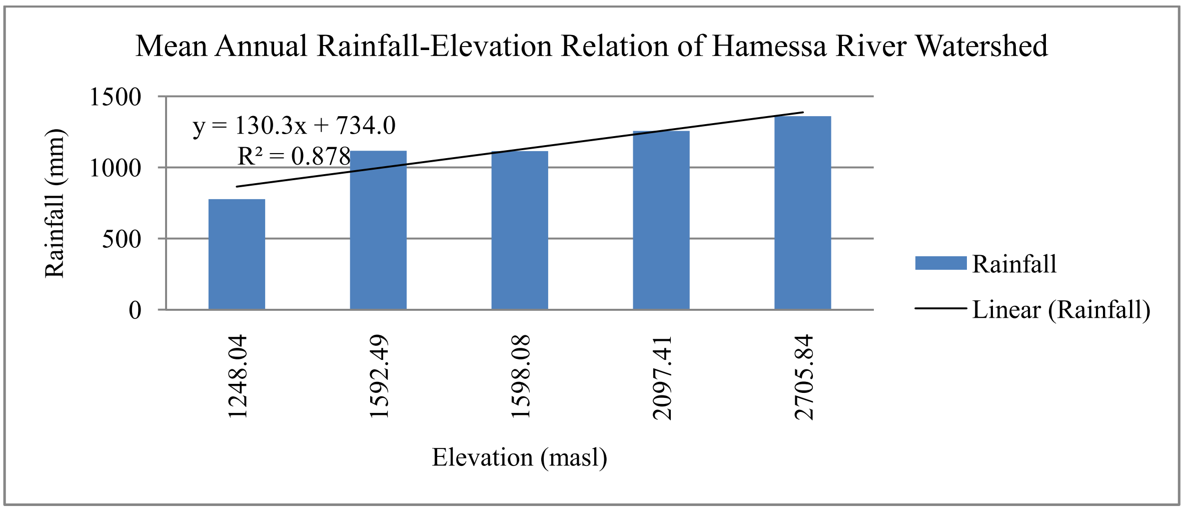


Figure 38 Mean Annual Rainfall- Elevation Relation of Hamessa River Watershed

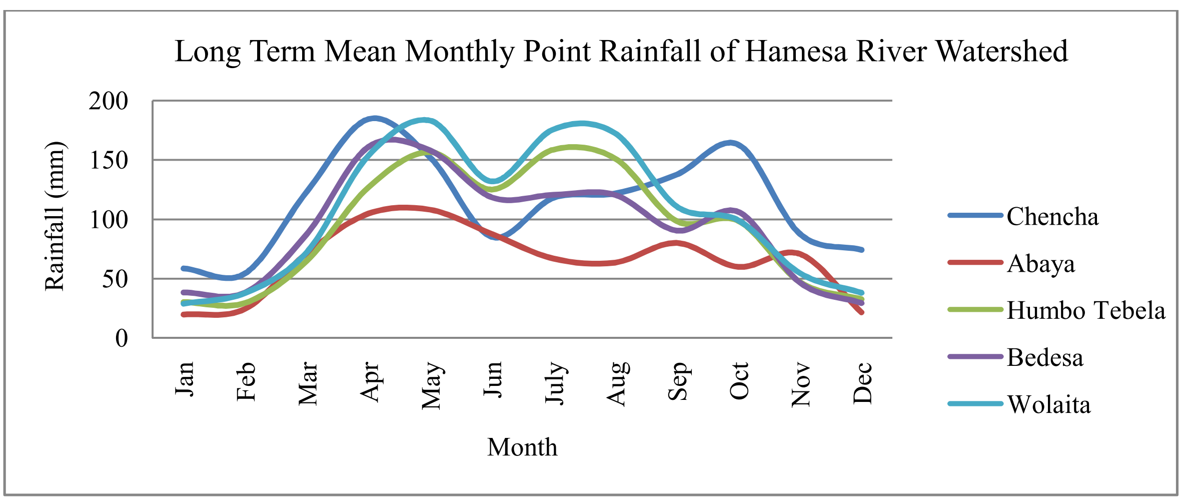


Figure 39 Long Term Mean Monthly Point Rainfall of Hamessa River Watershed

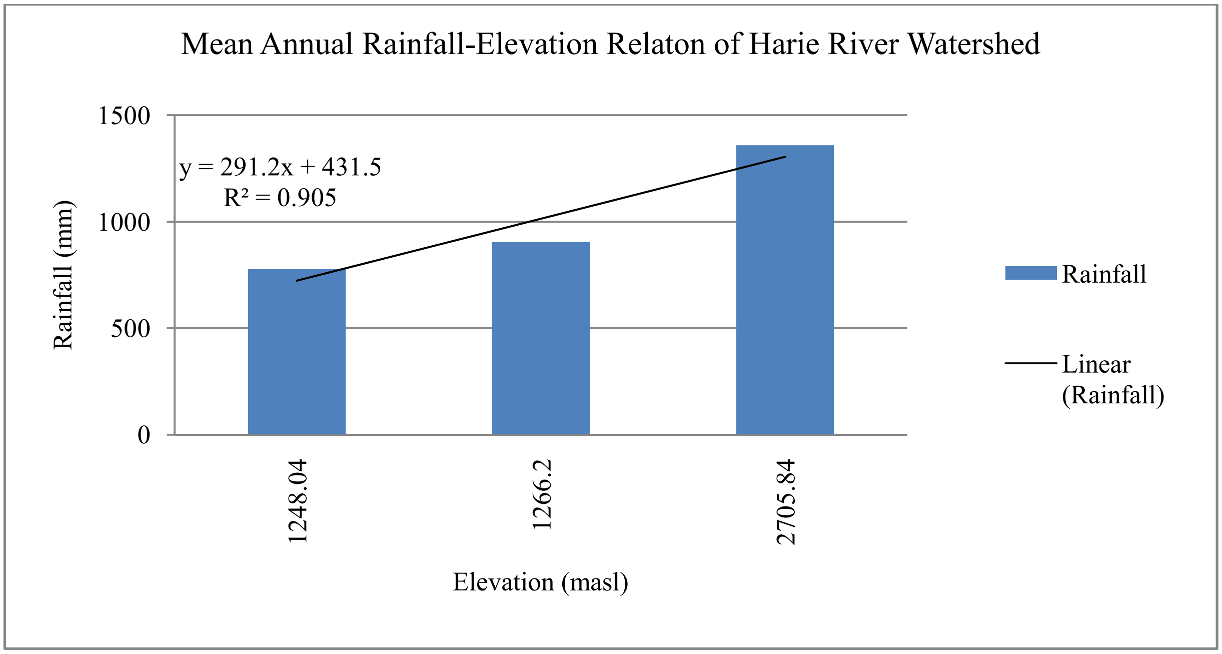


Figure 40 Mean Annual Rainfall- Elevation Relation of Harie River Watershed

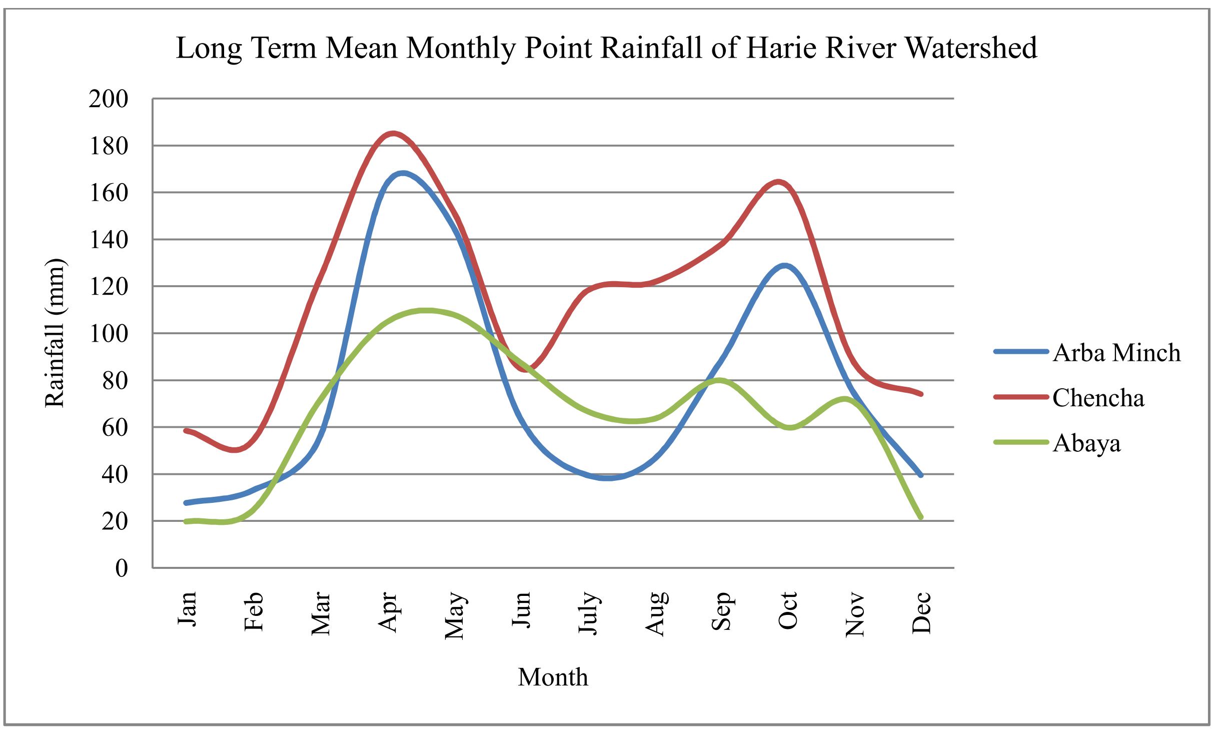


Figure 41 Long Term Mean Monthly Point Rainfall of Harie River Watershed

4.2.1.1. Identification of Homogeneous Rainfall Stations Based on Monthly Rainfall

The dimensionless computations of all stations where carried out for all 28 stations used in analyses and the profile plotted.

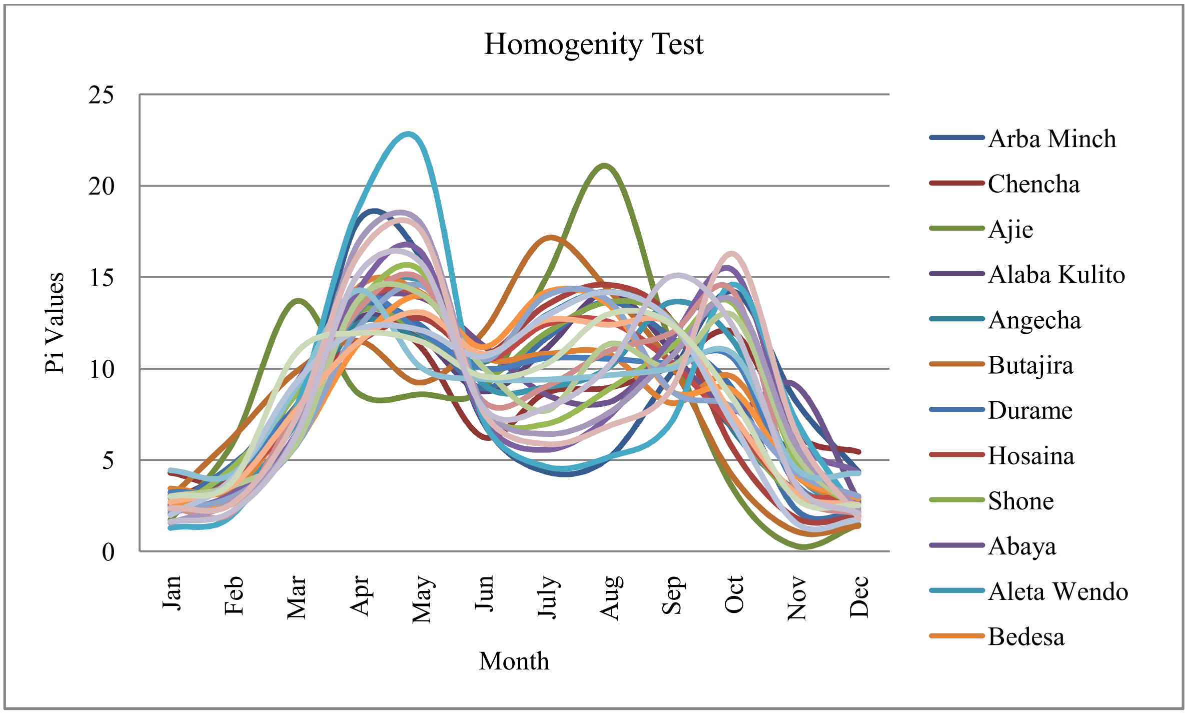


Figure 42 Homogeneity Test

Even though the basin has somewhat similar rainfall characteristics there is slight difference according to the river basin and elevation of the station with respect to each other.

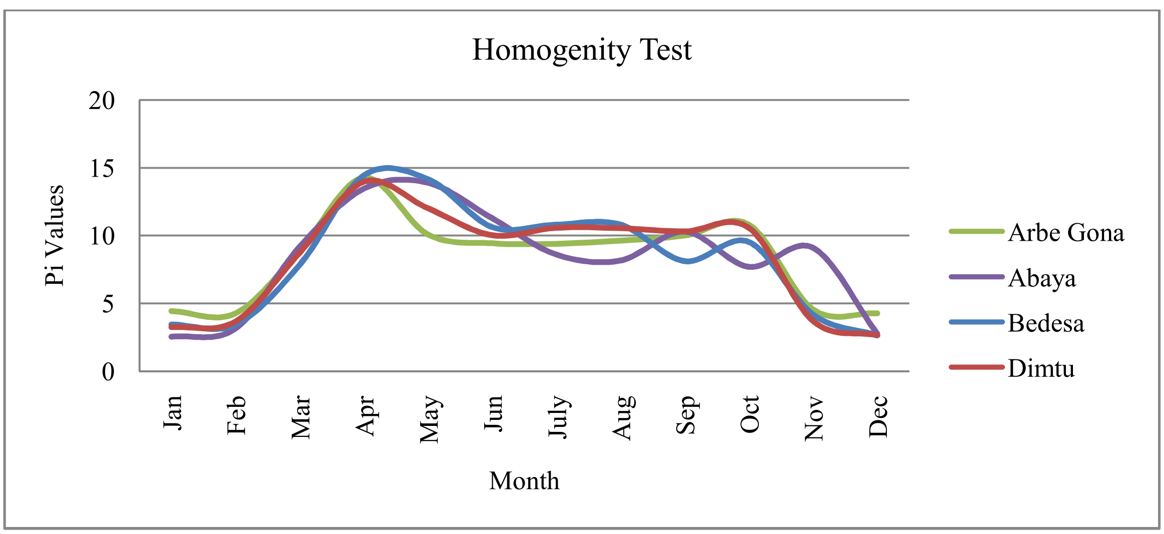


Figure 43 Homogenity Test of Four Meteorological Stations

The rainfalls at Arbe Gona, Abaya, Bedesa and Dimtu are Bimodal, maximum peak in April to May and going decreasing slowly the second (minimum) peak in between July to September. Bedesa and Dimtu Met stations in Bilate River watershed, Arbe Gona Met station in Gidabo River Watershed, and Abaya Met station is found in Hamesa River Watershed.

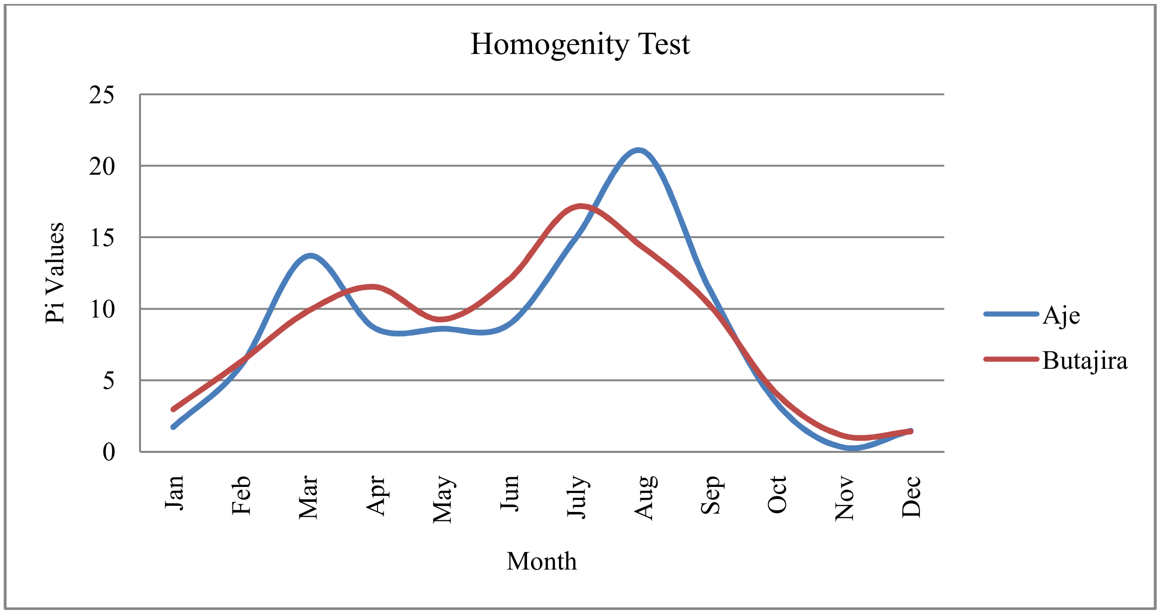


Figure 44 Homogeneity Tests of Two Meteorological Stations

The rainfalls at Ajie and Butajira are Bimodal, minimum peak in between Mar to Apr and second (maximum) peak in July to Sep. Both Ajie and Butajira Met stations are found in Bilate River Watershed.

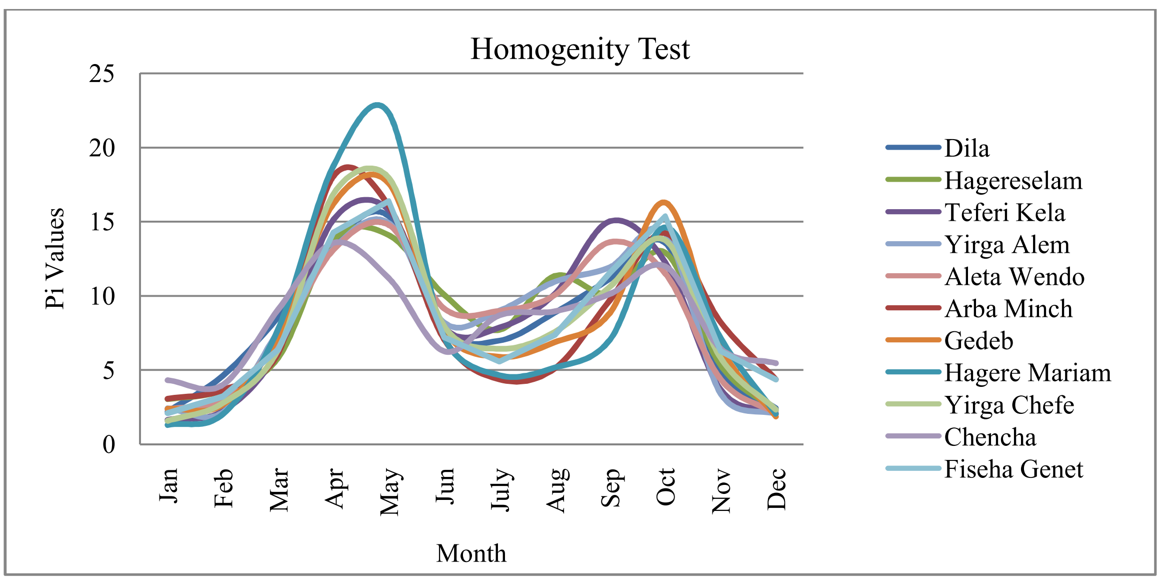


Figure 45 Homogeneity Tests of Eleven Meteorological Stations

The rainfalls at Dila, Hagere Selam, Teferi Kela, Yirga Alem, Aleta Wendo, Arba Minch, Gedeb, Hagere Mariam, Yirga Chefe, Chencha, and Fiseha Genet are Bimodal, maximum peak in April to May and going decreasing rapidly the second (minimum) peak in between Aug to Oct. Dila, Hagere Selam, Teferi Kela, Yirga Alem, and Aleta Wendo Met stations are in Gidabo River Watershed; Arba Minch, Gedeb, Hagere Mariam, Yirga Chefe, and Fiseha Genet Met stations are in Gelana River Watershed; and Chencha Met station is found in Harie River Watershed.

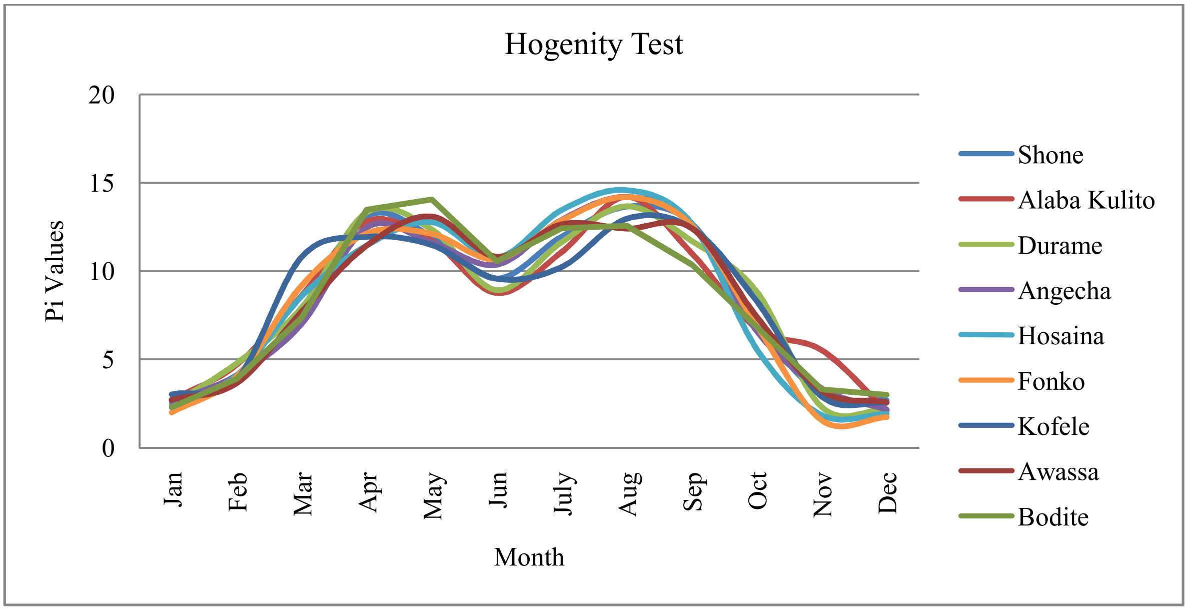


Figure 46 Homogeneity Tests of Nine Meteorological Stations

The rainfalls at Shone, Alaba Kulito, Durame, Angecha, Hosaina, Fonko, Kofele, Awassa, and Bodite Met stations are Bimodal, the two peaks are almost equal, the first peak is from Mar to May and the second peak is Jul to Sep. Shone, Alaba Kulito, Durame, Angecha, Hosaina, Fonko, Awassa, and Bodite Met stations are in Bilate River Watershed and Kofele Met station is found in Gidabo River Watershed.

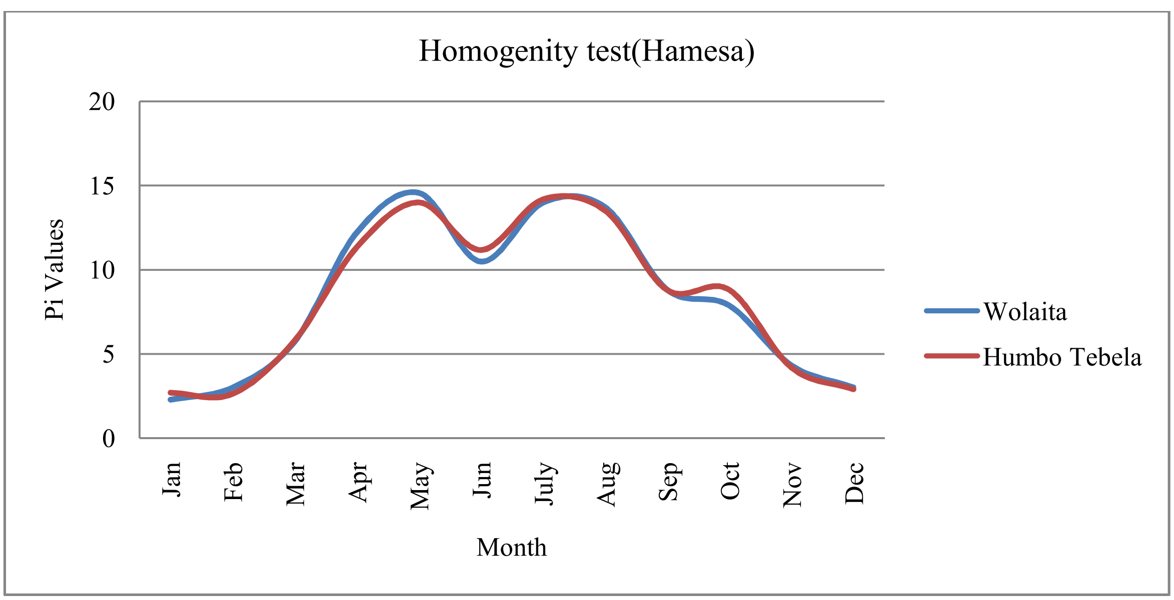


Figure 47 Homogeneity Tests of Two Meteorological Stations

The rainfalls at Wolaita and Humbo Tebela are Bimodal, the two peaks are almost equal and the second peak decrease slowly, the first peak is from Apr to May and the second peak in between Jul to Aug. Wolaita and Humbo Tebela Met stations are in Hamsa River watershed.

Generally, the rainfall distribution is divided in to three patterns in the Abaya catchment i.e. is normal bimodal with almost equal peaks, bimodal with the maximum left skewed and bimodal with the maximum right skewed.

4.2.1.2. Estimating Missing Data

Normal Ratio method is used to fill missed rainfall data in the study area since the difference in annual rainfall between most of the station exceeds 10% due to large elevation difference between the stations that is from the high mountains at Chencha about 3250masl to the floor of the rift valley 1250masl at Abaya stations. Selection of the station for the estimating the missing rainfall data is based on the homogeneity and similarity of the stations.

4.2.1.3. Checking Consistency of Data: Double Mass Analysis

Double mass curve analysis is carried out for 28 rainfall stations in the catchment. The curves show that all stations are consistent according to the criteria set. The grouping of the stations for the consistency checking is made according to the homogeneity test and topographic locations.

4.2.2. Lake Surface Areal Rainfall Distributions

In order to evaluate the rainfall component of the water balance which is falling on the Lake, gauging stations on the shore and inside the lakes are required. The number depends on climatic condition, relative importance of gauging stations, accuracy of measurements and other factors. In order to evaluate the rainfall component of the water balance which is falling on the Lake, gauging stations on the shore and inside the lakes are required. The number depends on climatic condition, relative importance of gauging stations, accuracy of measurements and other factors.

The total surface area of Lake Abaya excluding the Islands is 1095.06 Km^2 which receive direct precipitation on it. There are no meteorological stations on the lake; as a result the surrounding meteorological stations, such as Arba Minch, Chencha, Mirab Abaya, Dilla, and Humbo Tebela are used by virtue of their location with the lake, class and long period of observation consistency of the data base.

There are different methods of converting point precipitation to areal precipitation. Such as Station-Average Method, Theissen Polygon Method, Isohyetal Method. To determine the amount of precipitation water which falls directly on the Lake surface Thiessen Polygon Method used.

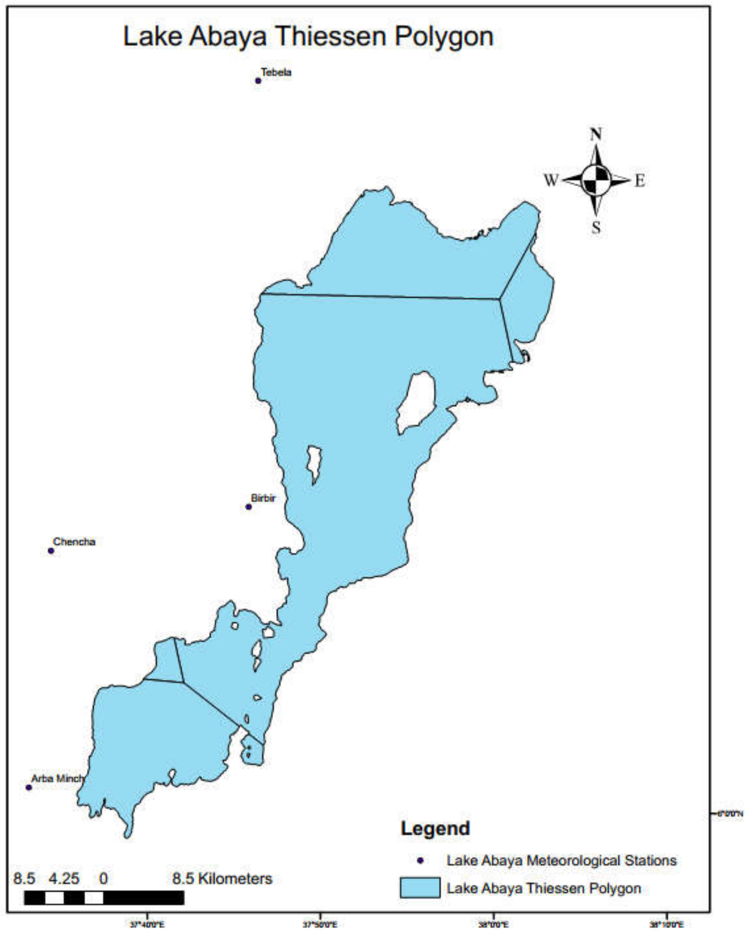


Figure 48 Lake Abaya Thissen Polygon

Table 5 Long Term Mean Monthly Areal Rainfall of Lake Abaya Lake Surface (MCM)

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Arba Minch	5.07	5.87	9.9	27.94	25.32	11.45	6.87	8.42	15.42	22.25	11.82	6.56	156.89
Chencha	0.57	0.55	1.31	2.29	2.02	1.15	1.39	1.4	1.58	1.88	0.95	0.57	15.66
Dila	1.27	2.63	5.05	7.62	8.45	4.27	3.93	4.92	6.17	7.43	2.72	1.25	55.71
Humbo Tebela	5.67	5.55	13.36	23.91	30.21	23.77	29.61	28.71	18.49	18.9	9.04	6.41	213.63
Mirab Abay	15.82	18.25	36.74	79.44	79.46	46.5	45.94	46.22	51.5	58.97	33.79	18.16	530.79
Monthly Total	28.4	32.85	66.36	141.21	145.46	87.15	87.74	89.66	93.16	109.42	58.32	32.95	972.68

The total volume of Precipitation Water on Lake Abaya is 972.68 MCM.

4.3. Evaporation

Evaporation is the process by which the phase of water is changed from a liquid to a vapor and is considered from two aspects: evaporation from an open water surface and evapo-transpiration, which is the evaporation of intercepted water and transpiration from vegetation. In areas where annual rainfall is low, evaporation losses can represent a significant part of the water budget for a lake, and evaporation losses may contribute significantly to the lowering of the water surface elevation.

For using the component evaporation, the values obtained by different methods are shown in table 6. For this study the result obtained by Pan Method is used for further analysis.

The total amount of evaporated water in volume from Lake Abaya per year is 2399.5 MCM.

Table 6 Long Term Mean Monthly Water Surface Evaporation of Lake Abaya (MCM)

Methods	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Pan	232.06	225.38	233.03	199.19	202.27	187.8	166.03	172.08	165.04	186.72	212.44	217.46	2399.5
Cropwat	142.73	142.28	164.89	145.83	143.37	123.86	116.51	127.56	137.77	140.10	134.26	134.89	1654.06
Penman	197.33	197.37	225.43	199.24	194.46	170.85	163.71	179.70	190.07	191.01	182.66	184.09	2275.92

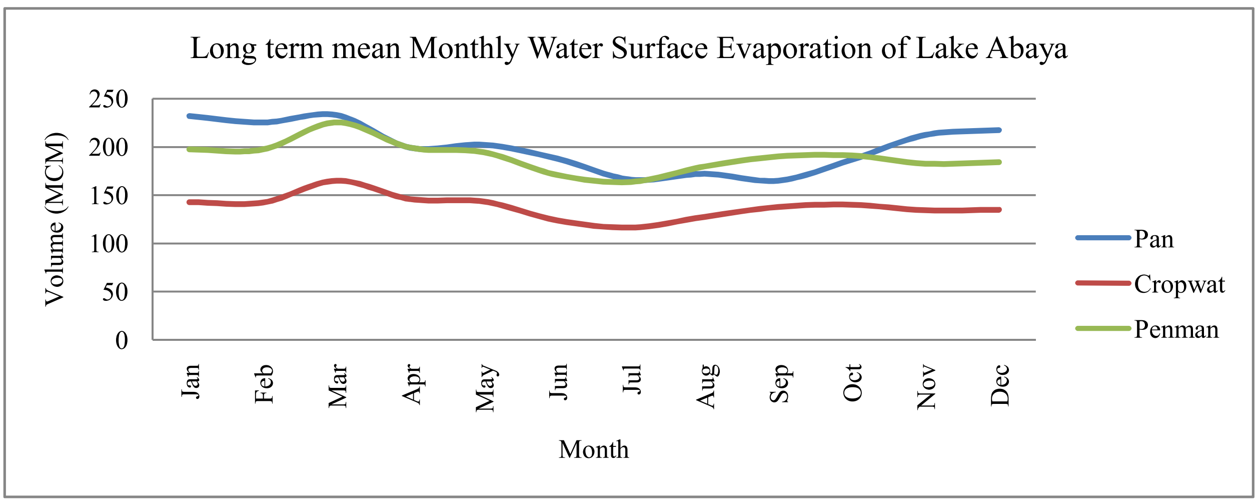


Figure 49 Long Term Mean Monthly Water Surface Evaporation of Lake Abaya

Net Evaporation=Total amount of evaporated water in volume from the lake-Total amount of precipitated water in volume on the lake

Net Evaporation=2399.52MCM - 982.56MCM

= 1416.96 MCM

CHAPTER FIVE

5. LAKE WATER BALANCE MODEL

5.1. Lake Water Balance Simulation

In order to understand the basic hydrological process, water balance computation of the lake is made using excel spread model. This model approach stems on solving the lake water balance equations.

5.1.1. Reservoir Storage

Lake level record at Lante is available for 29 years (1985 to 20013). Area Vs Elevation and Volume Vs Elevation curves as presented on Figure 18 and 19, section 4.1.3 are used for the water balance simulation of the lake. During the simulation process, storage is read from these curves applying the data obtained from lake level records. The storage of Lake Reservoir is obtained from the lake bathymetric survey which is conducted by Sleshi Bekele in 2006, which is 9.842 km^3 (9842 MCM).

5.1.2. Gauged Surface Runoff

After infilling the missing data, surface runoff for five gagging stations on Bilate, Gidabo, Gelana, Hamesa and Harie are considered for Water balance simulation of the reservoir.

5.1.3. Areal Rainfall over the Lake

Arba Minch, Chencha, Birbir (Mirab Abaya), Dilla, and Humbo Tebela, meteorological gauging stations are selected by virtue of their location with the lake, class and long period of observation consistency of the data base to calculate the precipitation on the lake surface using Thiessen polygon method. The available rainfall records for the period 1987-2013 have been considered for the inflow magnitude to the lake. Since the water balance is conducted on the basis of monthly time interval, monthly rainfall series have been adopted.

5.1.4. Lake Evaporation

Arba Minch meteorological station with 30 years (1987-2016) Monthly data is used to estimate open water surface evaporation. Result of evaporations obtained using Pan method is used in the simulation processes.

5.1.5. Abstractions

Irrigation activities in the lake catchments are common all year round due to scarcity of rainfall. According to Halcrow (2008) report 1971ha are directly dependent on Lake Abaya, 3746ha on Bilate River, 180ha on Gidabo River, 1579 on Gelana River, 2224ha on Harie River and 206ha on Hamessa

River. Then at present a total of 9906ha of land is directly or indirectly irrigated by the water from Lake Abaya with common crops of Banana, Tobacco, Cotton, Vegetables and diversified crops.

The abstraction for irrigation from the lake and tributary Rivers has been estimated using CROPWAT 8 model.

Table 7 Water Abstraction for Existing Schemes from the Lake and Tributary Rivers

Watershed	Water (MCM/Yr)	Land(ha)	Crop
Abaya	43.31	1971	Banana
Bilate	34.11	3746	Cotton, Tobacco, Divers
Gidabo	1.29	180	Divers
Gelana	11.33	1579	Divers
Hamesa	2.07	206	Divers
Harie	48.87	2224	Banana
Sum	140.98	9906	

5.2. The Simulation Process and Analysis of the Result

The water balance recursive formula as presented in section 3.1.5.1 equation 3.18 is used to run the simulation. Simulation is made using EXCEL spreadsheet software. The recursive formula has been adjusted to simulate reservoir storage on monthly basis and compare the result with the recorded values.

The simulation has been conducted on a monthly time scale. The output result as shown on figure 49 there is some misfit between the simulated and observed lake levels.

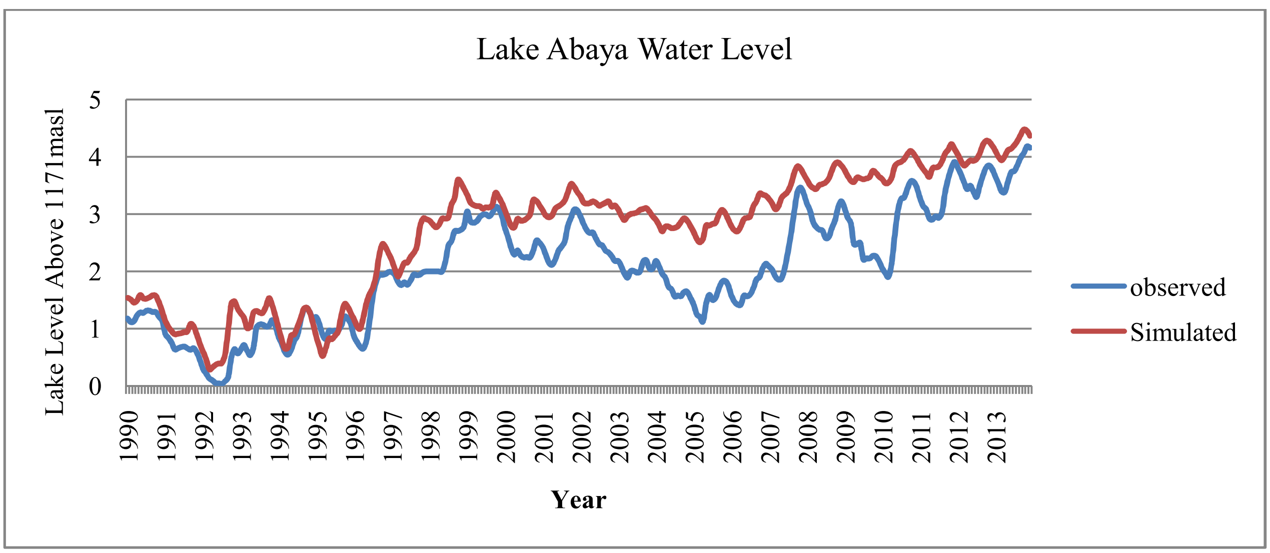


Figure 50 Observed and Simulated Lake Water Level of Lake Abaya

Table 8 Mean Monthly Water Balance of Lake Abaya

Month	Inputs to the lake			Output from the lake		Balance (MCM)
	Inflow from gauged catchment (MCM)	Inflow from un-gauged catchment (MCM)	Rain fall on the lake surface (MCM)	Evaporation from the lake (MCM)	Abstraction from the lake (MCM)	
Jan	23.30	0.00	28.99	232.06	11.37	-191.15
Feb	20.13	0.00	33.06	225.38	12.27	-184.46
Mar	33.28	0.00	66.28	233.03	10.99	-144.47
Apr	61.57	59.36	147.26	199.19	5.80	63.21
May	100.24	137.76	145.43	202.27	4.27	176.88
Jun	91.23	40.37	85.51	187.80	8.72	20.59
Jul	104.64	54.85	89.62	166.03	16.87	66.21
Aug	141.25	77.32	91.18	172.08	20.64	117.03
Sep	147.21	165.99	92.70	165.04	20.14	220.72
Oct	152.01	149.81	110.02	186.72	13.56	211.56
Nov	94.70	0.00	58.48	212.44	6.71	-65.97
Dec	29.46	0.00	34.02	217.46	9.65	-163.62
Sum	999.03	685.45	982.56	2399.52	140.98	126.54

The Mean Monthly water balance is tabulated on table 8 and presented in figure 50. The balance has an extra water of +126.54MCM. This is due to the imbalance between the total input to the lake and the total output from the Lake and it is the source for the increment of the Lake Level. It increases the Lake Level by 9 mm from the zero water levels which is 1171masl.

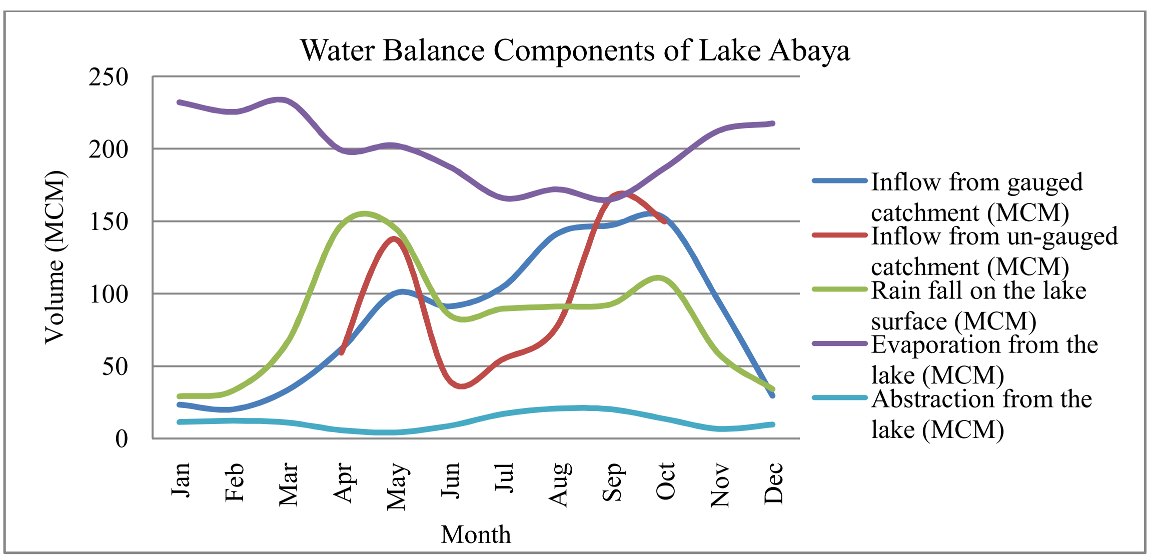


Figure 51 Water Balance Components of Lake Abaya

CHAPTER SIX

6. ASSESSMENT OF THE CAUSE OF FLECTUATION IN LAKE WATER LEVEL

6.1. Climatological Factors

6.1.1. Rainfall

Precipitation is the main driver of variability in the water balance over space and time and change in precipitation have very important implication for hydrology and water resources. Hydrological variability over time in a catchment is influenced by variations in precipitation over daily, seasonal, annual and decade time scale. In this study mean Annual areal rainfall of the sub-basin used for analysis of the impact. From the figure 52 the slope of the time serious mean areal rainfall of the sub-basin is Positive which shows that precipitation is in small increasing.

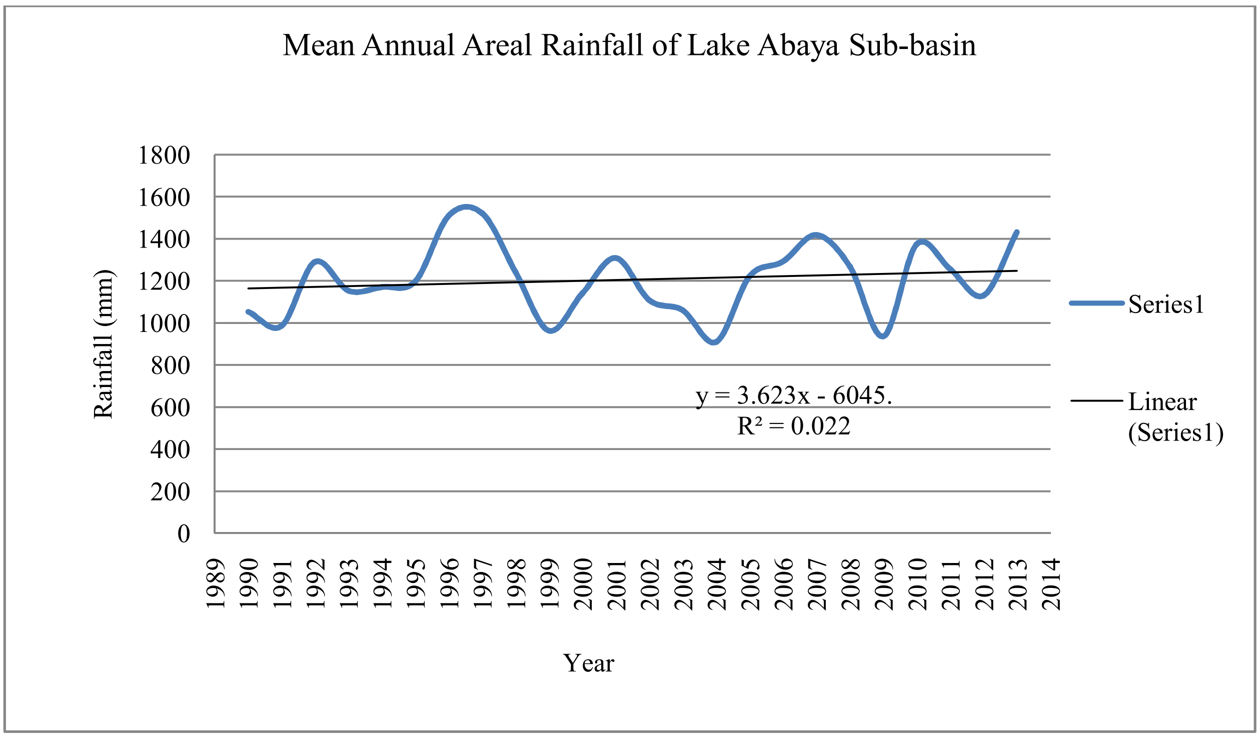


Figure 52 Mean Annual Areal Rainfall of Lake Abaya Sub-basin

6.1.2. Temperature

The main component of evaporation is temperature. Then in this study the temperature of Arba Minch station is used for analyzing the effects.

The trend of temperature is increasing slightly which increase the rate of evaporation and then affect the water balance of the catchment.

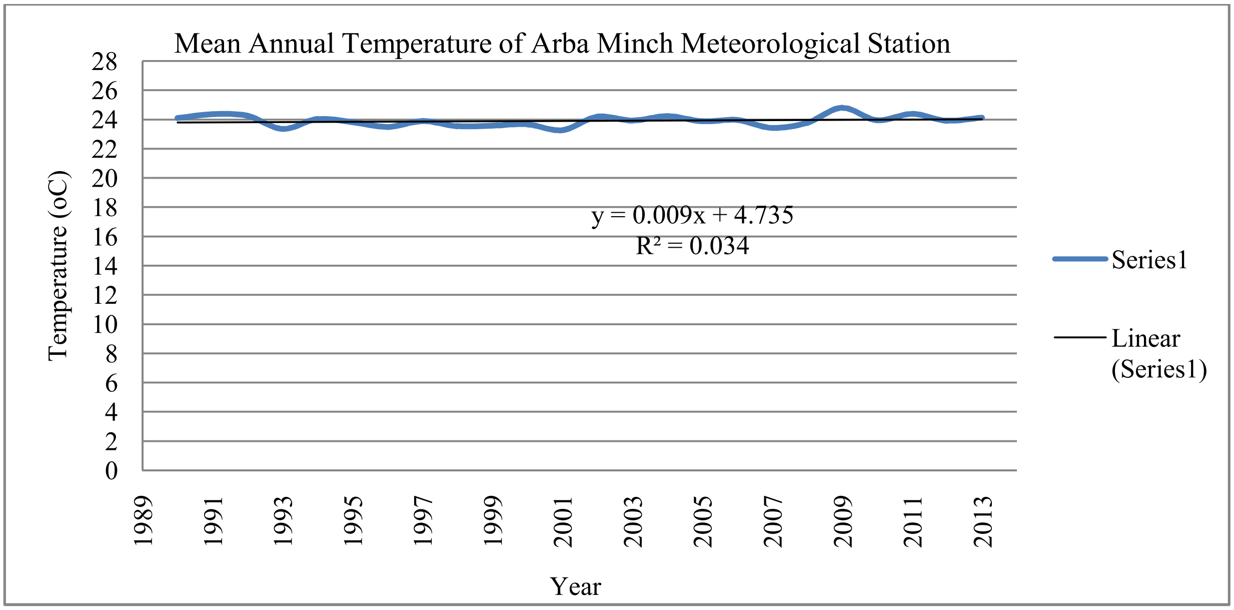


Figure 53 Mean Annual Temperature of Arba Minch Meteorological Station

6.1.3. Relative Humidity

Under humid weather conditions, the high humidity of the air causes the evapotranspiration rate to be lower. Relative Humidity of Arba Minch station is taken and shown in the figure 54. The graph shows apparently decreasing.

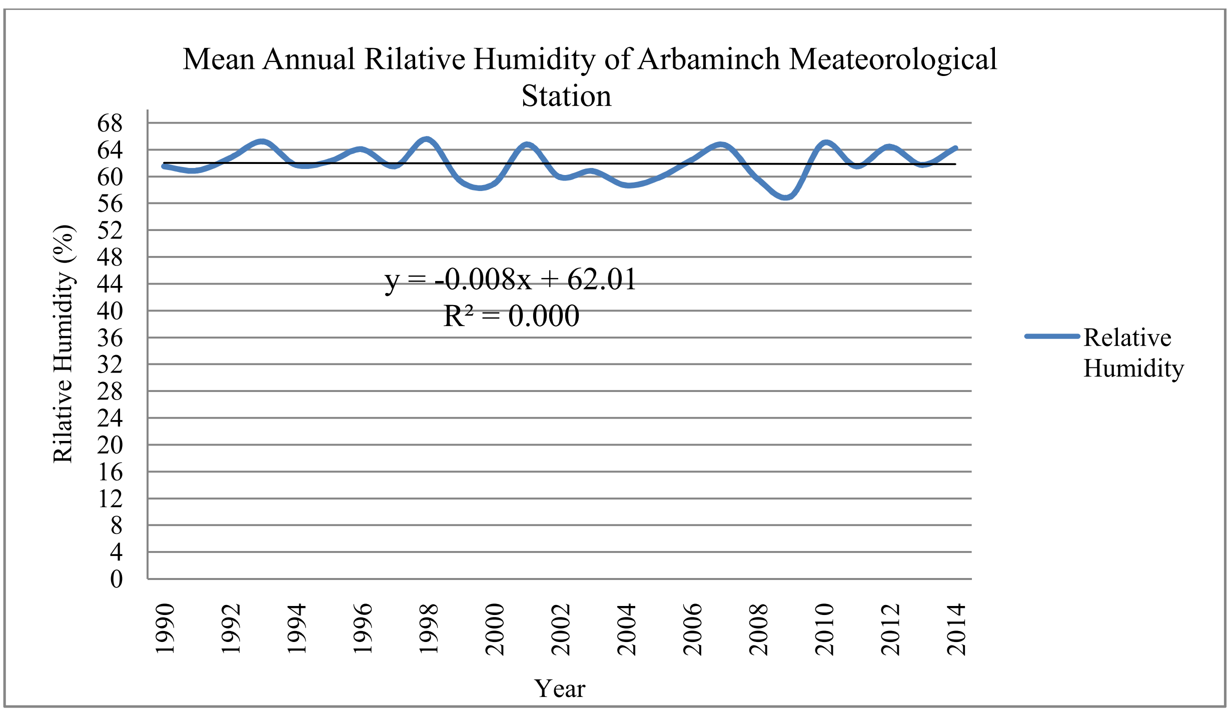


Figure 54 Mean Annual Relative Humidity of Arba Minch Meteorological Station

6.1.4. Wind Speed

Wind speed is used as a measure of the air mass movement. Evaporation rates are controlled, in part, by the vapor content of the air mass overlying the water body. As the volume of water evaporated increases, the evaporation rate from the water body decreases unless the more saturated air mass is transported from the overlying air space and replaced by air that has lower moisture content. For low rates of air mass movement, less water will evaporate from the water body because of the relatively higher vapor content of the overlying air mass. As shown in the figure wind speed of Arba Minch meteorological station is decreasing trend.

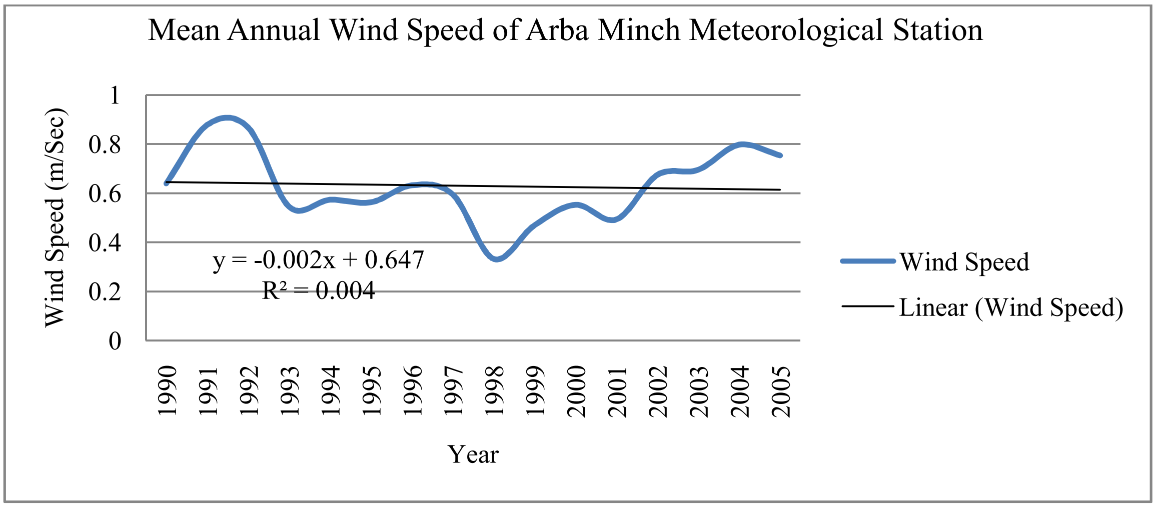


Figure 55 Mean Annual Wind Speed of Arba Mich Meteorological Station

6.1.5. Sunshine Hours

The evapotranspiration process is determined by the amount of energy available to vaporize water. Solar radiation is the largest energy source and is able to change large quantities of liquid water into water vapor. The potential amount of radiation that can reach the evaporating surface is determined by its location and time of the year. Due to differences in the position of the sun, the potential radiation differs at various latitudes and in different seasons. The actual solar radiation reaching the evaporating surface depends on the turbidity of the atmosphere and the presence of clouds which reflect and absorb major parts of the radiation. Relative Sunshine hour is the ratio of the actual duration of sunshine, n, to the maximum possible duration of sunshine or daylight hours N. In the absence of any clouds, the actual duration of sunshine is equal to the daylight hours (n = N) and the ratio is one, while on cloudy days n << N and consequently the ratio may be zero. In the absence of a direct measurement of R_s, the relative sunshine duration, n/N, is often used to derive solar radiation from extraterrestrial radiation. As we observed from figure 56 sunshine hour of Arba Minch Meteorological Station has decreasing trend.

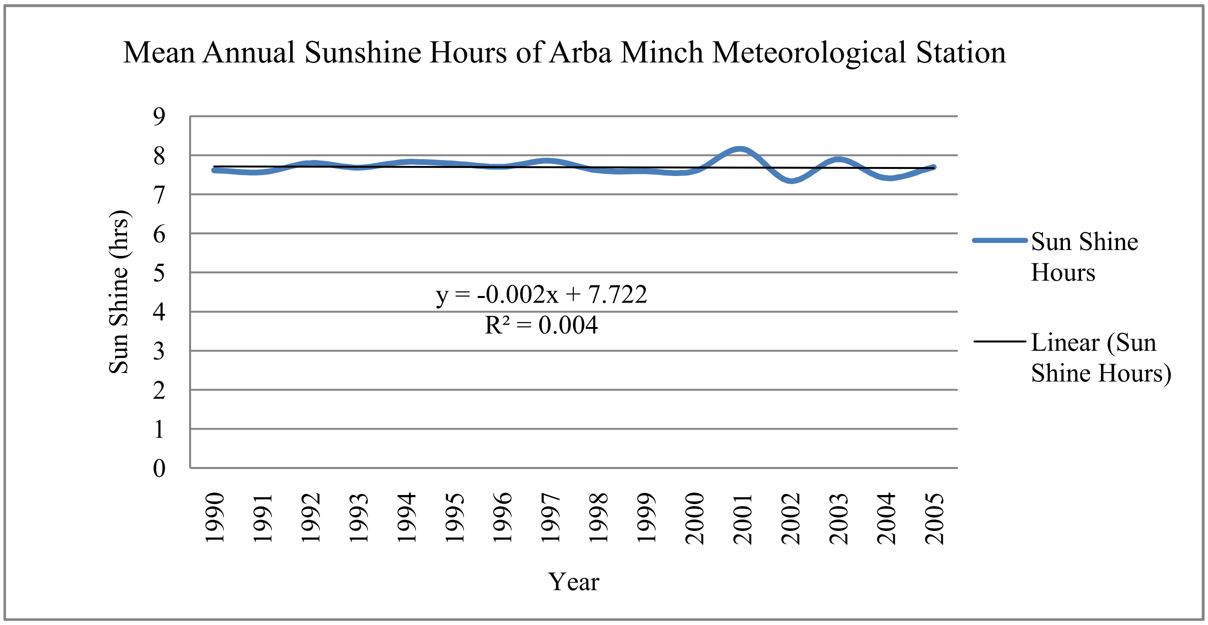


Figure 56 Mean Annual Sunshine Hours of Arba Minch Meteorological Station

6.1.6. Evaporation

Increasing temperature generally results in an increasing in potential evaporation largely because the water holding capacity of air is increased. In this study change in evaporation in the study area is assessed using Pan Method with the Arba Minch station Pan Evaporation data. As it can be observed from the figure 57 the rate of the evaporation is continuously decreasing which is one reason for the increasing of lake level.

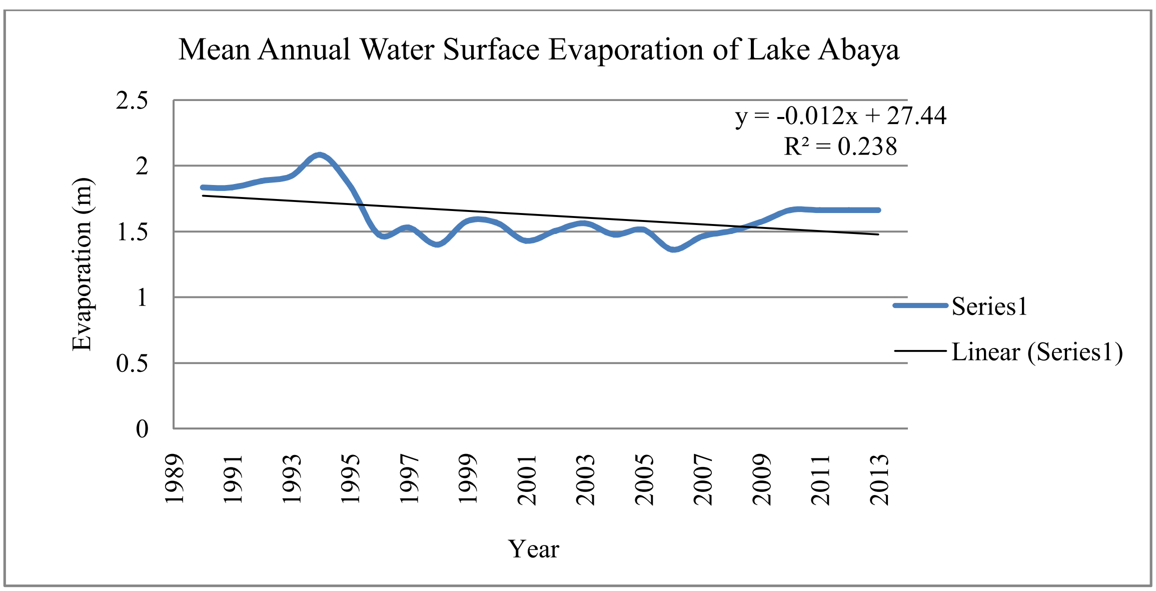


Figure 57 Mean Annual Water Surface Evaporation of Lake Abaya

6.2. Anthropogenic Factors

6.2.1. Deforestation, Intensively Cultivation, Urbanization and Over-grazing

When comparing the land cover map of 1996 to the land cover map of 2006 that the area under intensive cultivation, grassland, urban area and riparian has increased by 84.59, 32.64, 1.08 and 0.11 km^2 respectively and that of shrub-land, unidentified area, marshland, forest, moderately cultivated and exposed surface has decreased by 69.20, 35.90, 8.00, 4.92, 0.40, 0.01 km^2 respectively and that of water body and woodland has not changed yet. All of these changes can decrease the infiltration capacity of the soil, increase the quantity of runoff, increase rate of evaporation, increase sediment transport, and shortening time of concentration; as a result the level of the lake will be increase either by increasing the volume or by sedimentation of the lake bade level.

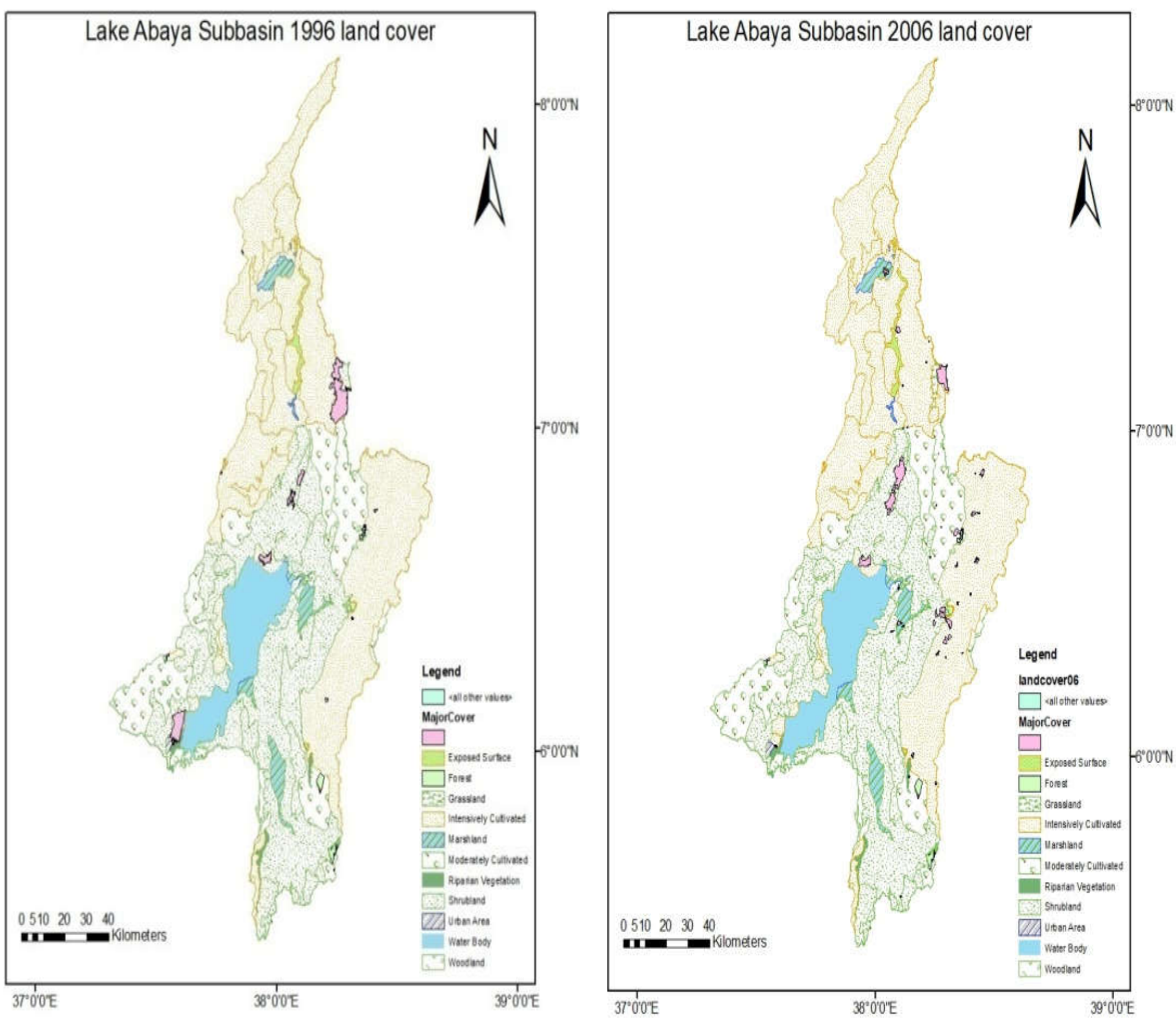


Figure 58 Land Use Land Cover of Lake Abaya Sub-basin

Table 9 Land Cover Area Comparison of 1996 and 2006 (Km^2 and %) of Lake Abaya Sub-basin

Lake Abaya Sub-basin Land Cover					
	1996		2006		
Major Cover	Area_Km^2	Area (%)	Area_Km^2	Area (%)	Area Difference in Km^2
Exposed Surface	80.56	0.51	80.56	0.51	-0.01
Forest	58.85	0.37	53.93	0.34	-4.92
Grassland	24.94	0.16	57.58	0.36	32.64
Intensively Cultivated	6713.23	42.51	6797.82	43.05	84.59
Marshland	374.20	2.37	366.20	2.32	-8.00
Moderately Cultivated	1965.01	12.44	1964.60	12.44	-0.40
Not identified	174.25	1.10	138.35	0.88	-35.90
Riparian Vegetation	66.75	0.42	66.87	0.42	0.11
Shrub-land	5097.33	32.28	5028.13	31.84	-69.20
Urban Area	14.86	0.09	15.94	0.10	1.08
Water Body	1140.32	7.22	1140.32	7.22	0.00
Woodland	80.21	0.51	80.21	0.51	0.00
Sum	14638.83	100.00	14638.83	100.00	0.00

In the case of Lake Abaya, as shown in the figure 58, the rate of lake surface areal rainfall is increasing but the main sources of the lake water, which is the inflow, is decreasing. To predict streamflow of Bilate, Gidabo, Hamessa, and Harie from 2006-2013 rainfall runoff model is used (HEC-HMS).

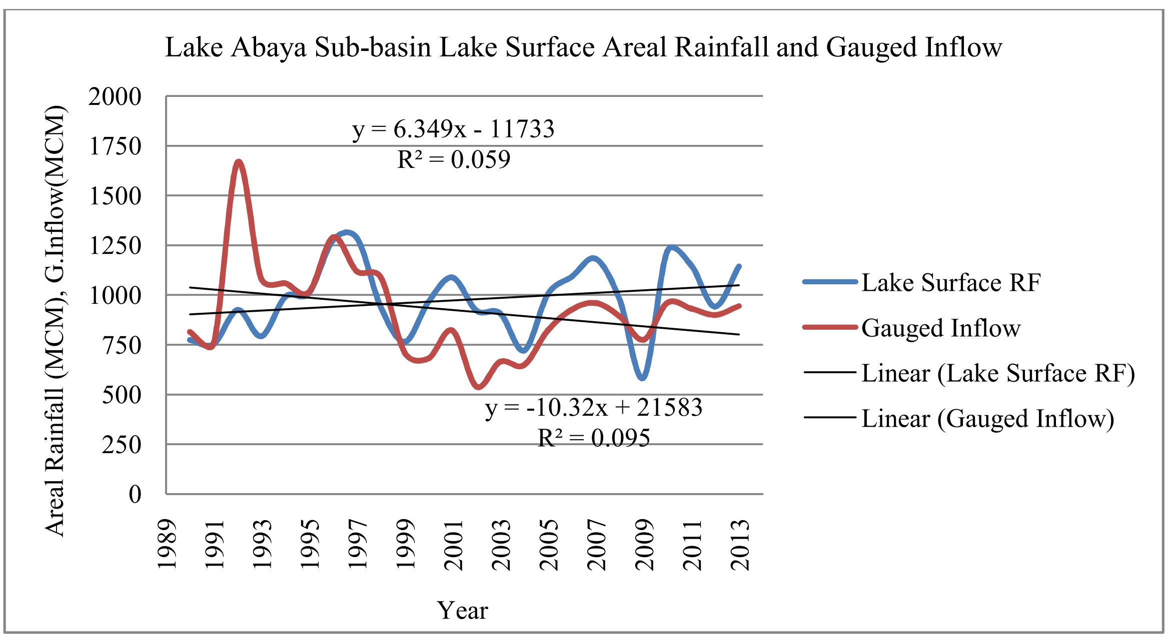


Figure 59 Lake Abaya Sub-basin Lake Surface Areal Rainfall and Gauged Inflow Trend

6.2.2. Water Abstraction and Future Scenarios

These estimates correspond to an overall efficiency of 50%, and are expressed for planning purposes in terms of continuous 24hr irrigation for the whole season.

6.2.2.1. Abstraction from Lake Abaya

A land total of about 1971 ha are irrigated by the community using the lake and Small Rivers which drained to the lake. Banana is the main crop which is grown in the area with a duty of 0.69l/s/ha, a total annual abstraction of lake water estimated will be about 43.31MCM.

6.2.2.2. Abstraction from Bilate River

Currently, 3746 ha of land is under cultivation using Bilate River as a state and community farm to produce cotton and tobacco in the state farm and diverse crops in community farm with a duty of 0.70, 0.40 and 0.23 l/s/ha for cotton, tobacco and diversified crops respectively. As a result the total annual abstraction from the river and its tributaries is 34.11 MCM.

6.2.2.3. Abstraction from Gidabo River

By using Gidabo River and its tributary currently the community irrigated 180 ha of land to produce diversified crop which required an average duty of 0.23l/s/ha. As a result the total annual abstraction from the river and its tributaries is 1.29 MCM.

6.2.2.4. Abstraction from Gelana River

From Gelana River, currently, the community diverted water to irrigate a total land of 1579 ha to produce diversified crops which required an average duty of 0.23l/s/ha. As a result the total annual abstraction from the river and its tributaries is 11.33 MCM.

6.2.2.5. Abstraction from Hamesa River

From Hamesa River, currently, the community diverted water to irrigate a total land of 206 ha to produce diversified crops which required an average duty of 0.23l/s/ha. As a result the total annual abstraction from the river and its tributaries is 2.07 MCM.

6.2.2.6. Abstraction from Harie River

From Harie River, currently, the community diverted water to irrigate a total land of 2224 ha to produce banana crops which required an average duty of 0.69l/s/ha. As a result the total annual abstraction from the river and its tributaries is 48.87MCM.

As a result to irrigate a total land of 9906 ha from the lake and all the tributary rivers 140.98 MCM of water is abstracted.

Two major irrigation development scenarios are considered in this study to evaluate, how irrigation activities affect the lake. They are:

Irrigation expansion on the tributaries to 10610 ha

Irrigation expansion around the lake catchment to 20221 ha

Scenario one: Irrigation expansion to 10610 ha on the tributaries needs additional 84.10 MCM water per year in addition to the present. Accordingly, this amount of water abstraction contributes to the lake level to reduce by 60 mm.

Scenario Two: If the irrigation development, in addition to scenario 1, expands by 20221ha around the lake catchment, it requires additional 444.35 MCM water per year and the lake level totally reduced by 42 cm.

Table 10 Water Abstraction for Irrigation Scenarios

Watershed	Water (MCM/Yr)	Land(Ha)	Crop
Abaya	444.3473	20221	Banana
Bilate	43.49424	5350	Cotton, Tobacco, Divers
Gidabo	17.22695	2400	Divers
Gelana	13.35089	1860	Divers
Hamessa	10.02499	1000	Divers
Sum	528.4444	30831	

CHAPTE SEVEN

7. CONCLUSIONS AND RECOMMENDATIONS

7.1. Conclusions

Gauge height data of Lake Abaya (m) from 1985-2013 at Lante is analyzed and shows an increasing lake level trend; especially from 1991 onwards the level of the lake water is increased by 2.54m (1990 the lake level was 1.23m above the reference height, which is 1171 masl and by the year 2013 it become 3.77 above the reference level).

Analyzing streamflow data from 1970-2006, 1977-2006, 1990-2013, 1980-2005 and 1985-27 of Bilate, Gidabo, Gelana, Hamesa and Harie Rivers respectively, Bilate shows a uni-modal peak in September with a total runoff of 568.87 MCM per year which is more than half of the total annual inflow of the lake catchment, the others show a bimodal peak. The total annual gauged inflow from these rivers in to the lake is 1034.07MCM per year.

There is no gauged stream flow of Bilate, Gidabo, Hamessa and Harie rivers in the year 2006-2013; the only gauged river within the years 2006-2013 is Gelana River. Stream flow from 2006 to 2013 is predicted by calibrating and validating the stream flow from 1989 to 2000 at Nr. Alaba Kuito, at Nr. Aposto, at Wajifo and at Nr. Arba Mich gauging stations by using HEC-HMS. As a result stream flow from 1990-2013 for all rivers has been obtained. Not all parts of the lake watershed gauged, due to this there is in need of calculating the inflow from the un-gauged catchment. The inflow from the un-gauged catchment is considered only during wet season, the area ratio method is used and the inflow calculated is 685.45 MCM per year. There is no observed outflow from Lake Abaya.

Lake Abaya sub-basin and lake surface areal rainfall is estimated by Thiesson polygon method, the rainfall stations have been selected by virtue of their location with the lake, class and long period of observation consistency of the data base to calculate the monthly and annual rainfall areal distributions. As a result the amount of precipitation directly fallen on the lake surface is estimated to 982.56 MCM per Year. Open water evaporation (lake evaporation) is calculated by three methods (Penman's method, Pan and Cropwat 8) for this study pan result is taken and the mean annual lake evaporation is estimated to 2399.52 MCM per year. The total land irrigated from the lake and tributaries is 9906ha. The amount of water required for the irrigation from the lake and tributaries is computed by Cropwat 8 software and 140.98MCM of water is abstracted per year.

As the main aim is to quantify the water balance components of the Lake Abaya and asses if the lake level fluctuation could attribute to natural or anthropogenic factors: Accordingly the components of the water balance for Lake Abaya are: Reservoir storage, inflows (Bilate, Gidabo, Gelana, Hamessa and Harie Rivers, runoff from un-gauged part of the watershed and direct rainfall over lake surface) and outflows (lake evaporation and water abstraction) and groundwater inflow or outflow on water balance of the lake for this study were treated as residual of other water balance components.

After analysis of all components of water balance for the lake, a water balance model has developed using continuity equation. Summing up of all the components, lake surface rainfall 18.87 %, inflow 32.35 % (Gauged 19.18 %, un-gauged 13.16 %), lake surface evaporation 46.08 % and Abstraction 2.71 % contributes for the lake water balance. Inflow and lake surface evaporation show decreasing trend and abstraction and lake surface rainfall show increasing trend.

Seasonal fluctuation (temporal variation) of Lake Abaya is associated with distribution and trend of adjacent lake rainfall in the watershed. The balance has an extra water of +126.54 MCM. This is due to the imbalance between the total input to the lake and the total output from the Lake and it is one source for the increment of the Lake Level. It increases the Lake Level by 9 mm from the zero water levels which is 1171masl.

Two major irrigation development scenarios are considered in this study to evaluate, how irrigation activities affect Lake Abaya water level i.e. Irrigation expansion of 10610 ha on the tributaries needs additional 84.10 MCM water per year in addition to the present and reduces the lake level by 60 mm, and if the irrigation development expands by 30,831 ha, it requires additional 528.45 MCM water per year and this will reduce the lake level by 420 mm. Generally, Lake Abaya is subjected to climatic factors, such as seasonal rainfall fluctuation, and anthropological activities such deforestation, intensive cultivation, etc., as that modifies hydrologic circulation processes.

7.2. Recommendation

- Establishment of buffer zone along shore of the lake to protect the danger of human life and property and major tributaries rivers for silt trap.
- Detailed land use planning, implementation of soil and water conservation measures and integrated land husbandry will be required.
- According to this study, lake level indicates significant increment; this might be volume of dead storage is occupied by silts. Bathymetry survey of the lake and investigation of rate of siltation should be major concern of researchers.

REFERENCE

Adam CHOIŃSKI, Agnieszka ŁAWNICZAK, Mariusz PTAK and Leszek SOBKOWIAk: Causes of Lake Area Changes in Poland: Journal of Resources and Ecology, 2011.

Amare Mazengia Wodyifraw, Assessment of lake Ziway Water Balance, Masters Thesis, Addis Abeba, 2008.

Azeb Belete, Climate Change Impact on Lake Abaya Water Level, Masters Thesis, Addis Ababa, 2009

Berihu Abadi, Brittle Fracture and Lake Level Change at Beseka: Main Ethiopian Rift, Metehara Area: Master Thesis Addis Ababa, 2007.

Brigitta Schutt and Stefan Thiemann; Kulfo River, South Ethiopia as the Regulator of Lake Level Changes in the Lake Abaya-Lake Chamo System; 2006.

Encyclopedia of Lakes and Reservoirs: 2012

H. M. Raghunath, Hydrology, Principles .Analysis .Design, New Age International (P) Ltd., New Delhi, 2006.

Halcrow Group Limited and Generation Integrated Rural Development (GIRD) Consultants: Rift Valley Lakes Basin Integrated Resources Development Master Plan Study Project Phase 1 Final Report: Addis Ababa Ethiopia, 2008.

Jon Finch and Ann Calver; Methods for the quantification of evaporation from lakes; 2008.

K. Subramanya, Engineering hydrology, Tata McGraw-Hill Publishing Company Limited, New Delhi, 1984.

Mulugeta Dadi Belete, Bernd Diekkrüger and Jackson Roehrig: Characterization of Water Level Variability of the Main Ethiopian Rift Valley Lakes: Hydrology, 25 December 2015.

Milan Novikmec, Marek Svitok, Dusan Kocicky, Ferdinand Sporka and Peter Bitusik: Surface Water Temperature and Ice Cover of Tatra Mountains Lakes Depend on Altitude, Topographic Shading, and Bathymetry: Arctic, Antarctic, and Alpine Reserch, 2013.

Pengcheng Li, Hengpeng Li, Guishan Yang, Qi Zhang and Yakin Diao: Assessing the Hydrologic Impacts of Land Use Change in the Taihu Lake Lake Basin of China from 1985 to2010: Water, 2018.

Randall E.Fish, Using Water Balance Models to Aproximate the Effects of Climate Change on Spring Catchment Discharge:Mt. Hanang, Tanzania: Masters Thesis, Michigan, 2011.

Richard H. McCuen Hydrologic Analysis and Design, Prentice-Hall Inc. Second Edition, New Jursey, 1998.

S. M. Onywere, C. A. Shisanya, J. A. Obando, A. O. Ndubi, D. Masiga, Z. Irura , N. Mariita and H. O. Maragia: Geospatial Extent of 2011-2013 Flooding from the Eastern African Rift Valley Lakes in Kenya and its Implication on the Ecosystems.

Seleshi Bekele Awulachew, Investigation of physical and bathymetric characteristics of Lakes, Abaya and Chamo, Ethiopia, and their management implications, 2006.

Siraj Jewaro, Adaptation Strategies of the Communities Surrounding Haramaya Lake Towards Its Disappearance, Eastern Hararghe Zone, Ethiopia: Master Thesis, 2013.

Tamiru Alemayehu, Wagari Furi and Dagnachew Legesse: Impact of water overexploitation on highland lakes of eastern Ethiopia Received: Springer-Verlag, 2006.

Teklu Gebretsadik and Kassahun Mereke, Threats and Opportunities to Major Rift Valley Lakes Wetlands of Ethiopia, Agricultural Research and Technology Open Access Journal, ISSN: 2471-6774, Hawassa Agricultural Research center, South Agricultural Research Institute, Ethiopia Submission: June 16, 2017; Published: July 28, 2017

UNEP (2006), “Africa’s Lakes: Atlas of Our Changing Environment.” Division of Early Warning and Assessment (DEWA) United Nations Environment Program (UNEP) P.O. Box 30552 Nairobi 00100 Kenya.

Unesco: Methods for Water Balance Computation: An International Guide for Research and Practice: The Unesco Press. Paris, 1974.

W F Vincent, Effects of Climate Change on Lakes, Elsevier Inc., Canada, 2009.

Wet season, Wikipedia: en.wikipedia.org/wiki/wet-season: last edited on 18 August 2019 at 06:52 (UTC): Assessed 16 September 2019.

Yemane Gebreegziabher, Assessment of the Water Balance of Lake Hawassa Catchment, Ethiopia: Master Thesis ,2004.

Zheng Duan, Estimating Water Balance Components of Lakes and Reservoirs Using Various Open Access Satellite Databases, Delft, 2014.

APPENDIXES

Appendix A: HEC-HMS Model Outputs

Appendix A.1 Bilate River Calibration (Nr. Alaba Kulito)

Project: BilatePro Optimization Trial: Trial 1
Subbasin: Upper Bilate Subbasin

Start of Trial:	01Jan1989, 00:00	Basin Model:	BilatePro
End of Trial:	31Dec1996, 00:00	Meteorologic Model:	BilatePro
Compute Time:	24Sep2019, 21:34:15		

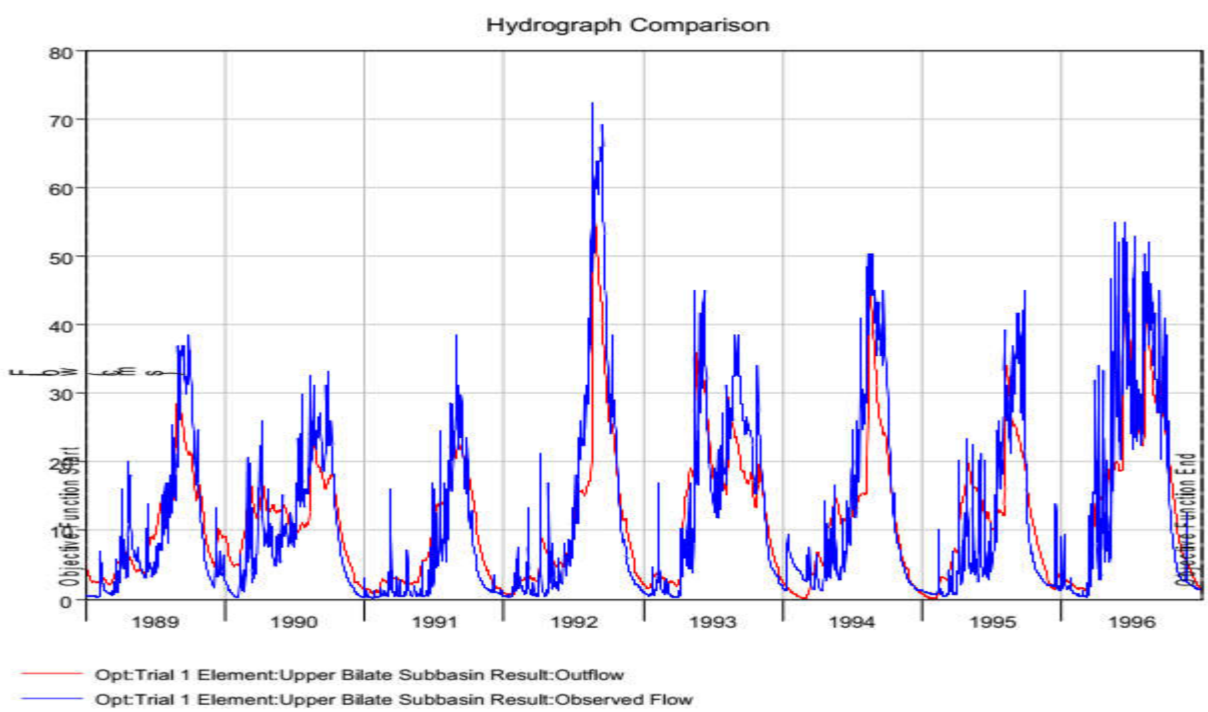
Volume Units: MM

Computed Results

Peak Discharge:	57.4 (M3/S)	Date/Time of Peak Discharge	25Aug1992, 00:00
Precipitation Volume	9199.94 (MM)	Direct Runoff Volume:	1685.53 (MM)
Loss Volume:	7513.22 (MM)	Baseflow Volume:	5.95 (MM)
Excess Volume:	1686.72 (MM)	Discharge Volume:	1691.49 (MM)

Observed Hydrograph at Gage Gage 1

Peak Discharge:	72.4 (M3/S)	Date/Time of Peak Discharge	19Aug1992, 00:00
Mean Abs Error:	4.6 (M3/S)	RMS Error:	6.5 (M3/S)
Volume:	1691.49 (MM)	Volume Residual:	-0.00 (MM)
Nash-Sutcliffe:	0.760		



Appendix A.2 Bilate River Validation

Project: Bilate Validation Simulation Run: Upper Bilate Validation
Sink: Outlet

Start of Run:	15Feb1997, 00:00	Basin Model:	Basin 1
End of Run:	31Dec2000, 00:00	Meteorologic Model:	Met 1
Compute Time:	29Sep2019, 10:06:50	Control Specifications:	Control 1

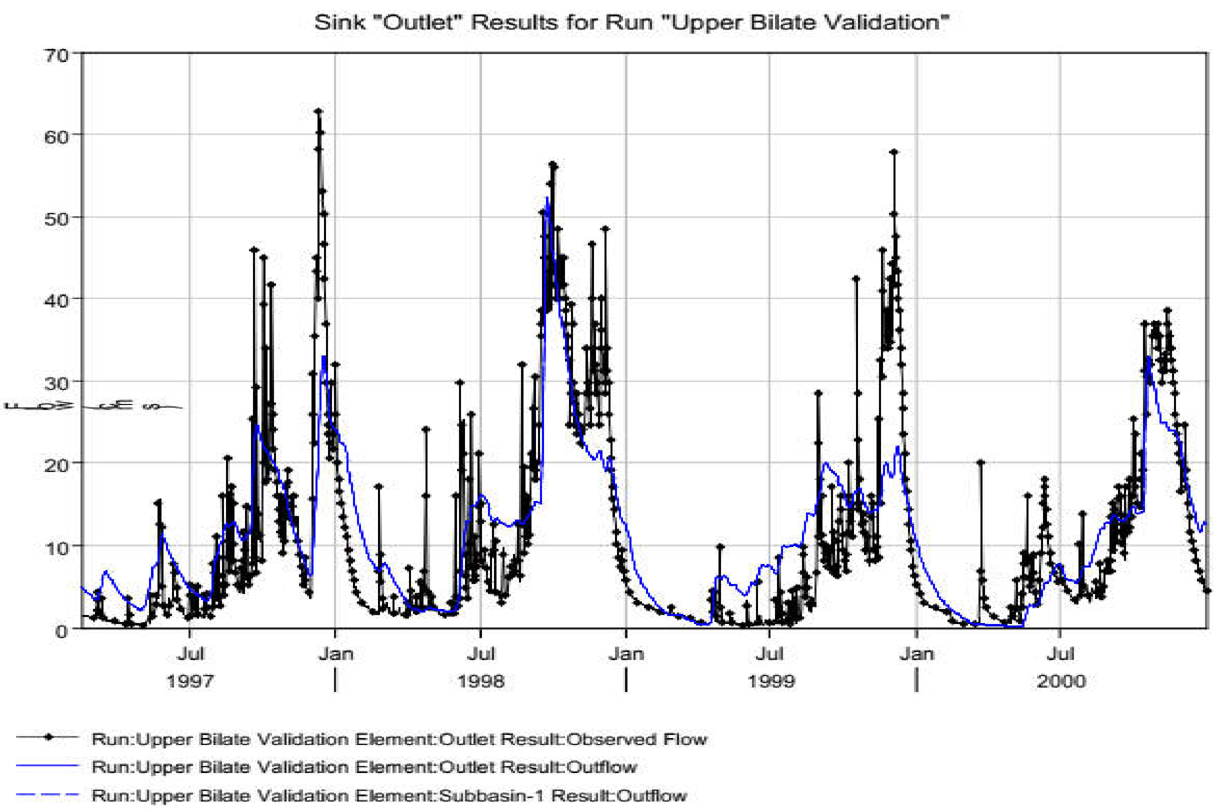
Volume Units: MM

Computed Results

Peak Discharge:	52.2 (M3/S)	Date/Time of Peak Discharge:	24Sep1998, 00:00
Volume:	770.23 (MM)		

Observed Hydrograph at Gage Gage 1

Peak Discharge:	62.8 (M3/S)	Date/Time of Peak Discharge:	11Dec1997, 00:00
Mean Abs Error:	4.9 (M3/S)	RMS Error:	7.0 (M3/S)
Volume:	710.45 (MM)	Volume Residual:	59.66 (MM)
Nash-Sutcliffe:	0.665		



Appendix A.3 Bilate River Prediction

Project: Upper Bilate Prediction   Forecast Alternative: Alternative 1
Subbasin: Subbasin-1

Start of Alternative:	01Jan2001, 00:00	Basin Model:	Basin 1
End of Alternative:	31Dec2013, 00:00	Meteorologic Model:	Met 1
Compute Time:	24Sep2019, 22:45:02		

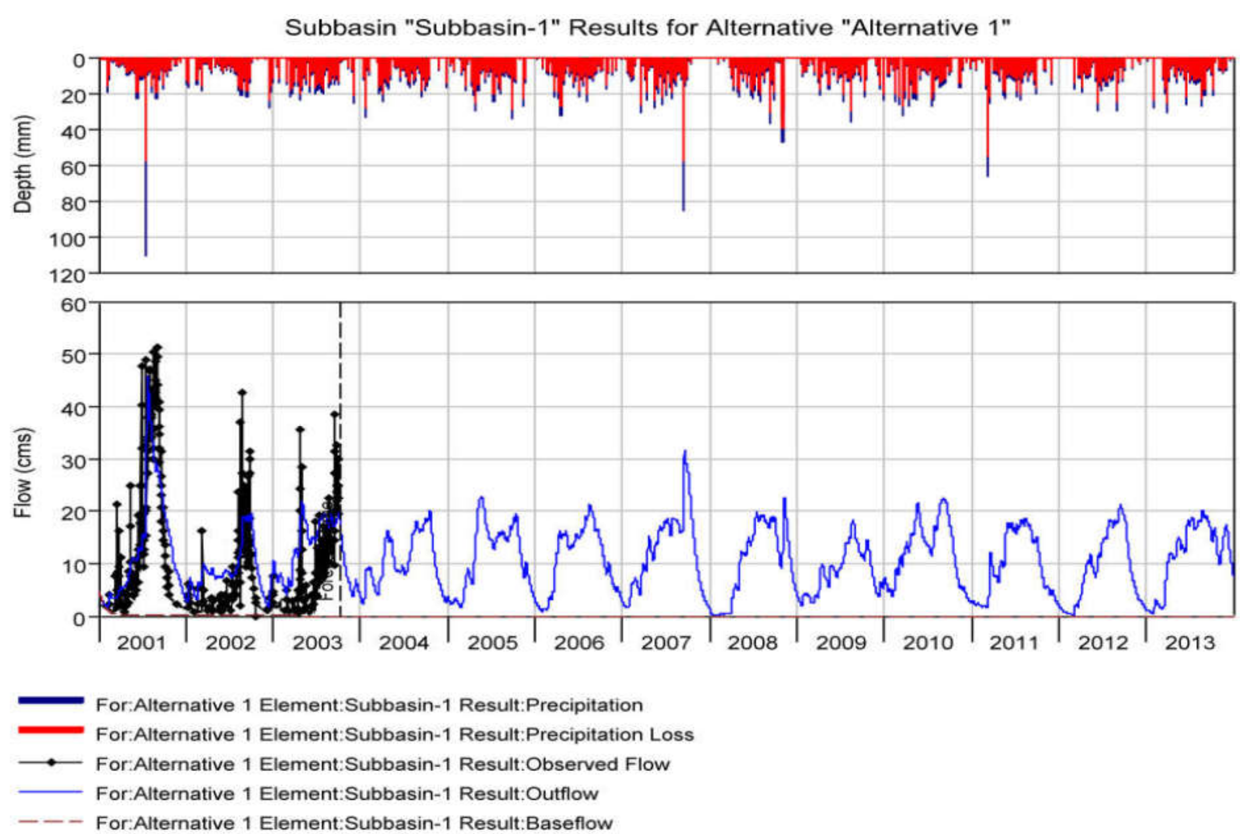
Volume Units: MM

Computed Results

Peak Discharge:	46.0 (M3/S)	Date/Time of Peak Discharge	24Jul2001, 00:00
Precipitation Volume	15557.76 (MM)	Direct Runoff Volume:	2528.51 (MM)
Loss Volume:	13019.04 (MM)	Baseflow Volume:	5.95 (MM)
Excess Volume:	2538.72 (MM)	Discharge Volume:	2534.47 (MM)

Observed Hydrograph at Gage Gage 1

Peak Discharge:	51.2 (M3/S)	Date/Time of Peak Discharge	01Sep2001, 00:00
Mean Abs Error:	6.3 (M3/S)	RMS Error:	3.5 (M3/S)
Volume:	374.67 (MM)	Volume Residual:	205.29 (MM)
Nash-Sutcliffe:	0.590		



Appendix A.4 Gidabo River Calibration (Nr. Aposto)

Project: GidaboPro Optimization Trial: Trial 2
Subbasin: Upper Gidabo

Start of Trial:	01Jan1989, 00:00	Basin Model:	GidaboPro
End of Trial:	31Dec1996, 00:00	Meteorologic Model:	GidaboPro
Compute Time:	23Sep2019, 16:28:46		

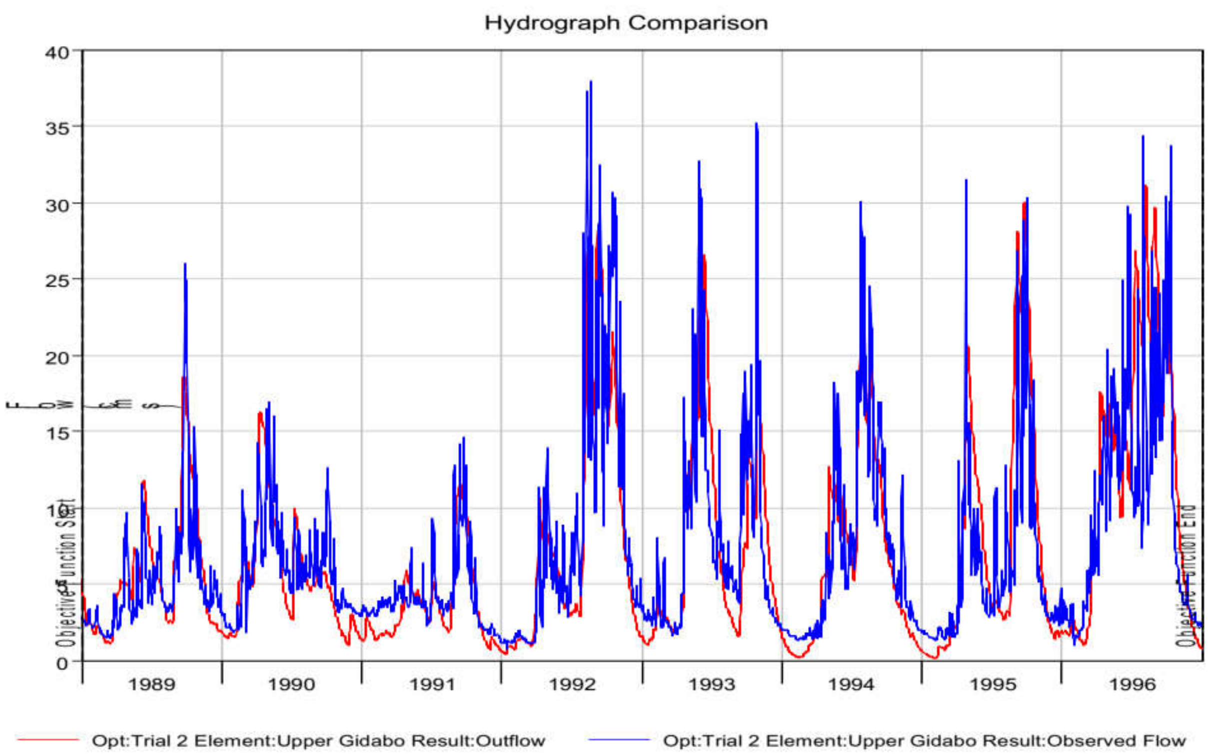
Volume Units: MM

Computed Results

Peak Discharge:	31.1 (M3/S)	Date/Time of Peak Discharge:	07Aug1996, 00:00
Precipitation Volume:	12476.10 (MM)	Direct Runoff Volume:	2579.30 (MM)
Loss Volume:	9895.76 (MM)	Baseflow Volume:	45.30 (MM)
Excess Volume:	2580.34 (MM)	Discharge Volume:	2624.60 (MM)

Observed Hydrograph at Gage Gage 1

Peak Discharge:	38.0 (M3/S)	Date/Time of Peak Discharge:	21Aug1992, 00:00
Mean Abs Error:	2.5 (M3/S)	RMS Error:	3.9 (M3/S)
Volume:	2624.59 (MM)	Volume Residual:	0.00 (MM)
Nash-Sutcliffe:	0.622		



Appendix A.5 Gidabo River Validation

Project: Gidabo Validation   Simulation Run: Run 1
Subbasin: Subbasin-1

Start of Run:	01Jan1997, 00:00	Basin Model:	Basin 1
End of Run:	31Dec2000, 00:00	Meteorologic Model:	Met 1
Compute Time:	23Sep2019, 18:21:50	Control Specifications:	Control 1

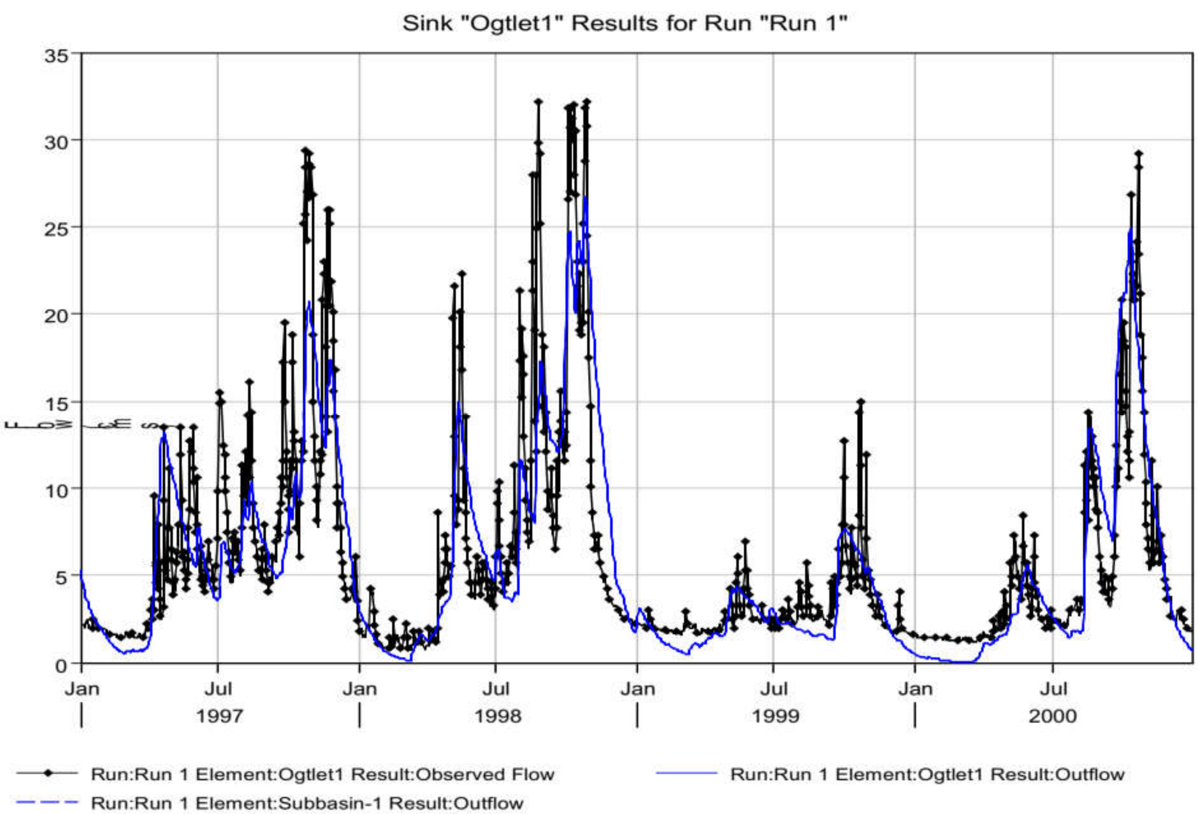
Volume Units: MM

Computed Results

Peak Discharge:	26.8 (M3/S)	Date/Time of Peak Discharge	26Oct1998, 00:00
Precipitation Volume	5247.74 (MM)	Direct Runoff Volume:	1013.49 (MM)
Loss Volume:	4233.76 (MM)	Baseflow Volume:	25.79 (MM)
Excess Volume:	1013.98 (MM)	Discharge Volume:	1039.28 (MM)

Observed Hydrograph at Gage Gage 1

Peak Discharge:	32.2 (M3/S)	Date/Time of Peak Discharge	25Aug1998, 00:00
Mean Abs Error:	2.1 (M3/S)	RMS Error:	3.4 (M3/S)
Volume:	1067.20 (MM)	Volume Residual:	-28.26 (MM)
Nash-Sutcliffe:	0.693		



Appendix A.6 Gidabo River Prediction

Project: Gidabo Prediction Forecast Alternative: Alternative 1
Subbasin: Subbasin-1

Start of Alternative:	01Jan2001, 00:00	Basin Model:	Basin 1
End of Alternative:	31Dec2013, 00:00	Meteorologic Model:	Met 1
Compute Time:	23Sep2019, 18:11:12		

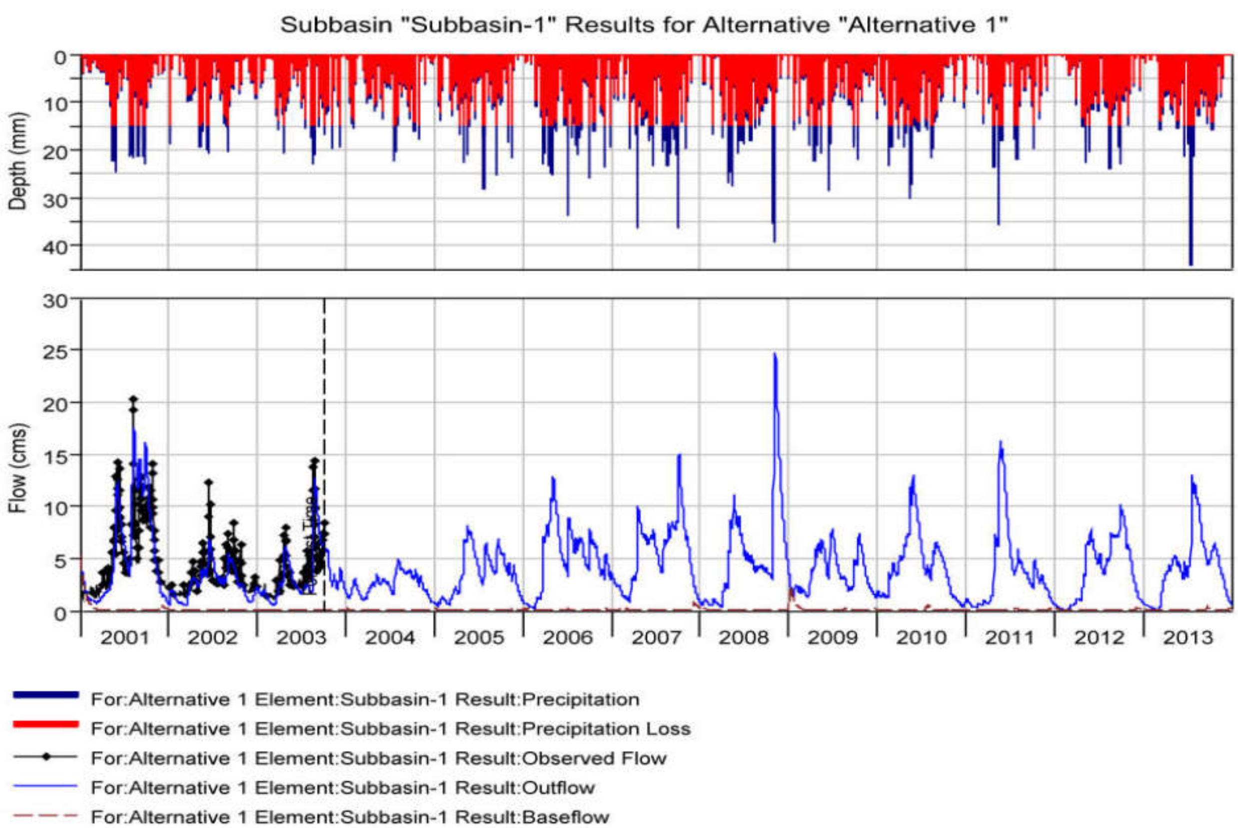
Volume Units: MM

Computed Results

Peak Discharge:	24.8 (M3/S)	Date/Time of Peak Discharge	05Nov2008, 00:00
Precipitation Volume	15317.91 (MM)	Direct Runoff Volume:	2420.41 (MM)
Loss Volume:	12896.81 (MM)	Baseflow Volume:	39.52 (MM)
Excess Volume:	2421.10 (MM)	Discharge Volume:	2459.94 (MM)

Observed Hydrograph at Gage Gage 1

Peak Discharge:	20.2 (M3/S)	Date/Time of Peak Discharge	09Aug2001, 00:00
Mean Abs Error:	1.3 (M3/S)	RMS Error:	0.9 (M3/S)
Volume:	494.42 (MM)	Volume Residual:	7.32 (MM)
Nash-Sutcliffe:	0.776		



Appendix A.7 Hamessa River Calibration (Nr. Wajifo)

Project: HamesaPro   Optimization Trial: Trial 1
Subbasin: Upper Hamesa

Start of Trial:	01Jan1989, 00:00	Basin Model:	HamesaPro
End of Trial:	31Dec1996, 00:00	Meteorologic Model:	HamesaPro
Compute Time:	22Sep2019, 19:43:21		

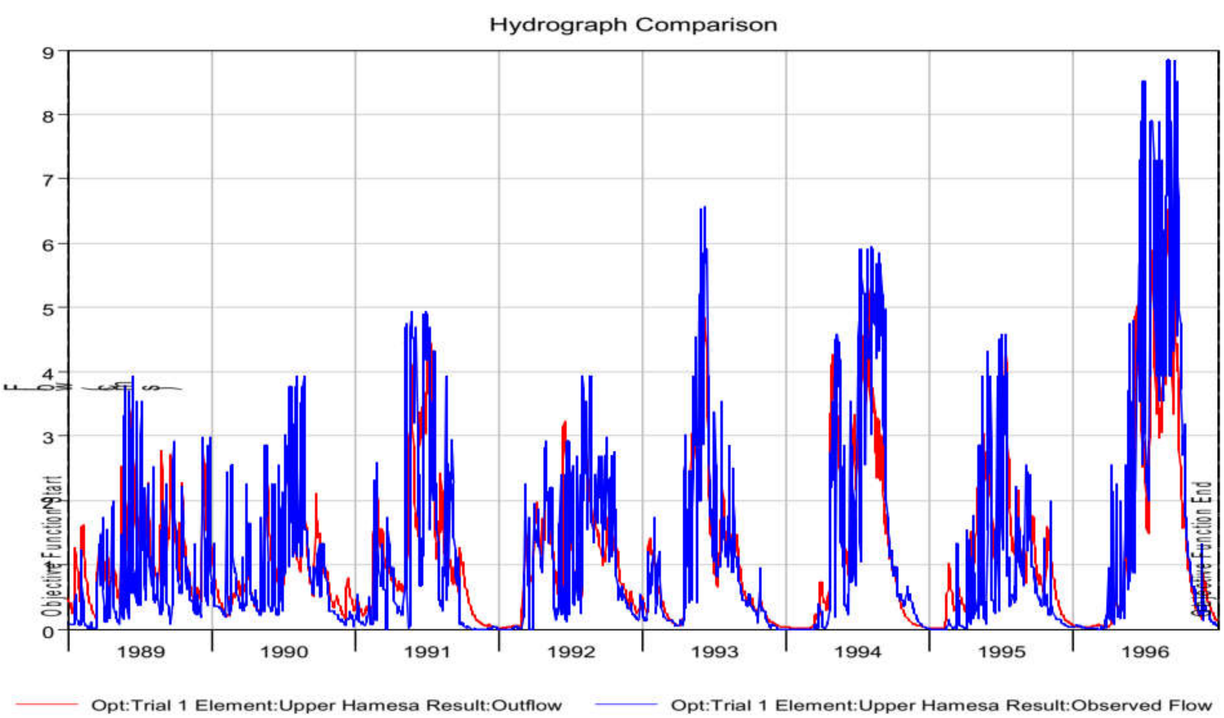
Volume Units: MM

Computed Results

Peak Discharge:	6.5 (M3/S)	Date/Time of Peak Discharge	26Aug1996, 00:00
Precipitation Volume	9192.20 (MM)	Direct Runoff Volume:	551.40 (MM)
Loss Volume:	8640.67 (MM)	Baseflow Volume:	59.94 (MM)
Excess Volume:	551.53 (MM)	Discharge Volume:	611.34 (MM)

Observed Hydrograph at Gage Gage 1

Peak Discharge:	8.8 (M3/S)	Date/Time of Peak Discharge	28Aug1996, 00:00
Mean Abs Error:	0.6 (M3/S)	RMS Error:	0.9 (M3/S)
Volume:	611.33 (MM)	Volume Residual:	0.00 (MM)
Nash-Sutcliffe:	0.663		



Appendix A.8 Hamessa River Validation

Project: hamessa Validation Simulation Run: Run 1
Subbasin: Subbasin-1

Start of Run:	05Feb1997, 00:00	Basin Model:	Basin 1
End of Run:	09Dec2000, 00:00	Meteorologic Model:	Met 1
Compute Time:	22Sep2019, 19:38:16	Control Specifications:	Control 1

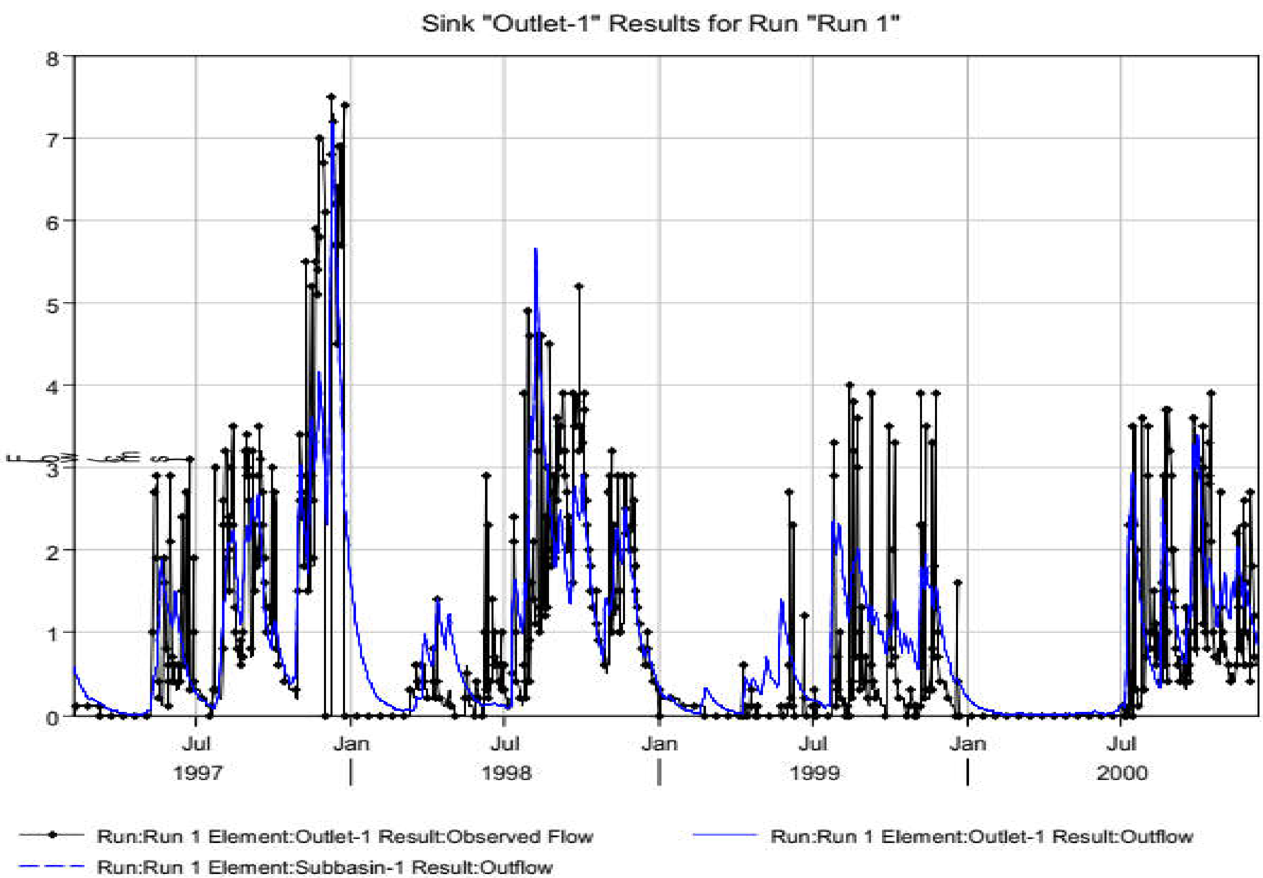
Volume Units: MM

Computed Results

Peak Discharge:	7.2 (M3/S)	Date/Time of Peak Discharge:	10Dec1997, 00:00
Precipitation Volume:	3714.09 (MM)	Direct Runoff Volume:	221.48 (MM)
Loss Volume:	3491.24 (MM)	Baseflow Volume:	16.57 (MM)
Excess Volume:	222.85 (MM)	Discharge Volume:	238.05 (MM)

Observed Hydrograph at Gage Gage 1

Peak Discharge:	7.5 (M3/S)	Date/Time of Peak Discharge:	08Dec1997, 00:00
Mean Abs Error:	0.6 (M3/S)	RMS Error:	0.9 (M3/S)
Volume:	200.64 (MM)	Volume Residual:	37.36 (MM)
Nash-Sutcliffe:	0.521		



Appendix A.9 Hamessa River Prediction

Project: Hamessa Prediction   Forecast Alternative: Alternative 1
Subbasin: Subbasin-1

Start of Alternative:	01Jan2001, 00:00	Basin Model:	Basin 1
End of Alternative:	31Dec2013, 00:00	Meteorologic Model:	Met 1
Compute Time:	22Sep2019, 20:01:27		

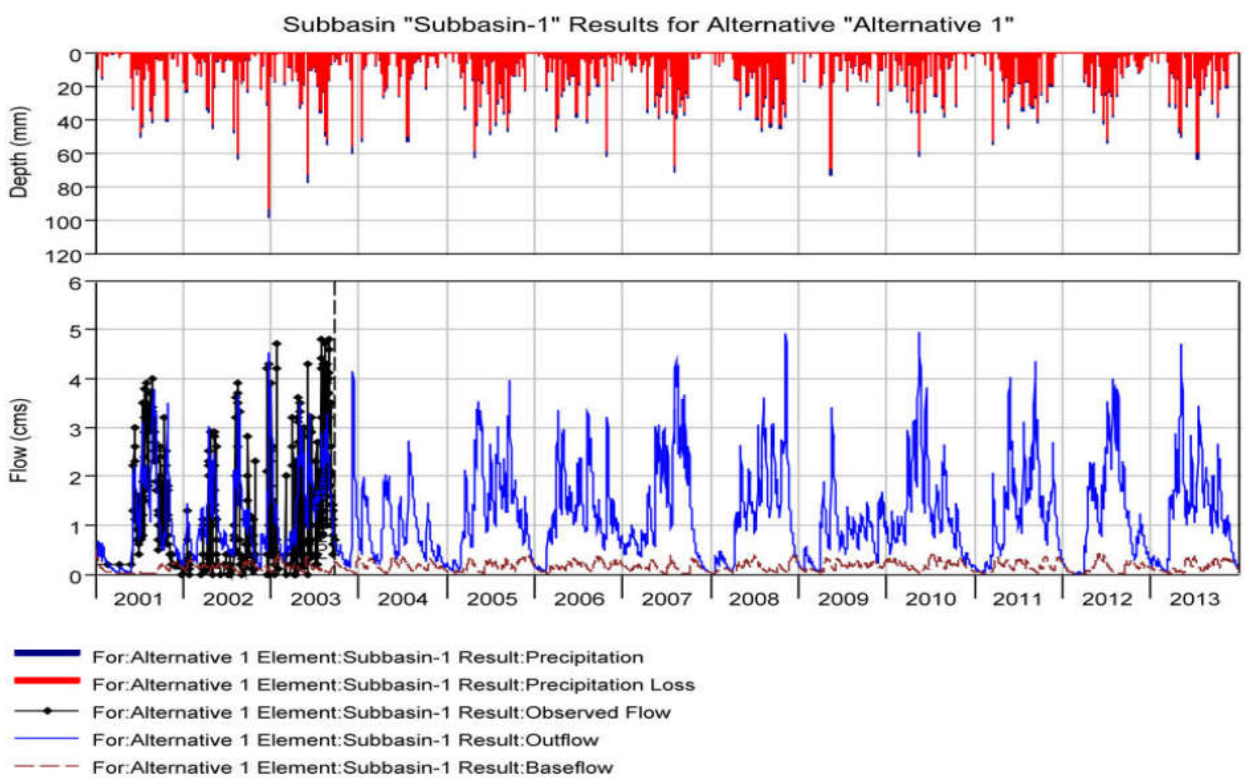
Volume Units: MM

Computed Results

Peak Discharge:	5.0 (M3/S)	Date/Time of Peak Discharge:	16May2010, 00:00
Precipitation Volume:	14662.58 (MM)	Direct Runoff Volume:	879.75 (MM)
Loss Volume:	13782.83 (MM)	Baseflow Volume:	130.39 (MM)
Excess Volume:	879.75 (MM)	Discharge Volume:	1010.14 (MM)

Observed Hydrograph at Gage Gage 1

Peak Discharge:	4.8 (M3/S)	Date/Time of Peak Discharge:	01Aug2003, 00:00
Mean Abs Error:	0.7 (M3/S)	RMS Error:	0.4 (M3/S)
Volume:	142.23 (MM)	Volume Residual:	58.94 (MM)
Nash-Sutcliffe:	0.447		



Appendix A.10 Harie River Calibration (Nr. Arba Minch)

Project: HariePro Optimization Trial: Trial 3
Sink: Outlet1

Start of Trial:	01Jan1989, 00:00	Basin Model:	Basin 1
End of Trial:	31Dec1996, 00:00	Meteorologic Model:	HariePro
Compute Time:	23Sep2019, 14:59:58		

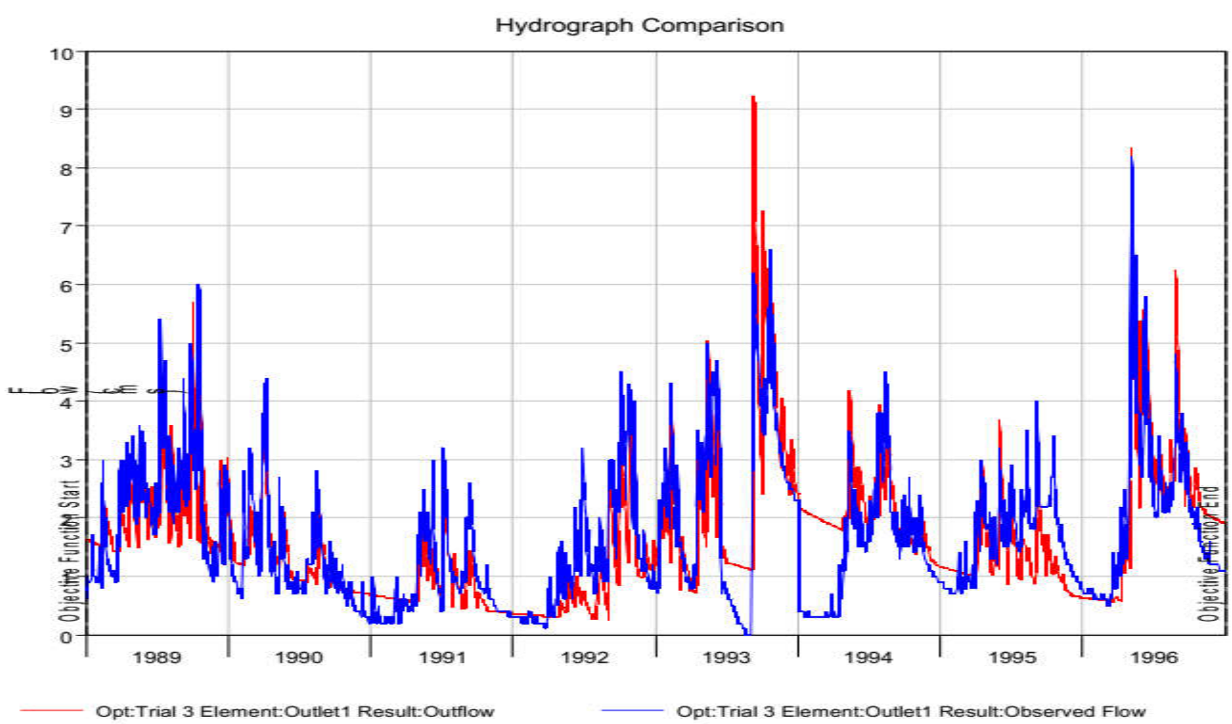
Volume Units: MM

Computed Results

Peak Discharge:	9.2 (M3/S)	Date/Time of Peak Discharge	09Sep1993, 00:00
Volume:	2645.17 (MM)		

Observed Hydrograph at Gage Gage 1

Peak Discharge:	8.2 (M3/S)	Date/Time of Peak Discharge	07May1996, 00:00
Mean Abs Error:	0.6 (M3/S)	RMS Error:	0.8 (M3/S)
Volume:	2645.16 (MM)	Volume Residual:	0.00 (MM)
Nash-Sutcliffe:	0.566		



Appendix A.11 Harie River Validation

Project: Hrie Validation   Simulation Run: Run 1
Sink: Outlet 1

Start of Run:	01Jan1997, 00:00	Basin Model:	Basin 1
End of Run:	31Dec2000, 00:00	Meteorologic Model:	Met 1
Compute Time:	23Sep2019, 15:55:45	Control Specifications:	Control 1

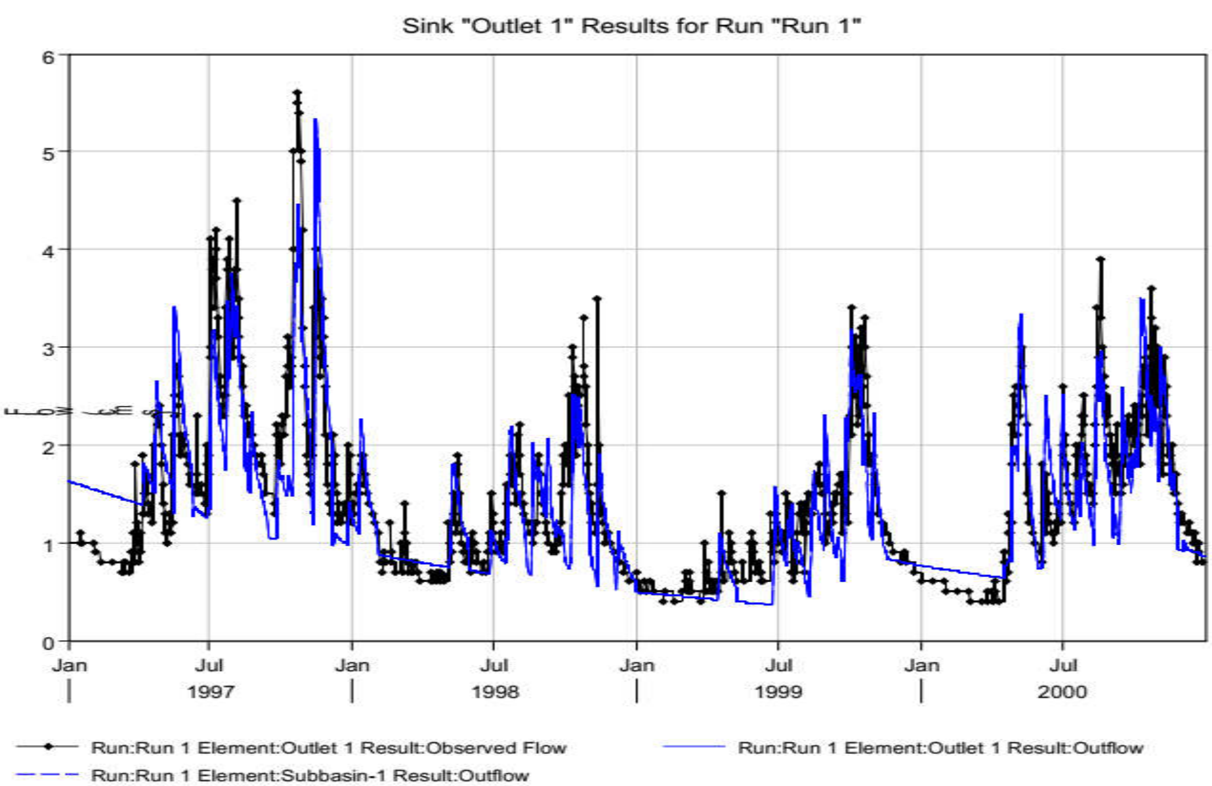
Volume Units: MM

Computed Results

Peak Discharge:	5.3 (M3/S)	Date/Time of Peak Discharge	16Nov1997, 00:00
Volume:	1060.90 (MM)		

Observed Hydrograph at Gage Gage 1

Peak Discharge:	5.6 (M3/S)	Date/Time of Peak Discharge	22Oct1997, 00:00
Mean Abs Error:	0.3 (M3/S)	RMS Error:	0.5 (M3/S)
Volume:	1097.98 (MM)	Volume Residual:	-37.53 (MM)
Nash-Sutcliffe:	0.687		



Appendix A.12 Harie River Prediction

Project: Harie Prediction Forecast Alternative: Alternative 1
Sink: Outlet-1

Start of Alternative:	01Jan2001, 00:00	Basin Model:	Basin 1
End of Alternative:	31Dec2013, 00:00	Meteorologic Model:	Met 1
Compute Time:	23Sep2019, 15:22:29		

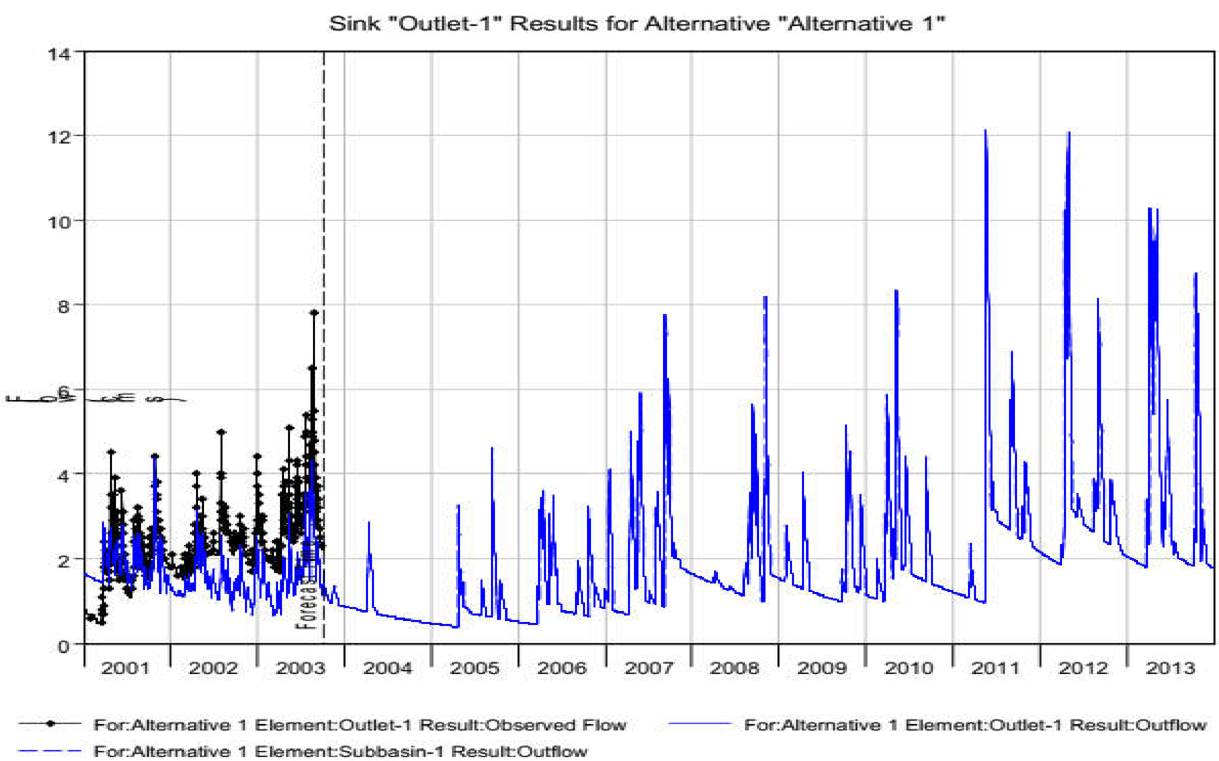
Volume Units: MM

Computed Results

Peak Discharge:	12.1 (M3/S)	Date/Time of Peak Discharge	20May2011, 00:00
Volume:	4858.91 (MM)		

Observed Hydrograph at Gage Gage 1

Peak Discharge:	7.8 (M3/S)	Date/Time of Peak Discharge	28Aug2003, 00:00
Mean Abs Error:	0.8 (M3/S)	RMS Error:	0.4 (M3/S)
Volume:	1231.27 (MM)	Volume Residual:	-329.94 (MM)
Nash-Sutcliffe:	0.779		



Appendix B: Inflow, Outflow and Storage Data

Appendix B.1 Bilate River Flow Gauged at Alaba Kulito (m^3/Sec)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1973	0.51	0.26	0.17	0.18	2.26	1.99	7.64	24.97	43.17	26.31	7.36	1.23	9.67
1974	0.43	0.36	1.42	1.06	1.47	2.41	8.50	16.07	25.97	13.39	3.42	0.51	6.25
1975	0.33	0.38	0.50	3.23	1.77	4.33	16.25	32.67	47.09	24.51	5.65	0.96	11.47
1976	0.40	0.28	0.66	1.50	3.71	3.64	13.00	26.05	31.33	13.71	10.92	2.59	8.98
1977	3.06	4.08	1.47	2.79	3.85	7.73	24.03	36.41	41.49	24.11	24.94	5.74	14.98
1978	0.51	1.22	3.62	1.15	2.23	4.10	20.28	41.89	42.71	31.39	7.15	1.79	13.17
1979	1.40	3.13	2.14	4.99	8.81	8.43	14.98	22.56	24.31	14.95	5.38	0.55	9.30
1980	0.32	0.29	0.51	2.87	13.26	4.74	11.61	16.92	22.11	12.64	3.31	0.47	7.42
1981	0.26	0.18	5.30	10.71	4.95	1.54	5.35	14.14	39.33	17.36	2.36	0.22	8.47
1982	0.50	0.76	1.02	2.98	4.80	2.85	5.38	19.45	26.77	25.02	12.65	3.60	8.82
1983	0.47	0.83	3.22	15.62	18.91	20.68	10.25	29.97	43.92	34.21	12.81	3.50	16.20
1984	0.44	0.25	0.28	0.17	3.58	6.36	9.65	20.01	27.55	11.19	0.66	0.37	6.71
1985	0.18	0.12	0.13	3.97	11.27	3.55	3.52	20.92	17.74	8.50	1.00	0.24	5.93
1986	0.27	1.32	1.92	5.72	7.14	12.63	25.12	28.29	25.96	13.13	1.83	0.52	10.32
1987	0.33	0.70	5.89	20.98	23.92	35.06	17.17	13.95	26.54	10.69	0.89	0.52	13.05
1988	0.53	0.57	0.53	2.27	2.43	3.74	9.33	40.73	43.01	35.71	10.92	2.50	12.69
1989	0.50	2.73	1.61	9.91	6.19	4.64	8.66	16.51	34.64	21.52	5.03	3.81	9.64
1990	1.22	3.02	8.07	15.31	7.17	9.34	16.95	20.63	23.54	16.18	3.56	0.77	10.48
1991	0.43	0.60	2.22	1.45	0.96	2.20	9.00	19.25	22.41	7.32	1.78	1.08	5.73
1992	0.73	2.48	2.12	3.24	2.85	6.38	17.92	44.55	56.72	24.94	6.84	2.07	14.24
1993	0.85	2.88	0.62	4.92	19.39	28.39	16.29	26.10	29.68	22.28	13.03	3.21	13.97
1994	4.53	3.74	3.96	4.06	6.17	8.84	21.26	41.60	37.96	15.67	4.66	1.59	12.84
1995	0.92	1.15	1.46	8.15	6.83	6.23	15.49	29.82	33.83	7.51	2.60	3.76	9.81
1996	2.39	0.66	9.59	10.23	27.22	42.73	31.98	42.70	30.48	11.76	3.16	1.71	17.88
1997	2.06	0.68	0.78	4.91	2.44	4.02	9.34	23.46	16.59	25.81	23.54	4.71	9.86
1998	3.09	2.27	4.11	10.33	9.08	6.05	15.40	48.54	29.02	31.50	7.01	2.51	14.08
1999	1.67	0.74	1.61	0.53	1.32	2.39	8.33	11.34	13.83	36.87	9.01	2.22	7.49
2000	0.50	2.73	1.61	9.91	6.19	4.64	8.66	16.51	34.64	21.52	5.05	3.81	9.65
2001	1.78	1.31	4.85	2.01	6.51	12.59	26.24	40.87	30.97	7.40	2.49	1.60	11.55
2002	1.91	1.04	2.34	1.33	1.29	2.18	3.88	13.78	15.70	4.28	1.37	3.38	4.37
2003	1.85	1.23	0.97	6.74	1.89	2.79	8.60	12.40	20.45	21.98	7.49	3.04	7.45
2004	1.56	2.05	3.24	7.21	0.70	1.36	9.01	17.30	17.10	14.75	2.04	1.01	6.44
2005	1.10	0.55	2.09	9.75	19.14	5.30	14.89	26.75	50.41	29.96	14.66	10.09	15.39
2006	7.95	7.87	21.21	39.71	28.00	30.63	52.26	86.11	67.30	32.23	17.61	12.97	33.65
2007	11.50	19.83	14.02	23.61	36.00	44.93	69.35	83.80	83.52	59.35	26.64	21.55	41.17
Mean	1.56	2.05	3.24	7.21	8.59	9.98	16.36	29.61	33.89	20.68	7.49	3.04	
MCM	4.19	5.01	8.67	18.70	23.00	25.88	43.82	79.32	87.85	55.39	19.42	8.13	

Appendix B.2 Bilate River Flow Gauged at Bilate Tena (m^3/Sec)

Year	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	Annual
1970	2.86	3.60	13.04	9.22	9.73	3.37	29.09	35.52	42.55	26.33	8.50	1.20	15.42
1971	1.03	0.89	1.18	2.54	4.12	44.58	20.19	16.73	46.25	11.56	8.70	2.16	13.33
1972	2.86	3.60	6.98	11.13	13.59	16.59	24.06	36.53	46.28	32.89	18.15	3.03	17.97
1973	1.18	0.64	0.49	1.25	6.65	5.67	12.21	25.13	52.69	27.78	6.49	1.67	11.82
1974	0.80	0.72	3.58	2.26	3.15	3.19	10.32	21.82	29.18	12.97	3.58	0.81	7.70
1975	0.54	0.69	2.10	6.68	4.77	5.60	26.54	36.71	54.92	19.12	0.11	0.00	13.15
1976	0.00	0.00	0.10	0.21	1.94	0.21	2.99	15.33	18.84	2.49	4.08	0.91	3.92
1977	3.11	5.64	2.97	7.26	10.19	16.22	51.90	76.66	95.49	73.80	52.85	7.25	33.61
1978	1.38	2.39	7.93	4.11	5.40	7.86	36.32	93.40	101.28	68.70	7.49	4.09	28.36
1979	5.27	17.74	10.62	11.14	14.58	14.03	17.38	38.09	43.93	27.06	7.81	1.61	17.44
1980	0.93	1.38	2.25	6.82	23.32	44.21	17.77	4.99	46.28	32.89	1.95	0.77	15.30
1981	0.55	0.84	29.66	28.90	8.00	5.27	15.10	13.64	64.15	28.66	1.46	0.55	16.40
1982	2.86	3.60	6.98	11.13	13.59	16.59	24.06	36.53	46.28	32.89	18.15	3.03	17.97
1983	1.13	2.62	10.89	31.68	41.60	45.08	20.77	77.12	114.65	71.36	15.13	1.68	36.14
1984	0.96	0.66	0.60	0.65	5.87	7.20	15.89	36.80	48.59	8.78	1.91	1.44	10.78
1985	1.57	0.57	1.04	16.54	33.14	19.90	32.02	32.36	24.43	12.43	135.57	4.00	26.13
1986	1.00	3.85	10.87	21.91	38.91	58.17	132.31	136.74	144.57	95.28	78.62	6.88	60.76
1987	2.02	1.15	2.64	15.88	20.76	49.12	45.70	19.01	16.37	37.07	13.99	1.34	18.75
1988	2.86	3.60	6.98	11.13	13.59	16.59	24.06	36.53	46.28	32.89	18.15	3.03	17.97
1989	0.82	9.98	2.64	25.41	14.63	8.91	12.14	20.46	62.25	79.46	18.15	3.03	21.49
1990	2.86	3.60	6.98	11.13	13.59	16.59	24.06	29.12	22.74	19.59	7.30	5.38	13.58
1991	2.69	5.50	19.32	6.88	22.14	26.47	21.91	25.66	26.59	6.62	8.00	7.16	14.91
1992	25.33	15.63	14.93	12.62	12.20	26.64	22.41	46.52	89.96	86.76	74.14	3.03	35.85
1993	2.86	3.60	6.98	11.13	13.59	16.59	24.06	36.53	46.28	32.89	18.15	3.03	17.97
1994	2.86	3.60	6.98	11.13	13.59	16.59	24.06	36.53	46.28	32.89	18.15	3.03	17.97
1995	2.86	3.60	6.98	11.13	13.59	16.59	24.06	36.53	46.28	32.89	18.15	3.03	17.97
1996	2.86	3.60	6.98	11.13	13.59	16.59	24.06	36.53	46.28	32.89	18.15	3.03	17.97
1997	2.86	3.60	6.98	11.13	13.59	16.59	24.06	36.53	46.28	32.89	18.15	3.03	17.97
1998	2.86	3.60	6.98	27.42	11.42	7.73	13.32	69.97	33.44	30.06	7.49	2.69	18.08
1999	1.93	1.22	3.78	2.48	3.83	6.67	18.14	19.11	31.09	70.86	12.03	2.63	14.48
2000	1.63	1.19	0.97	5.59	17.95	5.89	8.79	19.93	17.23	28.68	8.44	4.80	10.09
2001	3.17	2.42	10.47	5.72	11.60	12.18	16.78	15.30	24.21	15.49	4.93	2.61	10.41
2002	2.22	4.11	12.52	7.84	5.87	5.70	6.20	15.04	11.81	5.44	3.51	5.60	7.15
2003	6.78	4.95	4.74	11.72	5.97	8.24	8.67	12.82	17.83	13.08	18.15	3.03	9.67
2004	2.86	2.41	3.31	10.25	6.91	7.59	23.71	25.51	18.22	18.93	3.60	2.84	10.51
2005	3.37	3.01	5.14	15.07	25.74	8.04	19.27	24.40	19.46	12.43	6.88	3.11	12.16
2006	1.98	3.51	10.57	13.57	10.06	10.68	15.91	55.59	23.18	10.08	5.45	5.55	13.84
Mean	2.86	3.60	6.98	11.13	13.59	16.59	24.06	36.53	46.28	32.89	18.15	3.03	
MCM	7.65	8.80	18.69	28.85	36.39	42.99	64.45	97.85	119.96	88.09	47.04	8.11	

Appendix B.3 Gidabo River Flow Gauged Nr. Aposto (m^3/Sec)

Year	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	Annual
1977	4.38	3.51	2.94	4.03	6.38	6.71	7.60	11.49	14.32	22.82	13.92	4.80	8.58
1978	2.70	2.61	5.93	7.50	11.23	6.17	14.61	16.57	12.54	14.60	5.15	3.74	8.61
1979	3.77	3.98	4.05	4.71	7.14	8.79	6.00	12.01	12.32	13.43	6.78	5.24	7.35
1980	1.27	1.34	1.46	4.59	7.09	3.04	1.74	1.74	4.03	7.57	3.10	2.22	3.27
1981	1.44	1.53	2.89	9.22	9.85	4.14	5.32	12.75	22.32	13.24	5.43	2.64	7.57
1982	2.67	2.23	1.92	3.36	7.65	9.95	7.77	12.97	15.17	13.04	6.75	4.82	7.36
1983	2.75	2.43	2.68	8.19	15.89	11.70	8.59	23.15	17.43	20.52	10.83	5.41	10.80
1984	3.35	2.55	2.33	2.80	3.88	6.54	4.64	5.47	14.63	6.95	4.50	2.53	5.02
1985	2.13	1.66	1.88	5.48	16.94	7.69	7.07	7.75	14.39	11.16	3.53	2.63	6.86
1986	1.60	1.73	2.23	4.45	9.05	25.93	11.34	8.45	18.47	12.30	3.68	2.73	8.50
1987	1.97	1.93	2.99	4.89	13.75	10.38	4.99	4.38	7.02	11.92	0.00	0.09	5.36
1988	0.20	0.66	1.37	4.55	2.66	4.62	5.29	10.05	11.46	13.01	4.09	2.21	5.01
1989	2.59	2.30	1.97	4.95	4.01	5.85	5.76	3.60	11.67	12.42	4.61	4.25	5.33
1990	2.41	3.80	6.05	10.10	10.58	6.26	6.01	6.01	6.82	6.94	3.75	3.18	5.99
1991	3.19	3.44	3.75	4.60	4.65	3.37	4.82	4.35	10.36	5.46	2.11	1.77	4.32
1992	1.16	1.56	1.20	6.63	6.51	5.04	7.14	22.81	19.48	27.46	10.74	4.47	9.52
1993	2.92	4.31	2.33	5.57	16.32	16.56	7.74	5.45	9.31	16.47	7.54	2.70	8.10
1994	1.81	1.45	1.72	3.13	9.79	6.87	16.02	17.69	12.56	6.37	5.31	2.44	7.10
1995	1.64	1.67	1.85	9.51	9.07	4.23	4.76	6.53	16.84	12.47	3.84	2.94	6.28
1996	2.86	1.81	5.98	11.29	14.83	16.09	15.92	18.21	18.78	19.23	4.13	2.60	10.98
1997	2.12	1.53	1.55	5.38	8.08	5.80	10.12	12.95	8.16	21.41	16.76	5.83	8.31
1998	2.06	1.05	1.19	3.34	10.10	4.48	7.58	23.14	10.93	29.75	6.11	2.73	8.54
1999	2.17	1.74	1.91	1.91	3.67	2.47	2.47	3.07	3.95	6.83	2.99	1.89	2.92
2000	1.41	1.30	1.27	1.96	4.91	3.02	2.51	7.83	7.20	18.48	6.27	2.45	4.89
2001	2.24	1.81	1.90	2.77	5.63	8.36	3.93	8.81	9.92	9.83	4.14	2.48	5.15
2002	2.01	1.56	2.04	2.93	3.94	5.29	2.71	3.66	4.89	3.53	2.19	2.24	3.08
2003	1.84	1.47	1.71	4.02	2.99	2.40	3.01	6.55	4.84	7.93	5.55	3.10	3.78
2004	2.21	2.07	2.54	5.15	3.45	3.24	2.79	4.02	6.21	7.94	2.62	2.17	3.70
2005	1.77	1.37	1.72	2.84	10.53	6.76	5.56	6.01	8.78	6.27	3.67	2.02	4.78
2006	1.65	1.67	2.75	4.56	9.25	5.27	10.96	13.93	8.87	10.99	6.37	4.54	6.73
Mean	2.21	2.07	2.54	5.15	8.33	7.23	6.83	10.05	11.46	13.01	5.55	3.10	
MCM	5.92	5.05	6.79	13.34	22.30	18.75	18.28	26.91	29.69	34.85	14.38	8.29	

Appendix B.4 Gelan River Flow Gauged below the Bridge Nr. Tore (m^3/Sec)

Year	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	Annual
1990	1.59	1.05	1.04	2.99	9.30	7.31	2.04	2.11	2.62	7.00	5.07	1.83	3.66
1991	0.88	0.70	0.64	1.42	2.41	3.86	2.08	1.18	4.35	6.77	3.24	0.84	2.36
1992	0.33	0.37	0.30	1.83	8.05	7.12	3.24	1.98	4.40	13.84	4.78	2.09	4.03

1993	1.20	1.50	0.66	0.73	11.42	12.81	4.01	1.88	2.15	5.08	3.78	1.41	3.88
1994	1.05	0.50	0.31	2.12	13.72	8.14	5.93	7.19	3.20	3.56	3.86	1.50	4.26
1995	0.67	0.63	0.63	3.53	10.61	5.50	4.68	3.16	5.67	13.25	6.14	2.17	4.72
1996	1.43	0.80	1.28	6.83	13.70	14.60	7.41	7.05	14.77	11.87	6.25	2.78	7.40
1997	1.66	1.07	0.77	3.06	9.70	3.23	3.52	2.17	1.52	6.11	11.13	6.00	4.16
1998	5.96	3.89	2.32	3.68	11.23	9.10	4.26	4.06	2.87	7.78	5.93	1.94	5.25
1999	1.25	0.84	1.57	2.85	7.55	2.55	3.11	2.42	2.23	8.20	7.14	1.65	3.45
2000	0.84	0.60	0.51	0.91	6.89	2.78	1.92	2.93	2.81	12.34	11.54	3.39	3.96
2001	1.51	0.96	0.78	3.66	11.26	8.84	3.05	3.05	8.39	15.27	10.04	2.92	5.81
2002	1.67	0.93	1.18	1.99	6.95	4.82	2.04	1.71	1.80	11.02	4.53	2.32	3.41
2003	1.72	0.80	0.42	1.41	6.53	6.60	2.17	4.15	2.69	1.76	7.08	2.79	3.18
2004	1.59	1.05	1.04	2.99	9.19	3.54	1.47	1.49	2.97	6.37	5.88	2.64	3.35
2005	1.13	0.73	0.74	0.82	10.97	8.89	2.90	2.07	6.52	11.01	8.59	2.07	4.70
2006	1.02	1.05	1.04	2.99	12.48	8.52	5.01	4.50	3.85	8.54	8.54	4.94	5.21
2007	2.47	1.68	0.86	3.26	10.82	12.19	5.77	5.93	9.47	12.42	9.02	3.43	6.44
2008	1.75	0.99	0.67	2.13	3.87	5.40	3.42	3.90	7.18	10.19	10.07	2.90	4.37
2009	1.60	1.17	0.72	2.99	9.30	5.49	2.06	1.07	1.93	7.13	2.32	0.94	3.06
2010	0.60	0.27	3.69	12.13	17.08	11.34	4.99	4.23	7.29	15.37	7.23	3.25	7.29
2011	1.96	1.26	1.22	0.74	5.32	10.39	5.50	9.20	14.42	10.59	10.37	6.24	6.43
2012	2.36	1.24	0.81	2.25	5.63	4.48	3.92	5.00	7.94	10.70	10.32	4.21	4.91
2013	1.94	1.02	1.69	4.53	9.27	7.90	6.98	9.11	9.51	9.40	7.08	2.79	5.93
Mean	1.59	1.05	1.04	2.99	9.30	7.31	3.81	3.81	5.44	9.40	7.08	2.79	
MCM	4.26	2.55	2.78	7.76	24.92	18.94	10.21	10.22	14.10	25.17	18.36	7.48	

Appendix B.5 Hamessa River Flow Gauged Nr. Wajifo (m^3/Sec)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1980	0.36	0.31	0.15	1.69	2.61	2.32	1.02	0.58	0.34	0.16	0.11	0.06	0.81
1981	0.03	0.52	2.45	7.61	2.86	1.08	4.71	3.26	2.57	1.02	0.36	0.16	2.22
1982	0.22	0.08	0.10	1.26	2.32	1.58	2.11	3.93	2.83	4.20	4.55	3.51	2.22
1983	2.35	1.82	1.06	1.78	2.50	0.77	1.94	4.92	4.74	5.97	0.88	0.32	2.42
1984	0.16	0.09	0.10	0.19	1.69	2.03	0.39	2.78	3.06	0.57	0.19	0.16	0.95
1985	0.05	0.00	1.01	3.50	2.41	1.45	3.62	2.02	0.38	0.22	0.03	0.00	1.22
1986	0.00	0.03	0.09	1.58	3.91	2.67	3.74	4.12	1.56	0.81	0.15	0.80	1.62
1987	0.10	0.05	0.91	0.71	4.46	2.79	0.90	0.81	0.69	1.72	0.17	0.03	1.11
1988	0.49	0.35	0.82	3.93	5.07	2.49	6.37	16.28	2.17	1.79	0.33	0.18	3.36
1989	0.12	0.16	2.37	2.34	1.90	2.23	1.51	0.80	2.08	1.14	0.48	1.69	1.40
1990	0.43	1.03	0.59	0.74	0.99	0.86	4.72	3.36	0.97	0.76	0.21	0.14	1.23
1991	0.16	1.91	0.78	0.47	2.98	3.78	3.91	1.48	1.29	0.02	0.00	0.01	1.40
1992	0.00	0.01	2.03	3.94	2.29	3.68	3.04	2.76	2.30	2.86	0.46	0.26	1.97
1993	1.88	0.67	0.11	1.62	4.16	4.64	1.49	2.28	0.54	1.56	0.13	0.01	1.59

1994	0.00	0.00	0.09	1.81	7.01	1.46	9.33	7.93	2.39	0.59	0.39	0.04	2.59
1995	0.00	0.03	0.20	1.97	3.39	4.75	1.96	1.55	2.03	0.43	0.27	0.05	1.38
1996	0.03	0.00	0.09	0.65	1.99	6.01	4.18	5.31	5.88	1.58	0.63	0.15	2.21
1997	0.07	0.01	0.00	1.15	1.84	0.54	2.24	3.91	0.83	8.62	15.03	0.40	2.89
1998	0.36	0.33	0.22	0.25	0.62	1.49	3.31	3.81	1.81	2.49	0.60	0.15	1.28
1999	0.05	0.00	0.07	0.52	0.39	0.68	1.52	0.87	0.31	1.24	0.14	0.00	0.48
2000	0.00	0.00	0.00	0.00	0.01	2.35	2.78	2.63	1.64	2.12	1.05	0.18	1.06
2001	0.36	0.31	0.63	1.96	2.52	3.06	5.43	9.55	6.30	2.32	0.28	0.12	2.74
2002	0.35	0.00	0.14	2.13	3.64	0.07	0.15	3.86	1.36	0.54	0.00	1.45	1.14
2003	1.49	0.01	1.12	3.24	1.48	1.54	2.35	6.05	1.58	1.79	1.11	0.40	1.85
2004	0.36	0.31	0.63	1.96	0.04	1.99	0.95	3.46	0.61	0.76	0.17	0.01	0.94
2005	0.00	0.00	0.58	3.98	2.52	2.25	2.95	2.66	6.23	1.39	1.17	0.02	1.98
Mean	0.36	0.31	0.63	1.96	2.52	2.25	2.95	3.88	2.17	1.79	1.11	0.40	
MCM	0.97	0.75	1.68	5.08	6.76	5.84	7.89	10.40	5.63	4.81	2.88	1.06	

Appendix B.6 Harie River Flow Gauged Nr. Arba Minch (m^3/Sec)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1985	0.43	0.35	0.49	0.34	6.55	2.10	3.08	2.25	1.81	1.75	0.99	0.56	1.73
1986	0.41	0.64	0.92	1.85	3.69	5.58	2.59	2.23	5.87	2.90	1.53	3.23	2.62
1987	1.19	0.97	1.70	4.10	4.77	3.03	1.84	2.48	1.96	2.75	1.83	1.26	2.32
1988	1.19	1.27	0.96	2.07	3.10	2.46	4.61	4.26	3.69	3.94	1.76	1.19	2.54
1989	1.01	1.63	1.46	2.78	3.18	2.13	3.00	2.40	3.41	3.69	1.33	1.99	2.34
1990	1.23	1.88	2.04	2.20	1.32	0.87	0.91	1.82	1.02	0.94	0.56	0.34	1.26
1991	0.43	0.23	0.54	0.49	2.07	1.28	1.73	0.95	1.66	0.87	0.53	0.37	0.93
1992	0.27	0.29	0.21	0.99	1.03	1.52	1.38	1.41	2.34	4.10	2.14	1.13	1.40
1993	2.23	3.23	1.28	2.01	4.37	2.58	0.51	0.10	5.05	4.50	3.22	2.48	2.63
1994	0.37	0.31	0.34	0.60	2.44	1.80	2.36	3.33	1.78	1.73	1.54	1.02	1.47
1995	0.81	0.78	0.95	2.01	2.07	1.92	1.96	2.20	2.83	2.38	1.45	0.98	1.69
1996	0.70	0.62	0.87	1.89	5.60	3.69	2.44	2.94	2.99	1.95	1.36	1.14	2.18
1997	1.02	0.84	0.83	1.60	1.88	1.64	3.22	2.64	1.68	4.20	2.85	1.48	1.99
1998	1.48	0.85	0.78	0.63	1.07	0.88	1.27	1.42	1.19	2.30	1.31	0.75	1.16
1999	0.54	0.44	0.53	0.64	0.73	0.78	1.07	1.43	1.36	2.55	1.20	0.81	1.01
2000	0.60	0.51	0.41	0.92	2.15	1.25	1.77	2.28	1.93	2.63	1.86	1.03	1.45
2001	0.73	0.60	1.05	1.98	2.25	2.01	1.25	2.48	1.76	3.04	2.79	1.95	1.82
2002	1.77	1.60	1.88	2.60	2.49	2.19	2.33	2.92	2.35	2.44	2.12	2.19	2.24
2003	2.75	2.02	1.95	2.50	2.91	3.01	3.49	4.16	2.80	2.26	1.69	1.39	2.58
2004	1.10	1.08	1.12	1.82	1.81	1.75	1.74	2.42	2.94	3.24	2.40	2.02	1.95
2005	1.75	1.54	1.87	2.21	4.08	2.20	2.61	2.43	2.80	2.51	2.26	1.64	2.33
2006	1.44	1.42	2.13	3.23	2.69	2.23	1.85	2.92	2.16	2.74	2.17	1.63	2.22
2007	1.91	1.77	1.38	2.48	2.54	2.38	1.96	2.60	2.38	1.70	0.00	1.39	1.87
Mean	1.10	1.08	1.12	1.82	2.82	2.14	2.13	2.35	2.51	2.66	1.69	1.39	

MCM	2.95	2.64	2.99	4.73	7.54	5.56	5.70	6.30	6.51	7.12	4.39	3.72	

Appendix B.7 Lake Abaya Sub-basin Un-gauged Sub-Watersheds Runoff (MCM)

Watersheds	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Bilate	0	0	5.20	10.55	14.51	17.98	29.27	46.84	58.47	41.71	0	0	224.54
Gidabo	0	0	7.35	35.01	72.86	57.86	55.88	92.33	104.07	125.86	39.41	0	590.62
Gelana	0	0	0.25	5.60	24.04	17.61	8.23	8.24	12.41	24.31	16.99	0	117.68
Hamessa	0	0	0.07	0.34	0.48	0.41	0.57	0.77	0.39	0.32	0	0	3.35
Lake Hghlands and lake surrounding	0	0	4.56	11.07	20.87	18.50	19.94	29.83	34.94	35.04	0	0	174.73
Monthly Total	0	0	17.43	62.57	132.76	112.36	113.89	178.01	210.28	227.24	56.40	0	1110.93

Appendix B.8 Volume of Lake Abaya Using the Best Fit Curve of Bathymetry (Km^3)

Year	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	Average
1985	11.11	11.01	10.8	10.82	10.88	11.03	11.11	11.13	11.07	10.98	11.18	10.96	11.01
1986	10.72	10.52	10.38	10.29	10.32	10.44	10.7	10.79	10.79	10.87	10.83	10.7	10.61
1987	10.53	10.36	10.29	10.32	10.4	10.91	10.93	10.79	10.71	10.73	10.73	10.66	10.61
1988	10.46	10.34	10.16	10.08	10.23	10.13	10.13	10.64	11.04	11.36	11.56	11.42	10.62
1989	11.28	11.19	11	10.98	11.07	11.02	10.98	10.94	10.97	11.18	11.34	11.37	11.11
1990	11.37	11.28	11.3	11.44	11.51	11.5	11.55	11.56	11.52	11.52	11.41	11.31	11.44
1991	11	10.91	10.8	10.65	10.67	10.7	10.71	10.67	10.64	10.68	10.58	10.41	10.7
1992	10.21	10.11	10.01	9.96	9.9	9.9	9.89	9.95	10.04	10.47	10.65	10.56	10.13
1993	10.64	10.75	10.62	10.52	10.68	11.15	11.22	11.22	11.18	11.19	11.33	11.2	10.97
1994	10.94	10.78	10.6	10.53	10.64	10.84	10.97	11.31	11.56	11.63	11.51	11.36	11.05
1995	11.4	11.23	10.98	10.89	11.07	11.06	11.08	11.08	11.2	11.41	11.36	11.24	11.17
1996	10.95	10.82	10.7	10.67	10.86	11.33	11.91	12.27	12.45	12.46	12.48	12.54	11.6
1997	12.53	12.46	12.27	12.19	12.27	12.2	12.31	12.47	12.45	12.47	12.53	12.55	12.39
1998	12.55	12.55	12.55	12.55	12.55	12.79	13.24	13.39	13.67	13.67	13.71	13.82	13.07
1999	14.26	13.96	13.92	13.96	14.08	14.16	14.17	14.11	14.21	14.4	14.34	14.14	14.14
2000	13.76	13.5	13.19	13	13.12	12.98	12.93	12.94	12.93	13.11	13.4	13.34	13.18
2001	13.22	13	12.79	12.73	12.87	13.1	13.22	13.37	13.81	14.06	14.31	14.29	13.39
2002	14.11	13.89	13.7	13.62	13.63	13.44	13.3	13.26	13.12	13.06	12.96	12.83	13.4
2003	12.83	12.69	12.5	12.39	12.56	12.56	12.52	12.55	12.82	12.85	12.63	12.63	12.63
2004	11.99	11.99	11.99	11.99	12.16	12.09	11.91	11.93	11.91	12.02	12.02	11.87	11.99
2005	11.71	11.47	11.41	11.3	11.73	11.95	11.82	11.87	12.1	12.27	12.31	12.19	11.84
2006	11.94	11.78	11.71	11.7	11.92	11.91	11.96	12.11	12.34	12.41	12.64	12.76	12.09
2007	12.68	12.59	12.42	12.33	12.37	12.65	13.08	13.59	14.24	14.86	15.02	14.83	13.34
2008	14.51	14.3	13.94	13.79	13.71	13.68	13.47	13.5	13.76	13.99	14.39	14.58	13.96
2009	14.36	14.08	13.9	13.3	13.3	13.33	12.87	12.9	12.9	12.97	12.96	12.82	13.3

2010	12.64	12.5	12.42	12.77	13.56	14.29	14.65	14.69	14.98	15.22	15.2	15.02	13.94
2011	14.68	14.43	14.32	14.04	14.01	14.11	14.06	14.22	14.86	15.31	15.67	15.89	14.62
2012	15.69	15.47	15.2	14.96	15.08	14.89	14.71	15.07	15.41	15.68	15.76	15.63	15.29
2013	15.38	15.13	14.89	14.88	15.22	15.53	15.57	15.78	16.03	16.2	16.44	16.4	15.61
Mean	12.39	12.24	12.10	12.02	12.15	12.26	12.31	12.42	12.58	12.73	12.80	12.74	12.39

Appendix B.9 Area of Lake Abaya Using the Best Fit Curve of Bathymetry (Km^2)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Mean Annual
1985	1210.48	1200.74	1183.16	1184.63	1189.22	1202.83	1210.14	1212.86	1207.16	1198.74	1217.54	1196.19	1200.66
1986	1176.82	1163.32	1154.91	1149.92	1151.75	1158.34	1175.57	1182.01	1181.83	1188.75	1185.16	1175.42	1169.03
1987	1163.68	1153.70	1150.33	1151.68	1156.05	1191.94	1193.47	1182.05	1175.74	1177.87	1177.30	1172.14	1169.00
1988	1159.31	1152.53	1144.12	1140.88	1146.99	1142.87	1142.85	1171.14	1203.41	1236.65	1261.19	1244.06	1169.37
1989	1228.23	1218.60	1200.27	1197.92	1207.10	1201.91	1198.35	1194.63	1197.72	1218.17	1234.84	1237.82	1210.53
1990	1238.12	1228.47	1230.85	1246.28	1255.24	1254.05	1260.63	1260.74	1256.52	1256.46	1242.80	1232.12	1246.51
1991	1200.55	1192.13	1182.95	1171.58	1173.28	1175.17	1176.35	1173.40	1170.88	1173.49	1167.02	1156.63	1175.43
1992	1146.49	1142.10	1138.30	1136.82	1135.04	1134.94	1134.57	1136.31	1139.30	1159.83	1171.94	1165.30	1143.05
1993	1171.11	1178.97	1169.65	1162.81	1173.79	1214.83	1222.19	1221.96	1217.27	1218.90	1233.81	1219.21	1197.52
1994	1194.63	1181.58	1168.01	1163.54	1170.87	1186.52	1197.15	1231.48	1261.60	1270.16	1255.25	1236.70	1204.73
1995	1242.03	1222.87	1198.70	1190.17	1207.10	1206.04	1208.11	1208.11	1220.07	1243.28	1237.33	1223.78	1216.40
1996	1195.43	1184.20	1175.36	1173.12	1187.79	1233.76	1310.29	1367.15	1399.67	1401.40	1405.11	1415.23	1265.96
1997	1413.86	1401.63	1368.13	1354.61	1366.82	1356.08	1374.75	1402.74	1399.12	1402.56	1414.20	1417.90	1388.74
1998	1417.90	1417.90	1417.90	1417.90	1417.90	1464.99	1563.62	1596.60	1665.94	1667.70	1676.35	1704.51	1525.24
1999	1826.60	1743.48	1731.01	1742.52	1777.03	1798.52	1800.56	1784.19	1813.53	1866.88	1851.22	1793.92	1793.32
2000	1690.98	1623.40	1550.00	1509.81	1535.61	1505.28	1493.28	1496.28	1493.55	1533.09	1599.34	1585.15	1548.80
2001	1558.49	1509.28	1463.91	1452.44	1480.49	1531.80	1558.85	1592.97	1703.77	1771.47	1840.95	1836.24	1596.56
2002	1784.50	1723.63	1675.30	1653.00	1656.23	1610.89	1575.46	1566.62	1534.40	1521.99	1499.44	1473.32	1600.75
2003	1473.63	1445.05	1408.13	1388.10	1419.48	1420.59	1411.85	1418.55	1470.80	1476.76	1432.39	1432.39	1432.39
2004	1321.51	1321.51	1321.51	1321.51	1348.52	1336.74	1309.25	1312.79	1310.21	1326.33	1326.87	1303.99	1321.51
2005	1281.16	1250.44	1242.55	1230.25	1283.28	1315.25	1296.32	1304.40	1339.01	1367.72	1373.65	1354.20	1299.26
2006	1313.62	1290.45	1280.48	1279.98	1311.81	1309.56	1316.72	1341.23	1379.72	1391.37	1434.62	1458.46	1337.88
2007	1443.33	1425.85	1393.90	1378.49	1384.47	1436.30	1526.05	1647.60	1820.19	2008.34	2058.65	1998.15	1586.71
2008	1900.63	1837.18	1738.28	1698.45	1677.66	1670.20	1617.60	1624.21	1691.27	1751.93	1864.37	1920.26	1744.05
2009	1856.79	1775.68	1726.88	1575.66	1575.66	1583.03	1481.85	1488.38	1487.83	1502.88	1499.77	1471.26	1575.66
2010	1434.07	1408.79	1392.85	1460.60	1639.06	1836.70	1941.85	1956.32	2045.30	2123.74	2120.33	2059.14	1738.31
2011	1951.42	1875.29	1842.83	1764.89	1757.69	1785.19	1771.62	1815.27	2009.15	2157.23	2280.59	2359.19	1932.51
2012	2288.25	2209.42	2117.58	2040.68	2078.56	2017.80	1962.53	2077.36	2189.99	2285.52	2312.78	2266.95	2149.60
2013	2178.03	2095.94	2016.52	2013.07	2124.56	2230.45	2244.59	2318.84	2411.47	2474.91	2567.26	2550.43	2258.52
Monthly Mean	1464.20	1433.59	1406.36	1391.42	1413.42	1431.47	1437.12	1458.14	1496.43	1530.14	1549.73	1540.00	

Appendix B.10 Mean Monthly Gauge Height of Lake Abaya (m) (Reference Point 1171 masl)

Year	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	Average
1985	0.99	0.91	0.76	0.77	0.81	0.93	0.99	1.01	0.96	0.90	1.04	0.87	0.91
1986	0.70	0.54	0.43	0.36	0.39	0.48	0.68	0.75	0.75	0.81	0.78	0.68	0.61
1987	0.55	0.42	0.36	0.39	0.45	0.84	0.85	0.75	0.68	0.71	0.70	0.65	0.61
1988	0.49	0.40	0.26	0.19	0.31	0.23	0.23	0.64	0.93	1.17	1.32	1.22	0.62
1989	1.11	1.05	0.91	0.89	0.96	0.92	0.89	0.86	0.89	1.05	1.16	1.18	0.99
1990	1.18	1.12	1.13	1.23	1.28	1.28	1.31	1.31	1.29	1.29	1.21	1.14	1.23
1991	0.91	0.84	0.76	0.64	0.66	0.68	0.69	0.66	0.63	0.66	0.59	0.46	0.68
1992	0.30	0.22	0.13	0.10	0.05	0.05	0.04	0.08	0.16	0.50	0.64	0.57	0.24
1993	0.63	0.72	0.62	0.54	0.66	1.02	1.07	1.07	1.04	1.05	1.15	1.05	0.89
1994	0.86	0.74	0.60	0.55	0.63	0.79	0.88	1.14	1.32	1.37	1.28	1.17	0.94
1995	1.20	1.08	0.90	0.82	0.96	0.95	0.97	0.97	1.06	1.21	1.17	1.08	1.03
1996	0.87	0.77	0.68	0.66	0.80	1.15	1.57	1.81	1.94	1.94	1.95	1.99	1.34
1997	1.99	1.94	1.82	1.76	1.81	1.77	1.84	1.95	1.93	1.95	1.99	2.00	1.89
1998	2.00	2.00	2.00	2.00	2.00	2.16	2.44	2.53	2.70	2.71	2.73	2.79	2.34
1999	3.05	2.88	2.85	2.87	2.95	2.99	3.00	2.96	3.02	3.13	3.10	2.98	2.98
2000	2.76	2.60	2.41	2.29	2.37	2.28	2.24	2.25	2.25	2.36	2.54	2.50	2.40
2001	2.43	2.29	2.15	2.12	2.21	2.36	2.43	2.52	2.79	2.94	3.08	3.07	2.53
2002	2.96	2.83	2.72	2.67	2.68	2.57	2.48	2.45	2.36	2.33	2.26	2.18	2.54
2003	2.18	2.09	1.97	1.89	2.01	2.01	1.98	2.00	2.18	2.19	2.05	2.05	2.05
2004	1.62	1.62	1.62	1.62	1.74	1.69	1.56	1.58	1.57	1.64	1.64	1.54	1.62
2005	1.43	1.26	1.21	1.13	1.44	1.59	1.50	1.54	1.70	1.81	1.84	1.76	1.52
2006	1.58	1.47	1.42	1.42	1.58	1.57	1.60	1.71	1.86	1.90	2.06	2.14	1.69
2007	2.09	2.03	1.91	1.86	1.88	2.06	2.34	2.66	3.04	3.38	3.47	3.36	2.51
2008	3.19	3.07	2.86	2.78	2.73	2.71	2.58	2.60	2.76	2.89	3.12	3.23	2.88
2009	3.11	2.94	2.84	2.48	2.48	2.50	2.21	2.23	2.23	2.27	2.26	2.18	2.48
2010	2.06	1.97	1.91	2.14	2.64	3.07	3.26	3.29	3.44	3.57	3.56	3.47	2.86
2011	3.28	3.14	3.08	2.92	2.91	2.96	2.94	3.03	3.38	3.62	3.80	3.91	3.25
2012	3.81	3.70	3.56	3.44	3.50	3.40	3.30	3.50	3.67	3.81	3.85	3.78	3.61
2013	3.65	3.53	3.39	3.39	3.57	3.73	3.75	3.86	3.98	4.07	4.18	4.16	3.77
Mean	1.83	1.73	1.63	1.58	1.67	1.75	1.78	1.85	1.95	2.04	2.09	2.04	

Appendix B.11 Bilate River Watershed Point Rainfall Distribution (mm)

Station	Year	Elevation (masl)	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	Sum
Humbo	1988-2017	1592.49	30.06	29.34	64.84	126.75	156.45	124.88	158.49	151.06	98.28	98.44	46.89	32.42	1117.90
Dilla	1988-2017	1511.47	31.03	65.30	121.34	193.50	217.61	109.19	98.74	125.35	157.80	192.00	70.58	34.26	1416.70
Aleta Wendo	1986-2017	1802.53	36.90	47.98	109.71	205.68	232.02	143.65	141.09	157.69	213.94	180.63	68.77	32.40	1570.44

Yirga Alem	1991-2017	1735.16	29.62	26.34	92.61	161.06	181.97	100.23	109.97	133.64	145.68	173.45	41.89	24.95	1221.41
Bilate Tena	1986-2015	1550.5	29.10	32.93	78.48	125.47	107.83	90.00	94.97	94.70	92.57	94.88	33.20	23.78	897.93
Bedessa	1987-2012	1598.08	38.31	38.29	87.43	160.86	157.85	118.38	120.47	120.47	90.41	106.16	46.57	29.38	1114.58
Wolaita	1986-2017	2097.41	28.75	37.76	72.16	153.43	182.95	131.72	175.59	172.37	110.74	98.98	54.40	37.95	1256.80
Bodite	1986-2017	1832.15	27.68	47.33	89.45	163.69	170.79	128.20	150.90	152.81	125.98	83.10	39.99	36.28	1216.21
Awassa	1986-2016	1768.72	26.23	35.32	74.51	110.73	126.67	104.59	122.40	120.06	120.24	71.83	31.13	24.85	968.55
Aje	1986-2017	1846.28	11.47	39.59	90.94	57.58	57.14	59.03	99.14	139.95	75.58	22.67	1.99	9.74	664.81
Shone	1986-2017	1949.5	38.67	55.30	110.48	187.28	171.22	136.95	170.85	195.19	181.67	101.39	43.34	38.21	1430.55
Alaba Kulito	1986-2017	1801.77	28.88	50.14	92.03	136.64	125.17	93.46	118.18	151.63	117.55	72.07	58.98	22.30	1067.04
Durame	1986-2005	2231.77	28.44	56.15	93.22	156.46	145.22	104.82	136.73	160.59	137.62	103.89	27.12	25.28	1175.54
Angecha	1987-2017	2265.34	37.69	59.64	102.05	181.43	169.12	150.73	187.78	206.58	184.24	96.17	48.89	31.31	1455.62
Hosaina	1986-2017	2235.56	27.28	48.53	101.70	135.85	151.50	127.71	159.57	173.00	150.76	66.33	21.89	22.63	1186.75
Fonko	1986-2016	2271.4	24.75	50.02	113.93	150.39	150.16	132.30	159.61	175.97	156.20	85.89	19.34	21.55	1240.11
Butajira	1986-2017	2028.4	32.21	68.08	106.73	125.54	100.60	130.64	186.55	155.90	111.78	44.18	12.02	15.22	1089.44

Appendix B.12 Gidabo River Watershed Point Rainfall Distribution (mm)

Station	Year	Elevation (masl)	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	Sum
Dilla	1988-2017	1511.47	31.03	65.30	121.34	193.50	217.61	109.19	98.74	125.35	157.80	192.00	70.58	34.26	1416.70
Kofele	1986-2016	2668.59	36.44	46.89	130.95	144.69	139.15	116.03	124.06	157.18	150.80	100.68	35.08	30.72	1212.66
Hagere Selam	1986-2016	2670.64	39.24	46.78	75.49	178.46	182.88	130.76	99.93	147.06	131.34	167.54	69.13	29.54	1298.14
Tefere Kella	1986-2016	1836.58	27.38	37.39	105.29	253.78	264.55	131.81	131.61	169.64	251.92	205.48	61.80	35.09	1675.73
Awassa	1986-2016	1768.72	26.23	35.32	74.51	110.73	126.67	104.59	122.40	120.06	120.24	71.83	31.13	24.85	968.55
Arbe Gona	1986-2016	2539.61	37.99	36.53	76.27	122.27	86.26	80.80	80.48	82.50	85.61	92.49	38.97	36.56	856.73
Yirga Alem	1991-2017	1735.16	29.62	26.34	92.61	161.06	181.97	100.23	109.97	133.64	145.68	173.45	41.89	24.95	1221.41
Aleta Wendo	1986-2017	1802.53	36.90	47.98	109.71	205.68	232.02	143.65	141.09	157.69	213.94	180.63	68.77	32.40	1570.44
Yirga Chefe	1986-2016	1895.56	21.54	37.89	87.28	230.69	245.63	108.99	88.01	103.48	145.31	188.07	79.72	31.91	1368.54
Mirab Abaya	2008-2017	1248.04	19.63	24.44	71.21	104.56	107.88	87.54	66.75	63.36	79.87	59.72	70.58	21.48	777.02
Humbo	1988-	1592.49	30.0	29.3	64.84	126.7	156.4	124.8	158.4	151.0	98.28	98.44	46.8	32.4	1117.9

	2017		6	4		5	5	8	9	6			9	2	0
Bilate Tena	1986-2015	1550.5	29.10	32.93	78.48	125.47	107.83	90.00	94.97	94.70	92.57	94.88	33.20	23.78	897.93
Fiseha Genet	1986-2017	2219.08	28.54	43.93	87.49	195.86	224.81	98.88	76.25	100.89	158.84	210.84	85.95	59.54	1371.81

Appendix B.13 Gelana River Watershed Point Rainfall Distribution (mm)

Station	Year	Elevation (masl)	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	Sum
Arba Minch	1987-2017	1266.2	27.70	33.09	55.50	163.45	145.38	64.04	39.57	46.14	87.89	128.74	74.47	39.53	905.49
Mirab Abaya	2008-2017	1248.04	19.63	24.44	71.21	104.56	107.88	87.54	66.75	63.36	79.87	59.72	70.58	21.48	777.02
Hagere Mariam	1986-2017	1823.65	11.36	17.76	68.12	164.70	195.96	63.54	40.83	45.28	61.82	128.34	62.91	17.92	878.54
Yirga Chefe	1986-2016	1895.56	21.54	37.89	87.28	230.69	245.63	108.99	88.01	103.48	145.31	188.07	79.72	31.91	1368.54
Gedeb	1986-2016	2625.87	34.22	38.17	104.20	232.76	252.41	110.08	84.50	98.56	127.05	233.86	94.17	26.67	1436.65
Kofele	1986-2016	2668.59	36.44	46.89	130.95	144.69	139.15	116.03	124.06	157.18	150.80	100.68	35.08	30.72	1212.66
Fiseha Genet	1986-2017	2219.08	28.54	43.93	87.49	195.86	224.81	98.88	76.25	100.89	158.84	210.84	85.95	59.54	1371.81

Appendix B.14 Hamessa River Watershed Point Rainfall Distribution (mm)

Station	Year	Elevation (masl)	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	Sum
Chencha	1989-2011	2705.84	58.47	54.32	123.21	184.43	152.07	85.09	117.98	121.70	137.58	162.94	87.58	74.08	1359.43
Mirab Abaya	2008-2017	1248.04	19.63	24.44	71.21	104.56	107.88	87.54	66.75	63.36	79.87	59.72	70.58	21.48	777.02
Humbo	1988-2017	1592.49	30.06	29.34	64.84	126.75	156.45	124.88	158.49	151.06	98.28	98.44	46.89	32.42	1117.90
Bedessa	1987-2012	1598.08	38.31	38.29	87.43	160.86	157.85	118.38	120.47	120.47	90.41	106.16	46.57	29.38	1114.58
Wolaita	1986-2017	2097.41	28.75	37.76	72.16	153.43	182.95	131.72	175.59	172.37	110.74	98.98	54.40	37.95	1256.80

Appendix B.15 Harie River Watershed Point Rainfall Distribution (mm)

Station	Year	Elevation (masl)	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	Sum
Arba Minch	1987-2017	1266.2	27.70	33.09	55.50	163.45	145.38	64.04	39.57	46.14	87.89	128.74	74.47	39.53	905.49
Chencha	1989-2011	2705.84	58.47	54.32	123.21	184.43	152.07	85.09	117.98	121.70	137.58	162.94	87.58	74.08	1359.43
Mirab Abaya	2008-2017	1248.04	19.63	24.44	71.21	104.56	107.88	87.54	66.75	63.36	79.87	59.72	70.58	21.48	777.02

Appendix B.16 Lake Abaya Lake Surface Point Rainfall Distribution (mm)

Station	Year	Elevatn (masl)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Arba Minch	1987-2017	1266.2	27.7	33.09	55.5	163.45	145.38	64.04	39.57	46.14	87.89	128.74	74.47	39.53	905.49
Chencha	1989-2011	2705.84	58.47	54.32	123.21	184.43	152.07	85.09	117.98	121.7	137.58	162.94	87.58	74.08	1359.43
Mirab Abaya	2008-2017	1248.04	19.63	24.44	71.21	104.56	107.88	87.54	66.75	63.36	79.87	59.72	70.58	21.48	777.02
Humbo	1988-2017	1592.49	30.06	29.34	64.84	126.75	156.45	124.88	158.49	151.06	98.28	98.44	46.89	32.42	1117.9
Dilla	1988-2017	1511.47	31.03	65.3	121.34	193.5	217.61	109.19	98.74	125.35	157.8	192	70.58	34.26	1416.7

Appendix B.17 Lake Abaya Lake Surface Areal Rainfall (mm)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1987	18.07	18.25	99.42	130.38	208.65	45.97	36.67	29.99	74.58	109.66	26.63	14.23	812.52
1988	36.47	30.33	31.95	177.38	107.59	76.10	141.94	130.09	76.71	129.54	24.53	13.67	976.31
1989	33.84	54.38	75.84	121.00	122.14	100.03	95.31	80.99	89.15	127.15	59.23	117.47	1076.52
1990	11.63	121.33	79.49	87.85	109.18	29.60	48.03	57.72	57.76	44.22	36.73	22.79	706.33
1991	33.59	64.42	72.60	52.62	95.76	69.26	53.95	63.63	111.19	41.52	18.95	10.56	688.03
1992	8.57	19.13	40.43	148.89	89.55	84.94	81.33	83.58	90.31	129.52	43.19	25.47	844.91
1993	91.25	75.70	21.65	129.13	171.14	65.58	17.76	36.84	24.26	74.40	14.02	2.08	723.82
1994	0.15	11.74	44.47	149.11	168.04	103.96	120.97	94.67	52.55	86.96	62.49	10.44	905.54
1995	0.69	31.42	51.35	185.93	178.32	82.84	90.43	55.46	88.68	90.26	42.17	24.65	922.22
1996	20.35	28.01	92.79	198.62	135.63	162.89	103.04	163.85	142.22	70.85	35.50	10.82	1164.57
1997	8.92	0.31	14.32	193.70	125.45	61.56	121.29	47.76	50.00	256.00	194.01	100.56	1173.88
1998	83.02	55.89	57.00	112.09	86.10	83.01	70.34	97.32	52.21	128.00	31.17	1.63	857.78
1999	13.47	1.42	77.32	95.19	58.80	62.51	84.65	58.27	65.13	153.01	11.52	17.44	698.73
2000	2.31	0.00	21.22	106.73	210.90	60.89	92.35	77.07	68.21	153.87	58.86	28.72	881.11
2001	35.93	34.74	79.23	130.37	156.61	81.63	89.06	112.25	88.51	131.66	44.40	9.41	993.80
2002	45.32	13.31	93.42	100.85	81.19	42.77	55.37	89.62	65.71	69.26	27.61	157.27	841.69
2003	36.32	14.24	53.23	155.86	107.09	98.36	83.55	103.95	31.89	50.32	36.93	57.63	829.36
2004	61.37	19.73	17.10	146.71	50.68	38.19	55.18	64.15	59.15	48.05	76.80	20.90	658.00
2005	15.48	5.71	70.60	177.18	189.76	59.39	71.20	59.13	122.25	107.22	36.71	2.82	917.46
2006	8.37	45.54	104.69	156.82	112.05	89.42	41.33	113.36	50.19	136.03	66.68	73.26	997.74
2007	51.94	28.81	34.07	112.69	185.77	103.39	114.75	150.35	189.96	69.67	37.21	0.65	1079.25
2008	7.04	8.86	65.90	105.35	72.25	55.02	111.33	73.49	146.43	153.16	75.09	19.77	893.69
2009	15.05	8.22	30.46	52.29	118.90	59.85	30.16	22.98	36.92	84.33	23.63	50.67	533.45
2010	54.71	68.74	166.81	177.27	209.09	141.55	88.63	62.16	65.24	50.61	7.38	21.06	1113.24
2011	2.11	49.32	46.37	33.68	193.27	63.53	81.30	108.62	140.13	84.01	244.58	2.23	1049.15
2012	0.89	4.34	22.52	192.73	83.16	66.91	99.26	131.95	145.93	36.01	54.28	21.96	859.94
2013	18.93	1.57	69.76	211.63	158.59	116.26	133.90	81.71	99.62	98.58	51.94	2.71	1045.20

2014	36.04	53.62	76.58	54.69	154.26	107.34	55.44	102.48	131.29	134.20	48.93	1.65	956.51
2015	0.30	0.95	46.77	42.73	112.28	95.10	54.95	21.04	50.99	49.75			474.85
Mean	25.94	30.00	60.60	128.95	132.83	79.58	80.12	81.88	85.08	99.92	53.26	30.09	885.37

Appendix B.18 Mean Monthly Maximum Temperatures of All Stations of Lake Abaya Catchment (^{o}C)

Station	Year	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
Abaya	2008-2017	31.00	31.80	31.46	30.15	29.40	28.58	28.31	28.55	29.22	29.52	30.09	30.41
Aje	1986-2017	27.00	27.47	27.89	28.33	27.84	27.69	26.09	24.70	25.86	26.52	27.19	26.72
Alaba Kulito	1986-2017	29.83	30.76	30.33	29.09	28.07	26.17	24.48	24.83	26.75	28.20	28.67	29.31
Angacha	1988-2017	24.64	24.61	24.42	24.04	24.08	23.83	23.56	23.44	23.51	24.29	24.69	24.75
Arba Minch	1987-2017	32.21	33.40	33.50	31.04	29.12	28.40	28.07	28.95	30.26	30.02	30.68	31.21
Bodite	1986-2017	26.53	27.29	27.03	25.47	24.29	22.54	21.05	21.55	23.17	24.48	25.68	25.89
Butajira	1986-2017	26.62	27.13	27.71	27.07	27.16	26.29	24.18	24.49	25.73	26.80	26.99	26.08
Dilla	1988-2017	30.14	30.27	31.17	28.49	27.26	26.46	25.54	25.99	26.27	27.01	28.14	28.88
Fiseha Genet	1986-2017	24.65	25.42	25.12	23.33	21.93	21.00	20.71	21.19	21.86	21.77	22.59	23.00
Hagere Selam	1986-2017	20.85	21.24	20.76	19.02	18.60	18.00	16.35	16.52	17.60	18.05	18.94	19.87
Hager Mariam	1986-2017	26.95	28.23	27.63	24.91	23.26	22.43	21.96	22.83	24.19	23.66	24.26	25.46
Hosana	1987-2017	24.21	24.95	24.90	23.95	23.25	21.24	19.74	19.91	21.32	22.60	23.55	23.80
Wolita	1986-2017	27.31	28.22	28.23	26.47	24.79	23.26	22.02	22.55	23.95	25.09	26.30	26.66
Yirga Alem	1991-2017	28.34	29.08	29.01	27.58	26.00	25.19	23.87	24.30	24.66	25.57	26.69	27.43
Yirga Chefe	1986-2016	27.63	27.70	27.24	25.60	24.48	23.79	23.22	23.76	23.76	24.11	25.31	26.15

Appendix B.19 Mean Monthly Minimum Temperatures of All Stations of Lake Abaya Catchment (^{o}C)

Station	Year	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
Abaya	2008-2017	12.65	13.09	13.49	13.14	14.64	14.22	13.84	14.04	13.78	12.94	12.64	12.54
Aje	1986-2017	11.12	12.23	12.96	13.31	13.58	13.29	13.35	12.48	13.04	12.68	12.35	12.11
Alaba Kulito	1986-2017	11.77	12.50	13.22	13.47	13.48	13.35	13.09	12.61	12.56	11.55	9.83	10.95
Angacha	1988-2017	14.27	14.33	14.07	13.82	13.80	13.35	13.28	13.08	13.31	14.02	14.54	14.40
Arba Minch	1987-2017	16.43	17.43	18.41	18.37	18.14	17.99	17.90	18.06	17.69	17.19	15.88	15.37
Bodite	1986-2017	12.14	13.11	13.73	13.56	13.38	12.77	12.27	12.26	12.52	12.30	11.40	11.46
Butajira	1986-2017	11.34	11.73	12.35	13.10	12.53	12.37	11.82	12.14	12.27	12.09	11.28	10.68
Dilla	1988-2017	10.11	10.36	12.58	14.08	13.87	13.77	14.36	14.19	13.70	13.35	11.69	10.31
Fiseha Genet	1986-2017	12.71	13.26	13.49	13.01	12.69	12.08	11.73	11.69	11.93	12.35	12.11	11.62
Hagere Selam	1986-2017	5.92	6.82	7.75	7.85	7.96	7.15	6.92	6.82	7.35	7.17	6.90	6.29
Hagere Mariam	1986-2017	9.57	11.19	11.96	12.72	12.90	12.17	11.50	11.06	11.11	11.85	10.58	10.03
Hosana	1987-2017	9.74	11.14	12.21	12.45	11.78	11.42	11.59	11.66	11.14	10.73	10.09	9.09
Wolita	1986-2017	14.15	15.26	15.35	15.13	14.94	14.47	13.87	14.11	14.17	14.16	14.56	14.15
Yirga Alem	1991-2017	10.06	10.47	11.65	12.24	12.31	12.49	12.90	12.63	12.16	11.68	10.79	9.73
Yirga Chefe	1986-2016	8.35	9.34	10.78	11.67	11.95	11.79	11.90	11.78	11.66	11.32	9.76	8.24

Appendix B.20 Mean Monthly Temperatures of All Stations of Lake Abaya Catchment (^oC)

Station	Year	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
Abaya	2008-2017	21.82	22.44	22.47	21.64	22.02	21.40	21.08	21.29	21.50	21.23	21.37	21.48
Aje	1986-2017	19.06	19.85	20.42	20.82	20.71	20.49	19.72	18.59	19.45	19.60	19.77	19.41
Alaba Kulito	1986-2017	20.80	21.63	21.78	21.28	20.78	19.76	18.78	18.72	19.66	19.87	19.25	20.13
Angacha	1988-2017	19.46	19.47	19.25	18.93	18.94	18.59	18.42	18.26	18.41	19.16	19.61	19.57
Arba Minch	1987-2017	24.32	25.42	25.95	24.71	23.63	23.19	22.98	23.51	23.98	23.60	23.28	23.29
Bodite	1986-2017	19.33	20.20	20.38	19.51	18.84	17.65	16.66	16.91	17.84	18.39	18.54	18.67
Butajira	1986-2017	18.98	19.43	20.03	20.08	19.84	19.33	18.00	18.31	19.00	19.44	19.14	18.38
Dilla	1988-2017	20.12	20.31	21.87	21.29	20.56	20.12	19.95	20.09	19.98	20.18	19.91	19.60
Fiseha Genet	1986-2017	18.68	19.34	19.31	18.17	17.31	16.54	16.22	16.44	16.89	17.06	17.35	17.31
Hagere Selam	1986-2017	13.39	14.03	14.26	13.43	13.28	12.57	11.64	11.67	12.47	12.61	12.92	13.08
Hagere Mariam	1986-2017	18.26	19.71	19.80	18.82	18.08	17.30	16.73	16.94	17.65	17.75	17.42	17.75
Hosana	1987-2017	16.97	18.04	18.56	18.20	17.52	16.33	15.67	15.79	16.23	16.67	16.82	16.45
Wolita	1986-2017	20.73	21.74	21.79	20.80	19.86	18.86	17.94	18.33	19.06	19.63	20.43	20.41
Yirga Alem	1991-2017	19.20	19.77	20.33	19.91	19.15	18.84	18.38	18.46	18.41	18.62	18.74	18.58
Yirga Chefe	1986-2016	17.99	18.52	19.01	18.64	18.22	17.79	17.56	17.77	17.71	17.71	17.54	17.19

Appendix B.21 Lake Abaya Sub-basin Mean Monthly Relative Humidity (%)

station	Year	Elevation(masl)	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
Arba Minch	1987-2017	1207	54.48	51.19	53.69	65.00	70.15	66.94	65.84	63.74	64.05	67.78	61.84	55.70
Dilla	1988-2017	1579	65.41	63.02	66.36	76.38	77.03	77.45	79.62	79.16	79.67	78.61	71.24	68.23
Hagere Mariam	1987-2017	1861	58.72	54.63	60.74	73.92	81.82	81.03	80.30	78.26	74.12	77.83	72.42	63.66
Hosaina	2013-2017	2307	68.39	68.39	62.03	60.06	77.40	77.28	69.68	69.68	76.26	67.61	69.68	69.68
Wolaita	2013-2017	1851	48.31	47.93	67.67	63.17	77.18	78.03	82.45	67.28	67.28	73.50	67.28	67.28

Appendix B.22 Lake Abaya Sub-basin Mean Monthly Wind Speed (m/sec)

Station	Year	Elevation (masl)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Arba Minch	1987-2014	1207	0.59	0.64	0.75	0.68	0.73	0.78	0.78	0.78	0.75	0.59	0.50	0.55
Dilla	1988-2015	1579	0.53	0.67	0.70	0.55	0.46	0.41	0.36	0.38	0.41	0.41	0.41	0.43
Hagere Mariam	1998-2013	1861	0.29	0.27	0.12	0.12	0.11	0.10	0.08	0.10	0.11	0.11	0.10	0.10
Hosana	1986-2015	2307	1.35	1.47	1.49	1.45	1.23	1.32	1.37	1.22	0.92	1.44	1.55	1.53
Wolita	1986-2013	1851	2.14	2.27	1.94	1.54	1.38	1.50	1.24	1.24	1.24	1.60	2.41	2.43

Appendix B.23 Lake Abaya Sub Basin Mean Monthly Sunshine Hours

Station	Year	Elevation(mamsl)	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec
Arba Minch	1987-2017	1207	9.15	9.00	8.44	7.54	7.87	6.38	4.74	5.53	6.92	7.68	8.90	9.04
Dilla	1988-2017	1579	8.58	7.99	7.82	6.09	6.12	4.87	3.40	4.29	4.65	6.02	7.75	8.01
Hagere Mariam	2005-2017	1861	9.28	8.76	7.71	6.22	5.30	4.01	3.16	4.01	5.33	5.89	7.76	9.03
Hosana	1986-2017	2307	8.48	8.62	7.81	6.70	6.75	5.57	3.56	4.03	5.53	8.34	9.14	8.73
Wolita	2004-2017	1851	8.74	8.34	7.92	6.91	6.15	4.42	3.33	4.25	5.25	7.34	8.71	8.91

Appendix B.24 Monthly Total Pan Evaporation at Arba Minch Station (mm/Month)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual(mm)
1990	201.53	145.51	162.64	187.97	190.83	190	155.86	145.02	159.17	200.37	197.8	221.28	2157.98
1991	226.2	185.33	192.52	171.32	213.44	171.72	118.44	142.33	160.93	175.68	206.23	193.62	2157.76
1992	203.95	180.52	246.98	217.77	187.95	185.59	172.14	151.91	134.92	167.54	178.67	187.06	2215
1993	190.88	167.15	241.06	176.06	191.32	161.82	160.43	181.4	150.2	178.42	224.44	234.25	2257.43
1994	257.55	247.89	234.29	196.86	182.12	178.94	138.79	146.03	162.2	220.93	233.01	250.72	2449.33
1995	268.85	245	240.27	184.98	199.75	192.08	131.38	119.42	126.23	143.78	158.98	169.77	2180.48
1996	155.01	178.18	158.31	140.94	138.34	125.99	115.93	117.67	113.27	149.66	164.88	176.4	1734.57
1997	171.58	216.92	204.99	129.2	155.61	133.56	118.42	138.43	133.32	136.86	118.2	143.47	1800.55
1998	130.61	149.08	149.9	164.03	142.66	141.04	118.14	110.99	113.23	108.24	145.78	171.6	1645.31
1999	180.45	198.78	150.39	156.68	157.04	157.5	122.35	139	138.47	112.64	168.72	173.89	1855.92
2000	201.2	209.38	218.21	160.74	138.56	142.46	123.25	121.89	110.88	118.54	137.36	160.23	1842.69
2001	168.77	175.27	142.43	141.56	145.8	115.33	112.93	119.3	109.26	125.66	153.88	169.79	1679.97
2002	163.13	184.46	147.56	150.46	145.97	127.78	155.2	119.61	117.54	133.88	183.47	140.08	1769.14
2003	160.01	182.8	178.44	136.19	142.95	134.71	104.13	120.25	127.45	160.91	196.4	192.3	1836.55
2004	152.83	154.47	186.64	120	155.42	128.79	139.74	134.6	95.96	138.48	164.46	165.13	1736.52
2005	167.86	182.06	165.82	162.81	122.85	135.84	124.57	141.73	110.18	132.81	156.99	176.18	1779.7
2006	187.5	152.55	154.88	132	140.3	128.64	102.35	115.81	103.4	117.86	137.38	127.69	1600.35
2007	159.06	151.13	200.14	138.3	142.72	119.65	120.9	108.61	125.1	129.58	152.9	170.91	1719
2008	178.15	158.74	212.14	138	117.4	160.55	111.91	115.97	131.04	150.83	142.5	152.62	1769.86
2009	192.23	186.14	193.12	162.22	165.03	151.82	131.93	137.46	87.52	132.06	173.04	136.62	1849.19
2010	192.23	186.14	193.12	162.22	165.03	151.82	131.93	137.46	131.04	150.83	174.32	178.91	1955.05
2011	192.23	186.14	193.12	162.22	165.03	151.82	131.93	137.46	131.04	150.83	174.32	178.91	1955.05
2012	192.23	186.14	193.12	162.22	165.03	151.82	131.93	137.46	131.04	150.83	174.32	178.91	1955.05
2013	192.23	186.14	193.12	162.22	165.03	151.82	131.93	137.46	131.04	150.83	174.32	178.91	1955.05
Mean	192.23	186.14	193.12	162.22	165.03	151.82	131.93	137.46	131.04	150.83	174.32	178.91	1955.05
Rdu Fct	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85
Rdu Mean	163.40	158.22	164.15	137.89	140.28	129.04	112.14	116.84	111.38	128.21	148.17	152.07	1661.79

Appendix B.25 Monthly Total Evaporation at Arba Minch Station (mm/Month) by Cropwat 8

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual(mm)
1987	151.59	142.0975	162.13	143.7	131.13	114	149.42	154.69	150.9	139.5	138.6	141.05	1718.808
1988	144.46	146.9	182.28	140.1	142.91	122.4	97.96	117.49	119.1	128.34	128.7	127.72	1598.36
1989	129.58	131.08	151.9	125.4	139.19	123.3	101.99	141.98	127.5	130.51	123.9	117.18	1543.51
1990	114.39	102.83	132.68	114.9	128.65	129	115.63	115.32	139.2	145.08	133.8	133.61	1505.09
1991	132.68	131.3625	148.8	145.5	140.12	121.8	94.24	118.42	132	137.33	129.6	126.17	1558.023
1992	134.54	133.0575	171.12	147	146.01	122.7	114.7	108.5	125.7	119.66	123	123.38	1569.368
1993	119.35	111.5875	148.18	129	127.72	107.7	102.3	122.45	121.8	126.79	125.1	126.48	1468.458
1994	136.09	133.0575	147.87	136.2	128.03	103.8	97.34	110.67	132	137.33	122.1	128.03	1512.518
1995	135.16	127.125	135.78	126.6	136.71	122.1	102.61	110.36	121.8	125.55	118.5	129.27	1491.565
1996	129.89	138.1425	156.55	136.2	129.58	90	96.72	115.32	117.9	132.99	123	129.27	1495.563
1997	134.23	139.2725	160.89	118.5	132.37	118.5	105.09	127.1	142.8	125.24	104.1	104.47	1512.563
1998	108.81	108.48	137.33	135	124.62	109.8	90.21	89.59	118.5	99.51	115.5	103.23	1340.58
1999	122.14	124.865	138.88	126.9	130.51	115.8	100.13	115.32	126	122.76	115.8	116.25	1455.355
2000	124.62	123.735	150.66	138	127.1	109.2	101.37	111.91	125.1	125.24	119.4	119.04	1475.375
2001	121.83	127.4075	131.13	135	127.1	107.1	103.23	109.43	125.7	122.14	119.7	121.52	1451.288
2002	128.65	127.9725	134.23	135.9	128.34	115.5	123.38	121.83	135.6	129.58	129.3	115.94	1526.223
2003	129.27	139.555	154.07	129	128.34	111.9	101.06	105.4	135.6	137.02	129.3	133.61	1534.125
2004	131.13	129.1025	146.63	121.5	138.26	123.3	120.59	106.02	131.4	134.85	122.7	128.34	1533.823
2005	140.12	138.99	150.35	142.2	117.49	111.9	104.16	128.03	119.1	125.55	124.8	128.65	1531.34
2006	139.5	135.3175	144.46	122.7	135.78	111.9	105.4	108.5	125.4	129.89	115.2	118.73	1492.778
2007	123.69	126.8425	154.07	135	127.41	95.4	102.61	101.37	105.3	129.27	122.7	125.55	1449.213
2008	131.13	129.6675	156.24	138.3	133.61	113.1	103.23	118.11	117	114.08	120.6	126.48	1501.548
2009	128.65	135.6	162.44	136.2	130.2	132.9	129.58	137.95	134.4	130.82	129.6	109.43	1597.77
2010	124.31	109.8925	131.75	128.1	119.97	111	88.97	106.95	116.1	124.93	127.8	128.34	1418.113
2011	135.16	137.86	150.04	152.1	130.82	100.5	101.99	106.95	112.5	124	123	119.66	1494.58
2012	128.65	137.86	158.72	120.6	132.68	110.7	100.13	115.01	114	133.92	120.9	122.45	1495.62
2013	124.93	132.4925	131.75	119.4	122.76	96	91.45	98.27	117	127.1	117	128.03	1406.183
2014	133.92	118.65	154.69	144.3	133.61	112.2	110.05	119.35	120	118.42	118.2	126.17	1509.56
2015	138.57	140.12	159.96	141.9	128.96	108.3	117.49	137.02	141	130.2	117	115.94	1576.46
2016	124	133.6225	160.27	115.5	124.93	110.4	115.94	113.77	128.7	130.51	119.1	121.83	1498.573
2017	139.5	133.34	162.13	147.6	133.61	124.2	109.43	118.11	120.9	128.03	122.7	122.76	1562.31
Mean	130.34	129.9318	150.58	133.171	130.92	113.1097	106.4	116.49	125.8065	127.94	122.6032	123.18	1510.472

Appendix B.26 Monthly Total Evaporation at Arba Minch Station (mm/Month) by Penman

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual(mm)
1987	198.28	189.04	213.62	191.54	177.77	159.97	197.04	203.63	200.51	186.58	184.20	182.61	2284.78
1988	196.19	197.33	237.38	187.45	192.52	165.75	135.81	161.41	164.25	173.84	172.40	172.05	2156.38
1989	173.99	179.20	205.49	170.81	186.59	166.43	141.89	191.42	174.68	176.73	169.12	160.91	2097.26

1990	174.90	162.73	190.90	167.29	176.03	174.88	160.30	162.89	190.51	196.79	182.17	179.70	2119.08
1991	183.15	180.75	204.19	196.47	190.07	165.30	133.07	166.86	181.41	187.60	176.80	171.89	2137.56
1992	186.50	185.19	229.72	197.06	195.14	166.41	157.99	153.34	172.75	161.44	165.64	169.45	2140.62
1993	161.76	151.53	202.18	178.95	171.56	148.27	146.06	167.55	158.17	176.01	171.21	175.49	2008.74
1994	185.91	185.44	205.02	184.75	173.90	145.77	139.57	157.85	184.11	184.68	166.88	171.39	2085.29
1995	183.39	176.74	190.22	173.61	184.17	166.74	144.90	157.96	168.67	172.64	164.43	177.18	2060.63
1996	180.93	188.78	206.77	184.38	173.80	123.53	135.21	161.68	162.33	180.99	167.35	174.20	2039.96
1997	183.86	187.14	219.76	159.50	178.03	162.52	147.59	177.25	194.04	171.02	147.98	152.20	2080.89
1998	153.11	153.00	191.54	185.99	170.60	151.92	131.18	133.03	168.91	139.58	158.04	146.28	1883.16
1999	172.40	175.06	191.20	176.05	180.57	161.86	140.72	165.07	174.82	164.88	158.41	160.74	2021.78
2000	173.97	176.36	209.78	188.04	170.45	152.36	145.27	157.94	173.66	170.66	160.70	161.21	2040.38
2001	168.13	173.55	183.51	181.93	171.38	147.48	146.56	154.60	174.16	167.80	161.40	166.32	1996.81
2002	176.89	176.96	185.57	185.71	176.20	159.91	171.31	171.06	186.11	177.86	176.61	159.56	2103.74
2003	176.04	190.42	210.37	176.79	171.64	153.68	142.38	148.66	187.59	187.08	174.95	176.81	2096.40
2004	179.14	176.21	201.41	167.80	187.75	169.12	166.21	173.16	180.09	182.98	167.40	174.94	2126.19
2005	189.26	190.07	205.64	192.67	158.09	154.01	148.15	178.15	165.74	172.91	168.90	171.95	2095.55
2006	191.59	185.01	196.29	168.42	183.75	154.62	150.43	154.05	176.16	177.36	156.89	163.98	2058.53
2007	172.28	176.96	210.23	184.79	173.74	131.94	142.85	142.19	146.83	175.28	165.27	167.09	1989.46
2008	179.76	179.06	211.66	187.74	181.95	156.74	146.71	166.46	162.94	156.43	161.43	170.86	2061.74
2009	176.13	186.43	220.22	184.38	177.90	181.37	178.38	190.04	185.94	179.22	177.64	155.00	2192.67
2010	172.72	157.60	181.49	175.37	164.33	152.73	128.50	152.34	163.45	174.52	176.92	176.72	1976.67
2011	190.94	190.30	211.67	209.37	177.19	141.29	146.44	152.74	157.95	173.12	164.67	160.45	2076.14
2012	175.78	190.74	214.65	164.71	179.90	152.20	140.87	159.40	155.69	181.27	162.91	166.18	2044.30
2013	180.13	190.18	186.57	168.16	169.78	137.60	134.87	146.25	166.47	172.51	158.53	176.87	1987.92
2014	186.46	165.72	209.76	196.70	180.87	156.00	154.95	165.47	165.49	160.17	160.61	173.67	2075.87
2015	192.60	194.18	216.48	192.77	174.63	150.30	164.95	188.99	192.19	175.55	161.88	164.61	2169.14
2016	176.41	188.22	216.07	159.12	172.86	153.73	161.22	160.52	178.76	175.43	162.72	162.77	2067.81
2017	193.63	187.47	222.45	201.86	181.75	172.15	153.06	165.27	166.38	174.46	166.88	168.40	2153.76
Mean	180.20	180.24	205.86	181.94	177.58	156.02	149.50	164.10	173.57	174.43	166.80	168.11	2078.36

Appendix B.27 Monthly Water Requirements of Common Crops in Lake Abaya Sub-basin (m^3/ha)

Crops	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Banana	1365.98	1610.93	1553.47	1036.80	1017.79	1944.00	3214.08	3615.84	3188.16	1740.96	829.44	857.09	21974.54
Tobacco	2115.94	2147.90	1339.20					642.82	699.84	455.33		964.22	8365.25
cotton							857.09	1499.90	2721.60	2785.54	1399.68	1874.88	11138.69
Vegetables	1982.02	1903.82	1687.39			362.88	374.98	589.25	518.40			776.74	8195.47
Diverse	1232.06	1147.18	1017.79	414.72	0.00	0.00	267.84	482.11	622.08	669.60	440.64	883.87	7177.90