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**ADDIS ABABA UNIVERSITY
SCHOOL OF GRADUATE STUDIES
COMPUTATIONAL SCIENCE PROGRAM**

Hydrodynamics of Selected Ethiopian Rift Lakes

**Thesis Submitted in Partial Fulfillment of
the Requirements for the Degree of Master
of Science in Computational Science**

By: Kassaye Bewketu

June 2010

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Abstract

The Main Ethiopian Rift Valley lakes suffer from water level fluctuations due to several natural and anthropogenic factors. Lakes located at terminal positions (no surface water outflow) are highly affected by the fluctuations. These fluctuations are disturbing the stability of the ecosystems, putting very serious impacts on the lives of many animals and plants around the lakes. Hence, studying the hydrodynamics of the lakes was found to be very essential. The main purpose of this study is to find the most significant factors that contribute to the water level fluctuations and also to quantify the fluctuations so as to identify the lakes that need special attention. The research methodology includes correlation and least squares regression of lake levels on rainfall, discharge and evaporation, multi-temporal satellite image analysis and land use change assessment. The results of the study revealed that much of the fluctuations in the lake water levels are caused by human activities especially for the lakes in the Central Ethiopian Rift. Lakes Abiyata, Chamo, Ziway and Langano are declining while Abaya and Hawassa are rising. Among the studied lakes, Abiyata is drastically reduced in size (about 28% of its area in 1986) due to both human activities (most dominant ones) and natural factors. The other seriously affected lake is Chamo with about 11% reduction in its area between 1986 and 2010. Lake Abaya was found to be relatively stable during this period (showed only a 0.8% increase in its area).

Keywords: Correlation, fluctuation, hydrodynamics, lake level, Landsat satellite images, land use change, least squares regression.

1. Introduction

1.1 Background

A lake is a large, inland body of standing water that occupies a depression in the land surface. Lakes and lake shores are attractive places to live and play. Clean, sparkling water, abundant wildlife, beautiful scenery, aquatic recreation and fresh breezes all come to our mind when we think of going to the lake. Despite their great value, lakes are fragile and ephemeral (Thompson et al., 2005)

The water-level of a lake changes seasonally and fluctuates annually due to the difference of seasonal or yearly precipitation and evaporation (Kinshiro, 1974). The levels and sizes of lakes are governed by many natural and anthropogenic factors. Climatic, hydrological and man-induced factors control lake levels in many ways. Changes in lake levels result from a shift in the water balance or the net steady-state removal of water via various surface and subsurface processes. In particular, closed terminal lakes fluctuate significantly in response to climatic changes but tend to maintain equilibrium between input and output (Tenalem Ayenew, 2002). Only when we pay attention to the vicinity of a lake, we happen to recognize some terrace which shows the past shore-line or water level of the lake. In such a case, it is evident that stable and unstable periods existed in the past in regard to the secular balance of water in the lake. In general, the main factors working on the regulation of such a lake-level, that is, the reducing factors in the range of fluctuation of water storage are river discharge, ground water discharge, river inflow, ground water inflow and lake surface area (Kinshiro, 1974). Especially, the change of river discharge (open lake) or ground water discharge (closed lake) greatly affects annual lake-level stability. In an arid zone, such stability of a closed lake is regulated by the change of evaporation surface, too (Kinshiro, 1974).

The Ethiopian rift is characterized by a chain of lakes of various sizes and hydrological and hydrogeological settings. The rift lakes and feeder rivers are used for irrigation, soda extraction, commercial fish farming, and recreation, and they support a wide variety of endemic birds and wild animals. The levels of some of these lakes have changed dramatically over the last three decades. Lakes that are relatively uninfluenced by human activities (Langano and Abaya) remain stable except for the usual inter-annual variations, strongly influenced by rainfall. Some lakes have shrunk due to excessive abstraction of water (such as Abiyata); others have expanded due to increases in surface runoff and groundwater flux from percolated irrigation water such as Beseka (Tenalem Ayenew, 2009). Apart from the various inflow and outflow components, the water balances of lakes are governed by climate, anthropogenic factors, volcano-tectonism, and sedimentation (Karrow, 1963; Slay, 1973; Street, 1979 cited in Tenalem Ayenew, 2004).

1.2 Importance of the study

The size and level of lakes are changing due to the influence of many natural and anthropogenic factors. Climatic changes such as decreasing trend of precipitation in the highlands and increasing of temperature (and hence increasing of rate of evaporation) are the most important factors that cause a decline in the size and level of the Ethiopian Rift Valley Lakes (Tenalem Ayenew, 2002). These anthropogenic and hydro-climatic changes cause a grave consequence on the easily fragile ecosystem and affect the lives of many animals and plants in the area. This in turn hinders the tourism of the country. Therefore, it is extremely essential to identify the most important factors that cause the decline in the level and size of lakes so as to propose some appropriate water resource management measures and practice them towards the protection of the lakes.

1.3 Research Problems and Questions

- I. What factors have significant contributions to the lake water level fluctuation?
- II. Which lakes have the most significant water level fluctuations? Why?

1.4 Objectives

1.4.1 General Objective

The main objective of this thesis is to assess the fluctuations of the water levels of the lakes under consideration.

1.4.2 Specific objectives

The specific objectives of the research are indicated as follows.

- I. Test if there is a significant correlation between lake level and precipitation, river discharge and rate of evaporation.
- II. Identify the most important human, hydrological, meteorological, topographic or geological factors that cause the change in the levels of the lakes under consideration.
- III. Identify the lakes which have the most significant level change.

2. Literature Review

2.1. Previous studies

Although the issue of lake level fluctuation is critically important, only few studies have been carried out so far. Tenalem Ayenew (2004) studied the spatial and temporal variations in the level of Lake Abiyata and controlling natural and manmade factors and found out that the level of Abiyata is declining due to extraction of water for irrigation, soda ash production and diminishing of the long-term annual average inflow from Ziway (from 210×10^6 to $60 \times 10^6 \text{ m}^3$) in 1994 and 1995 due to the low rainfall of these two years which resulted in a substantial reduction of volume of water in the lake.

Tenalem Ayenew et al. (2006) studied the Vulnerability of selected Ethiopian lakes to climatic variability, tectonism and water use and pointed out that highland rainfall is the driving force of the hydrology of the rift lakes and the dramatic rise of water use along with the increased evaporation rate affected the lakes dramatically, especially after 2000 (after the beginning of large-scale water abstraction). The study also indicated that despite a slight decline in rainfall and rise of temperature, the river discharge records show locally increasing trends indicating increase in the runoff because of considerable deforestation during the past three decades. Despite the classical common assumptions, groundwater plays a vital role in most of the lakes in the rift valley. This is particularly the case for terminal lakes at lower elevations. Moreover, rift valley floor faults and marginal normal open faults play a vital role in transferring or hindering groundwater going into and out of the lake. These faults divert substantial groundwater parallel to the axis of the rift diverting groundwater from one catchment into another catchment at the expense of some lakes.

Tenalem Ayenew (2002) studied the recent changes in the level of Lake Abiyata and realized that the level of Lake Abiyata is affected strongly by the input from Lake Ziway, which transfers water through the Bulbula River. But the monthly input into the storage of Lake Abiyata from Ziway is very small in amount and is less than 5% in most dry months. The mean annual lake stage has a strong correlation with the mean annual rainfalls before the beginning of large-scale water abstraction. However, the water level of the lake drastically declined after the start of the large-scale water abstraction for irrigation and soda ash extraction.

According to the studies made by Tenalem Ayenew and Yemene Gebreegiabher (2006) entitled "the application of a spreadsheet hydrological model for computing the long-term water balance of Lake Hawassa", the major water balance components of the lake in decreasing importance are evaporation, precipitation and runoff which have long term mean annual values of 131, 106 and $83 \times 10^6 \text{ m}^3$, respectively. Moreover, the study pointed out that there is an agreement, within acceptable limits, between the recorded and calculated lake levels up to the late 1980s; but after that date onwards, there is an increasing divergence between the values, which is because of land-use changes (deforestation) resulting in high surface runoff. This high surface runoff, along with neotectonism resulted in higher groundwater input into the lake which in turn resulted in the rising of the level of Lake Hawassa.

Azeb Belete (2009) studied the climate change impact on Lake Abaya Water level and realized that the average yearly inflow into the lake from river discharge, ungauged runoff and precipitation are 750, 691 and 980 mcm respectively while the average yearly outflow due to evaporation is 2009 mcm resulting in a rise in the water level of the lake. Moreover, according to this study, the lake level fluctuation is mostly due to climatic and anthropogenic factors (precipitation, evaporation and land use land cover changes) and the contributions from groundwater components are negligible. Irrespective of the climatic variability, the level of the lake is

rising at the moment and will rise in the near future (2015-2022) due to the increase in runoff volume and land use land cover changes in its catchment.

According to the study made by Habtom Gebremichael (2007) entitled "Modelling and Forecasting the Hawassa Lake Level Fluctuation", the yearly inflow into the lake in the form of runoff is 167 million cubic meter (mcm), precipitation is 90 mcm, totaling 257 mcm; the yearly outflow from the lake 148 mcm. The study further indicated that surface runoff accounts about 81% in the lake level fluctuation due to increased land use/cover changes in the short run and evaporation accounts about 38% of the fluctuation while precipitation accounts 45% in the long term lake level fluctuation. The study also indicated that the contributions to the fluctuation from climatic factors are less than those from land use/cover changes and the role of groundwater should be given attention during water balance computation for the lake.

Ebrahim Esa (2008) studied the Impacts of Soda Ash Mining on Abiyata and Shalla Lakes Subwatershed and pointed out that substantial hydrological and hydrogeological changes occurred in the rift lakes particularly in Abiyata due to improper utilizations of water resources. According to this study, rapid changes have been pronounced shortly after the commencement of large-scale water abstractions for irrigation, domestic uses and soda ash extraction which resulted in a 10% reduction in the surface area of Lake Abiyata for the last forty years and reached the lowest level ever recorded in March 2006.

According to the study made by Shewadeg Molla (2008) entitled "Decision Support Tool for Estimating Lake Water Balance With Particular Emphasis to Lake Abiyata", the water level of the lake was found to be remarkably sensitive to the area coverage of the irrigated farm and the amount of water abstracted for soda ash extraction.

Generally, most of the studies undertaken so far were concentrated in the Lake Hawassa and Ziway-Shalla basins. Very few studies were made concerning the Abaya-Chamo basin. No Water balance analysis was made regarding Lake Chamo and the reasons for the fluctuations in the levels of the lake were not assessed to any significant extent.

2.2 Natural and man-induced factors affecting lake water level

The water-level of a lake changes seasonally and fluctuates annually due to the difference of seasonal or yearly precipitation and evaporation (Kinshiro, 1974). The stable condition of the lake-level is decided by a balance between inflow and outflow. In an arid zone, such stability of a closed lake is regulated by the change of evaporation surface, too (Kinshiro, 1974). Apart from the various inflow and outflow components, the water balances of lakes are governed by climate, anthropogenic factors, volcano-tectonism, and sedimentation (Karrow, 1963; Slay, 1973; Street, 1979 cited in Tenalem Ayenew, 2004). The sensitivity of lake level changes to the balance between inflows and outflows is higher in closed lakes than in open lakes (Murimi, 1994).

The Ethiopian Rift Lakes are located in a hydrogeologically complex rift environment where many natural and anthropogenic factors played important role in changing the size and level of most of the lakes (Tenalem Ayenew et al., 2006). Generally, the anthropogenic factors that bring about lake level fluctuation in the Ethiopian Rift are changes in land use, water abstraction for irrigation, and extraction of minerals (such as soda ash) and construction of dams for generation of hydroelectric power. The newly established floriculture and horticulture enterprises are also abstracting water from the Central Ethiopian Rift lakes (Huib and Herco, 2006). The natural factors include the change in the average annual amount of precipitation and evaporation rates (climatic), volcano-tectonism and sedimentation (geological) and runoff amounts (hydrological).

2.3 Environmental repercussions of lake water level fluctuations

Changing water levels and the resulting shifts in the location of the shoreline and the littoral zone have an important impact on structure, function, and productivity in aquatic systems. Changes in surface water, water exchange, and the ability of fish to move between coastal wetlands, embankments, and the open lake are directly related to the size, timing, duration, frequency, and rate of change of these fluctuating water levels. Moreover, reduced water levels will alter nearshore littoral (shallow water) and sub-littoral habitats, permanently altering benthic and fish community structure throughout the lake. The effects of lower water levels may also fundamentally affect seasonal timing and connectivity, food web dynamics, and the distribution, structure, composition and abundance of fish communities in the lake (Keddy and Reznicek, 1986).

Forest ecosystems contribute greatly to the prosperity and quality of life in the lake regions as well as to cleaning its air and water, and the reduction of soil erosion. Their diversity also provides important habitat to wildlife (Heathwaite and Burt, 1991).

Climate computer models suggest that the waters of the Great Lakes will be warmer by the end of the 21st century. In addition, models suggest that lengthening warm seasons will reduce the seasonal mixing that replenishes critical oxygen to biologically productive lake zones, possibly shrinking lake biomass productivity by around 20 % (Ramsis et al., 2002). This will include losses of zooplankton and phytoplankton that form the very base of aquatic food chains, and are critical to the survival of many species of fish that live in the Great Lakes including economically important ones such as quaking aspen, yellow birch, jack pine, red pine and white pine. People who lack protection to high temperature extremes may also suffer from heat stress, dehydration, respiratory distress, and occasionally heat stroke or cardiac malfunction (Sousounis, 2000).

Changes in precipitation patterns may alter seasonal flow and volume patterns in streams and rivers feeding the Great Lakes (Niko and Bardhyl, 2009). Findings indicated that cold water stream habitats could be significantly altered by a warming climate, threatening cold-water species such as walleye and trout, and even some warm-water species such as smallmouth bass (Sousounis, 2000).

Declines in water levels caused by climate change will reduce fish's access to the emergent vegetation of coastal marshes, which provide breeding habitat, shelter for young fish, and plenty of food in the form of vegetation and invertebrates (Keddy and Reznicek, 1986).

The Ethiopian rift lake environment is known for its biodiversity. The Ethiopian Rift is home for many endemic animals. An extraordinarily rich fauna inhabit the Rift Lakes and the Wetlands. Growing population density, excessive water use and catchment land-use change are putting increasing pressure on the Ethiopian Rift lakes and the rivers draining into them (Tenalem Ayenew, 2004a)

The lakes form an important migration route for Palaearctic birds during the northern winter. The increase in the alkalinity of the lake and its shrinkage will result in the reduction of the fish population, ultimately leading to the death of the birds. Therefore, the protection of the lake is critical to saving the precious fauna and flora. A drop in the level of the lake may also result in an increase in the transpiration loss from the marginal vegetation and a drop in the groundwater level, which in turn causes the springs used for community water supply purposes to dry up, especially on the eastern shore of Lake Ziway (Tenalem Ayenew, 2004).

3. Approach and Methodology

3.1 Collection and organization of data

This study is based on an assessment of existing hydrometeorological records of lake level, rainfall, river discharge and evaporation for the period of 1980-2007. The rainfall stations used for estimating the areal depth of the rainfalls corresponding to the lakes were: Arba Minch, Chench, Hagere Selam and Hossana for Lakes Abaya and Chamo; Assela, Butajira, Kersa, Langano, Meki, Meraro, and Shashemene for the Lakes Abiyata, Langano and Ziway; Hawassa and Wondo Genet (incomplete data) for Lake Hawassa. The research is also based on the interpretation of multi-temporal satellite images acquired during 1986, 2000 and 2010. The data required for the study (appendices 3, 4, 5 and 6) have been collected from various sources. Meteorological data (appendix 4 and 6) for twenty eight years (incomplete most of the time) have been collected from the Ethiopian Meteorological Agency and the hydrological data (appendices 3 and 5) for seven rivers (Bilate, Horakelo, Katar, Kerkersitu, Kulfo, Lipis, Meki and Tikur wuha) and six lakes (Abaya, Abiyata, Hawassa, Chamo, Langano and Ziway) have been collected from the Ministry of Water Resources.

The lake level records were used to reconstruct the recent changes and to correlate the lake levels with other catchment hydrometeorological factors. The required softwares (Microsoft Excel, ArcGIS, ERDAS IMAGINE, SPSS and Matlab) that are anticipated to support the study have been collected from different sources. Moreover, satellite Land Sat images for three different years (Appendix 1) but the same month have been collected from Addis Ababa University department of Earth Sciences and other sources. After collecting all the required hydrologic and meteorological data, it was arranged and reorganized. Some of the required data were averaged (lake levels) and some of them were summed up (rainfall, discharge and

evaporation) and used for the analysis of the hydrodynamics of the lakes. The average rainfall corresponding to each lake has been calculated and analysis on the change of lake level and size has been made by looking the historically recorded data of rainfall, lake level, river discharge and evaporation rate.

3.2 Correlation of lake water level with precipitation, river discharge and evaporation

To see the significance of the hydroclimatic, geologic and anthropogenic factors on lake water level fluctuations, correlation with most important hydrometeorological factors (precipitation, river discharge and lake evaporation) were made. For lakes with low correlation coefficients, some possible explanations regarding the reason for the fluctuation of the water levels were presented.

3.3 Multiple regression of lake water level on precipitation, river discharge and open lake evaporation

To identify the relative importance of precipitation, river discharge and evaporation on lake level fluctuation, regression of lake level on these factors was made. Least squares regression of lake level on rainfall, discharge and evaporation was made via curve fitting methods (linear, quadratic, cubic, exponential, logarithmic, inverse etc) .By looking the level of significance (0.01,0.05 and 0.1) in each curve fitting method, the importance of each factor in lake level fluctuation was determined.

3.4 Trend analysis

After rearranging the hydrometeorological data (lake level, precipitation, river discharge and evaporation rate), the five year moving averages were calculated and plotted against time. The rainfalls, discharges and lake evaporations were also plotted against time. The long-term trend analysis of lake water level, precipitation, river discharge and lake evaporation rates were made.

3.5 Multi-temporal satellite image analysis

By zooming in the images and then digitizing their boundaries (perimeters), shape files for each lake corresponding to each year were created. By stacking the layers and then clipping the lake images with the corresponding shape files, the clipped images for each lake were presented for better visualizations (appendix 2). The areas of the lakes for each year were then obtained by calculating the areas of the corresponding shape files using the ArcGIS and ERDAS IMAGINE softwares.

3.6 Land use/cover change analysis

Based on the land use/cover data obtained from FAO (1997) and Ministry of Water Resources (2008), the change in the proportion of the land cover types to the total area of the Rift Valley Basin has been assessed (only the end results of the land use land cover classifications done by the above two organizations was used). This is done to relate the depletion of vegetation with lake level fluctuations.

The general methodology of the research is depicted by Figure1.

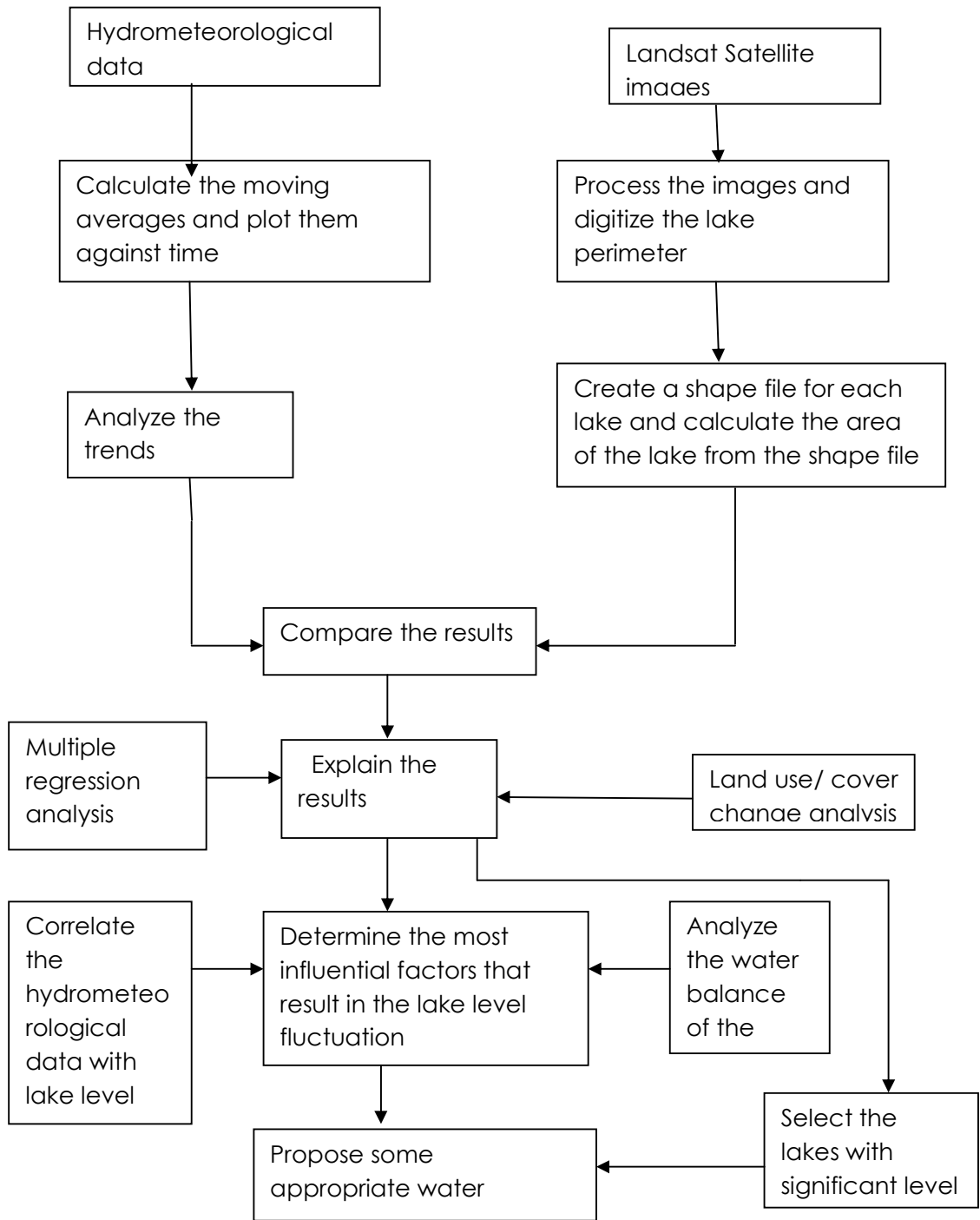


Figure 1. Methodology flowchart

4. General overview of the study area

4.1 General

The study area (the Rift Valley Basin) covers a total area of 53034 km² and lies between 04°23'N and 08°28'N latitude and 36°37'E and 39°22'E longitude (Figure 2).

The Ethiopian Rift Valley is part of the Great East African Rift which is the largest, longest and most conspicuous feature of its kind on earth, stretching for nearly 5,600km from the Red Sea into the mouth of the Zambezi River in Mozambique. The elevation, width and tectonic setting of the Ethiopian Rift Valley are extremely variable. The interesting feature of the northern and central sectors is the existence of open and closed lakes situated within large depressions. The major lakes are located within the central Main Ethiopian Rift with relatively higher elevations as compared to Afar and Chew Bahir Rift bordering Kenya. These lakes occupy an enclave of internal drainage basins separating the tributaries of the Nile and Wabishebele River Basins (Tenalem Ayenew, 2009).

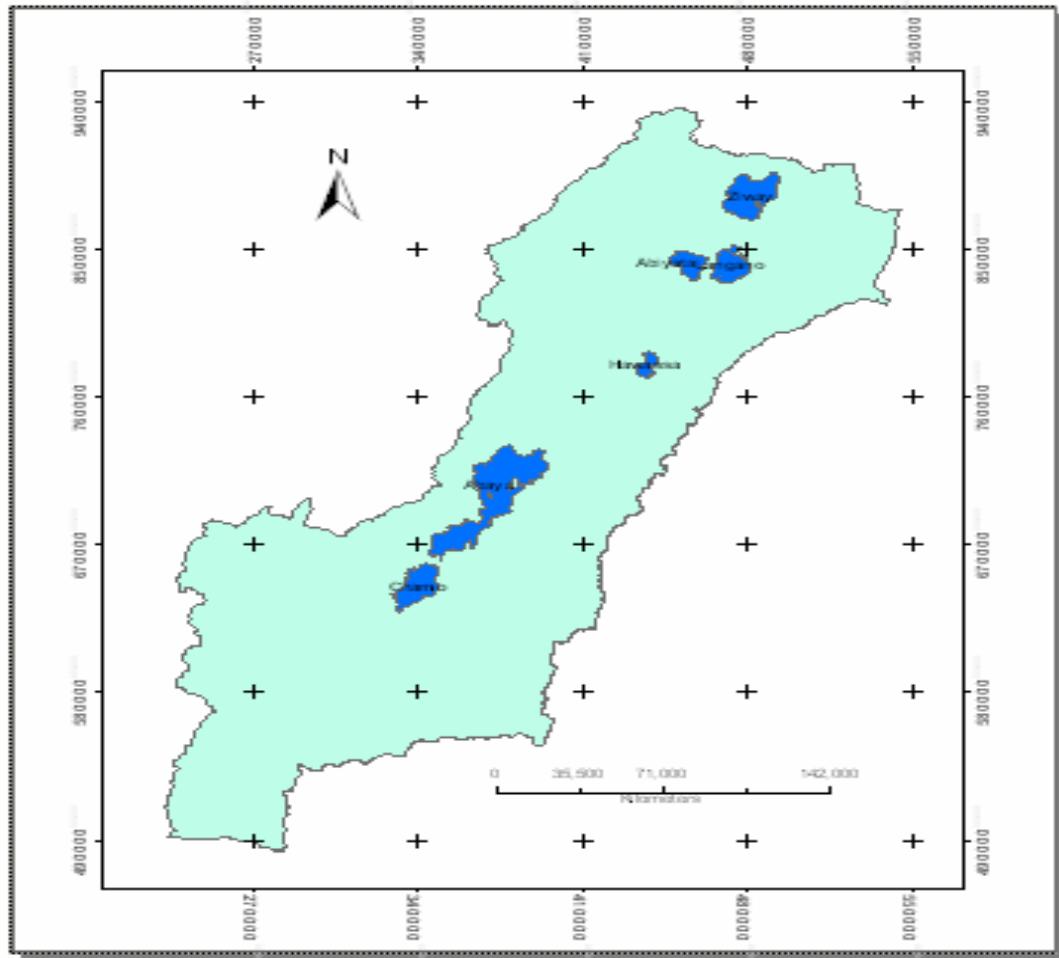


Figure2.The study area

The map of the Rift Valley Basin together with the studied lakes is shown in Figure 2.

The Rift Valley of Southern Ethiopia runs NNE from the Kenya frontier of 600km to the Koka Dam on the Awash River where the rift begins to open out into the Afar and Danakil depressions (Grove et al., 1975). The Ethiopian rift valley basin has three physiographic regions: the rift, escarpments and highlands. The rift where large lakes exist starts in the neighborhood of Lake Abhe and extends some 1000km southwards into northern Kenya (Tenalem Ayenew, 1998). The altitude ranges from 1600 m a.m.s.l. in the rift to over 4000 m a.m.s.l. in the large volcanic peaks of the Eastern Highlands. There are highly elevated volcanic mountains both

within the rift and the highlands. The highest elevation is 4245 m.a.s.l, which is the peak of Mount Kaka located on the eastern boundary of the Ziway-Shala lake basin (Tenalem Ayenew 1998).

The floor of the Rift valley encompasses three major water basins from NE to SW (Tamiru Alemayehu et al., 2004 cited in Huib et al., 2006):

- Awash basin with the Koka, Beseka, Gemari, and Abe as most important lakes.
- Central Ethiopian Rift (CER) valley with the Ziway, Langano, Abyata and Shala lakes as most important ones.
- Southern basin with Hawassa, Abaya, Chamo and Chew-Bahir as most important lakes. These three basins are not connected by surface water, but it is suggested that they may be connected by underground faults running in NE-SW direction (Tenalem Ayenew, 2004). However, the geohydrology of the three main water basins in the Rift valley are highly complex and the spatial dynamics of groundwater resources are poorly understood. The locations of the studied lakes are shown in Figure 3.

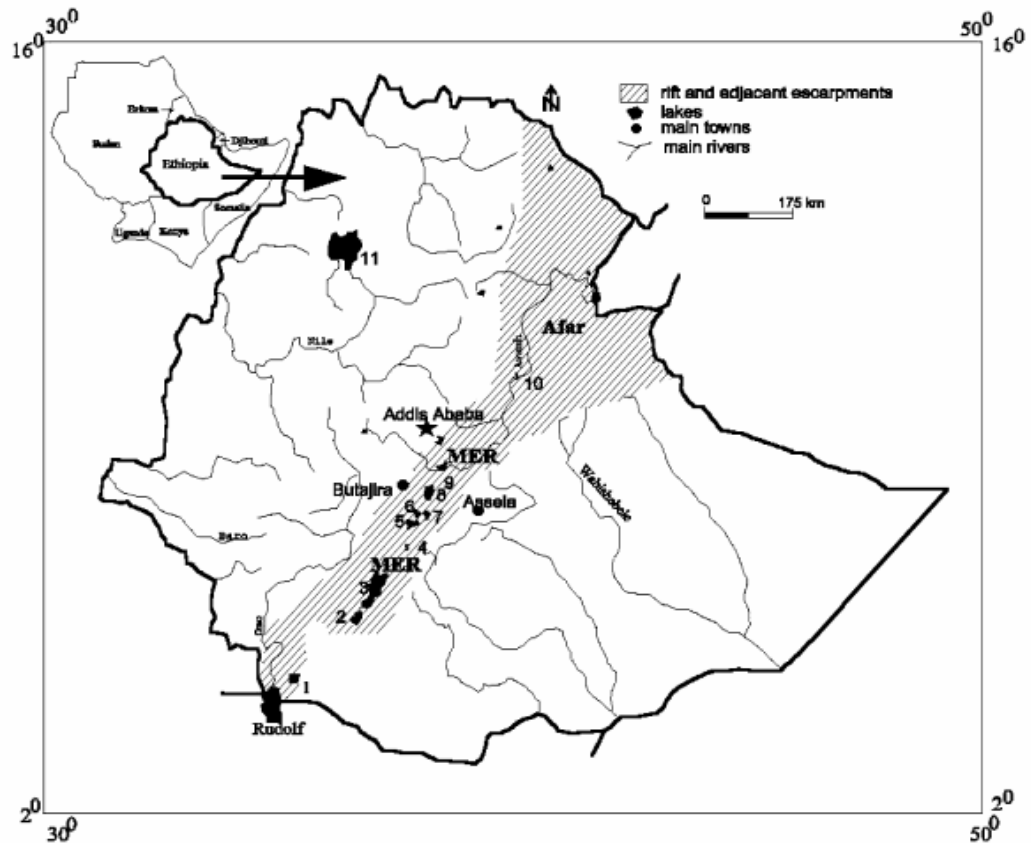


Figure3. Location map; 2:Chamo; 3: Abaya; 4:Hawassa;6:Abiyata;7:Langano;8:Ziway

Source: Tenalem Ayenew (2004)

Ziway-shalla Basin (CER) is a closed basin with catchment area of about 13,000km² of which 1,443km² is covered with permanent open water bodies. The basin comprises of four major lakes (Abiyata, Langano, Ziway and Shalla) occupying volcano-tectonic depressions at its center (Tenalem Ayenew, 2009). The location map of the Ziway-Shalla Basin is indicated in Figure 4. The two major lakes in the CER valley are Lake Ziway and Lake Abiyata. Lake Ziway is the centre of agricultural development. Lake Abiyata and Lake Shala are important nature reserves and they belong to the Abiyata-Shala Lakes National Park (Tenalem Ayenew, 2003 cited in Huib and Herco, 2006). Lake Langano stayed relatively stable for long period of time. However, it is affected in recent years which may be due to neotectonic activities and diversion of the water in its feeder tributary

rivers for small-scale irrigation in the highlands of Arsi (Tenalem Ayenew, 2009). The Lake is connected to Lakes Ziway and Shalla by rivers, with Shalla being unconnected to surface waters from other lakes (Tenalem Ayenew, 2002).

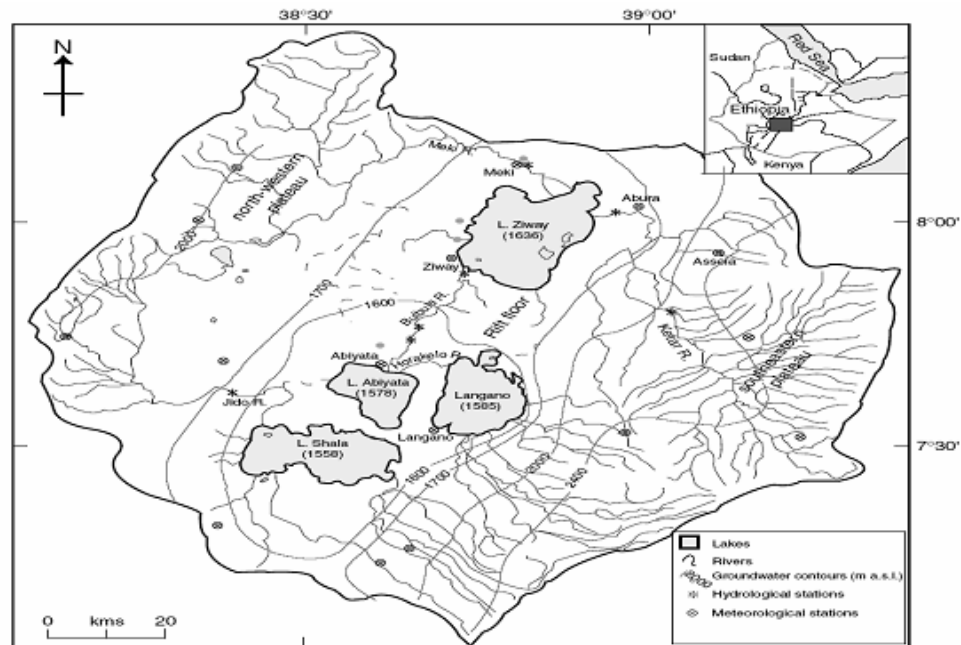


Figure 4. General location map, topography, and drainage pattern of the Central Ethiopian Rift

Source: Huib and Hercon (2006)

Lakes Hawassa, Abaya and Chamo are contained in the Southern basin. The total area of the basin, together with the lakes, is about 20055Km² (Tenalem Ayenew, 2009; Tenalem Ayenew and Yemene Gebreegziabher, 2006).

The Hawassa catchment represents a large collapse caldera bordered by highlands to the north and east. It is located at a distance of 275km south of the country's capital city, Addis Ababa. The center of the caldera is occupied by Lakes Hawassa and Shallo. Lake Hawassa's elevation is at 1680 m.a.s.l depicting the end of the Ethiopian Rift floor level occupied by lakes. Hawassa is the smallest of all the major lakes south of the Awash Basin and its catchment has no surface water outlet. The caldera of Lake

Hawassa is clearly separated from the surrounding highlands by scarps and steep mountain slopes. Hawassa is a fresh water lake and is a major source of fish for the local community (Tenalem Ayenew, 2009).

Lake Abaya is located at an elevation of 1268 m.a.s.l having a surface area of 1160km². The lake is characterized by strong topographical differences between the Rift floor, the slopes and the basaltic highlands over short distances (Susanne et al., 2004). It is comparatively less saline and is used for fishing and recreation. Lake Abaya is connected to Lake Chamo by a bridge known as Angels.

Lake Chamo is located south of Abaya at an elevation of 1235 m.a.s.l and has a maximum depth of 13m (Fethangest Woldemariam, 2004 cited in Tenalem Ayenew, 2009). Chamo is relatively more saline than Abaya. However, its water is less saline as compared to the lake waters in the Ziway-Shalla Basin indicating groundwater outflow to the nearby regions analogous to Lake Hawassa.

The area distribution of the meteorological stations is patchy; most of the stations are located on the Graben Shoulder of the Highlands, only few stations are situated in the Rift valley (Stefan et al., 2004)

4.2 Geological and geomorphological characterizations

During the beginning of the Cenozoic Era, Eastern Africa was deluged under molten lava and thick beds of explosive rocks with intense tectonic activity that initiated the formation of the rift valley. The Ethiopian Rift is created by volcanic and faulting activity that formed various volcano-tectonic depressions in the floor of the rift, which later became lakes. The Ethiopian Rift is part of the Great East African Rift Valley, also called the Afro-Arabian rift, which extends from Jordan in the Middle East, through Eastern Africa to Mozambique in Southern Africa. It also extends from the Kenyan border up to the Red Sea and divides the Ethiopian highlands into a northern and southern halve.

The wide areas buried under volcanic materials, the thickness and variety of the rock sequences and the prolonged duration of the eruptions make East Africa one of the world's most remarkable volcanic regions. Without composite volcanic centers made largely of lava, there would have been no mountains and crater lakes and without faulting, there would have been no imposing escarpment gorges, canyons and extended rift valley floor occupied by a series of lakes (Tenalem Ayenew, 2009). The extraordinary faults and rift lakes occupying volcano-tectonic depressions tend to follow the northeast-southwest axis of the Ethiopian Rift System. Fault lines appeared and in time, magma welled through tensional fissures in places weakened by faulting in this active region. Simultaneously, in the same time span, the interrelated forces of doming, faulting, and subsidence began to thrust, twist, crumple, and buckle the earth's crust until it acquired the shape and form of today's unique valley system covered with a series of lakes where early man settlement began in their vicinity (Tenalem Ayenew, 2009).

The lakes occupy the rift floor, and are bounded to the east and west by escarpments and high elevation plateaux formed by Cenozoic volcano-tectonic processes. Most of the flat rift plains around the lakes are covered with thick lacustrine sediments and volcanoclastic Quaternary deposits with scattered volcanic centers (Barbieri et al., 1975; Zanettin et al., 1980 cited Tenalem Ayenew, 2004).

The Rift Valley floor is covered by Quaternary sediments and volcanics, the slopes and the highlands are predominantly composed of Tertiary basalts, locally subordinated by Precambrian basement (Mohr, 1961 cited in Susanne, 2004). Most of the flat rift plains around the lakes are covered with thick lacustrine sediments and volcanoclastic Quaternary deposits with scattered volcanic centers (Barbieri et al., 1975; Zanettin et al., 1980 cited in Tenalem Ayenew, 2004).

The rift is distinctly separated from the plateaux by a series of normal step faults oriented parallel to the north north-eastern and south south-eastern trending rift axis. A persistent belt of intense and fresh faulting marks the floor of the Main Ethiopian Rift (MER). Numerous geothermal manifestations and caldera volcanoes characterize this active region.

Volcanism has persisted up to the present day in the Afar within small eruptive centers (Baker and Wohlenberg, 1971 cited in Tenalem Ayenew, 2004). There are also frequent earthquakes all over the Ethiopian Rift; the epicenters are almost exclusively related to the major rift structures. The largest number of epicenters is located along and on the margin of the western plateau escarpment and along the large axial faults (Gouin, 1979 cited in Tenalem Ayenew, 2004). Although the effect of recent tectonism on the hydrogeology of the lakes is unclear, there are some changes in lake levels, possibly due to the formation and/or reactivation of rift faults. This has been observed through changes in the discharges of springs around Lake Langano after recent seismic activities and formation of new faults (Tenalem Ayenew, 1998).

The Ethiopian Rift valley has highly variable elevation, width and tectonic setting. Very interesting feature of the northern and central sectors is the existence of open and closed lakes situated within the large depressions. We find the major lakes in the central Main Ethiopian Rift with relatively higher elevations as compared to the Afar and Chew Bahir Rift bordering Kenya.

4.3 Climate of the rift valley basin

Lakes in the Ethiopian Rift are sensitive indicators of Late Quaternary climates (Grove et al., 1975). The strong topographic characteristics control the expected tropical climate, soil, natural vegetation and as a result the population distribution. The lakes of the Ethiopian Rift

experience a wide range of climate, stressed by the annual north-south movements of inter- and sub-tropical frontal zones across the country. The climate is humid to subhumid in the highlands and semiarid in the rift valley with distinct wet and dry seasons (Daniel Gemechu, 1977 cited in Tenalem Ayenew, 2009).

Rainfall in Ethiopia is erratic and subject to large spatial variability, which is largely determined by altitude. Areas above 2500 m may receive 1400-1800 mm y⁻¹, mid-altitude regions (600-2500 m) may receive 1000-1400 mm per year, and coastal lowlands generally receive less than 200 mm per year (Huib and Herco, 2006). The rainfall pattern is largely influenced by the annual oscillation of the inter-tropical convergence zone, which results in warm, wet summers and dry, cold and windy winters (Huib and Herco, 2006). The average annual rainfall ranges from 1150 mm in the highlands to 650 mm in the rift floor (Tenalem Ayenew, 1998). There is no clear trend (increase or decrease) in rainfall characteristics in the rift valley region during the last 40 years (Tamiru Alemayehu et al., 2006 cited in Huib and Herco, 2006).

The main rainy season is between June and September and the dry season lasts from October to February. The main rainy season accounts for 70-90% of the total annual rainfall in the basin. Minor rain events, originating from moist south-easterly winds, occur between March and May. Due to their nature, these rainfall events are more pronounced in the highlands (Huib and Herco, 2006). The adjacent highlands experience higher rainfall and lower evaporation. During the wet season between June and September, north-westerly monsoon wind bring dry air from Arabia which results in limited rainfall in few areas near the Red Sea coast and Danakil depression (Tenalem Ayenew, 2009). The highland rainfall is the ultimate source of replenishment of the rift lakes in the form of groundwater, river discharge and overland flow (Tenalem Ayenew, 2009). The prevailing temperatures largely depend on altitude. The mean annual

temperature is around 15°C in the highlands and 20°C in the rift valley (Huib and Herco, 2006).

Most of the rainfall in the CER is intercepted by the highlands. Open water evaporation (lake evaporation) is in the order of 1800-2000 mm per year (Dagnachew Legesse, 2004; Tenalem Ayenew, 2003 cited in Huib and Herco, 2006). Actual evapotranspiration depends on the landuse and availability of water and varies between 700 and 900 mm per year (Tenalem Ayenew, 2003 cited in Huib and Herco, 2006). Reference evapotranspiration (based on Penman-Monteith) is about 1400-1500 mm per year.

4.4 General hydrology of the lakes under consideration

The East African Rift lakes are bordered to the east and west by large altitude highlands where the major tributary feeder rivers originate. The rift consisting of large lakes starts in the neighborhood of Lake Abhe and extends some 1000km to the south into northern Kenya (Mohr, 1962 cited in Tenalem Ayenew, 2009)

Many of the studied lakes are located within a closed basin fed by perennial rivers. The major rivers are Meki-Katar and Bilate, which feed Lakes Ziway and Abaya respectively. The Meki River discharges the runoff from the plateau west of Lake Ziway and the Ketar River discharges the water from the eastern and south-eastern plateaus. The catchments of these two rivers cover 5610 km² (Dagnachew Legesse et al., 2004 cited in Huib and Herco, 2006). Lakes Abaya and Chamo are seasonally connected by an overflow channel, Langano and Abiyata by the Horakelo River, Ziway and Abiyata by the Bulbula River. Lake Chamo is fed by Sille and Kulfo Rivers. It outflows to the Chew Bahir during extreme wet seasons via Metenfesha (Tenalem Ayenew, 2009). The long term (1980-2007) average annual volumes of Feeder Rivers are given in Table 1.

Table 1. The long-term (1980-2007) average annual volumes of Feeder Rivers

No	Feeder river(s) system	Volume in million cubic meter(mcm)	Flow into lake
1	Bilate	4682.4	Abaya
2	Kerkersitu- Horakelo	1491.6	Abiyata
3	Tikur Wuha	35376	Hawassa
4	Kulfo	96027.6	Chamo
5	Horakelo	528	Langano
6	Katar+Meki	7952.4	Ziway

Abiyata and Hawassa are terminal lakes without surface water outlets. Lake Hawassa is connected to a wide swampy area and the small lake Cheleleka through the Tikur Wuha River. A major part of the water inflow of Lake Abyata originates from Lake Ziway through the Bulbula River. Hence both lakes are hydrologically connected. Considerably less water is discharged from Lake Langano to Lake Abiyata through the Horakelo River. Lake Abyata is the terminal lake of the catchment (CER), from where the water evaporates.

Table 2. Some basic hydrological data for the studied lakes (some variables average out between 1970 and 2000)

Lake	Altitude (m.a.s.l)	Lake area (km ²)	Catchment area (km ²)	Max Depth (m)	Mean Depth (m)	Volume (10 ⁶ m ³)	Salinity (g/l)
Abaya	1285	1162	17300	13.1	7.1	8200	0.771
Abiyata	1580	180	10740	14.2	7.6	957	16.200
Hawassa	1680	100	1340	20.0	10.7	1340	0.290
Chamo	1233	551	2210	13.0	-	-	1.099
Langanano	1585	230	2000	47.9	17.0	3800	1.88
Ziway	1636	440	7380	8.9	2.5	1466	0.349

Source: Wood and Talling (1988); Halcrow and Partners (1989); Tenalem Ayenew (1998); WWDSE (2001) cited in Tenalem Ayenew (2004)

The long-term average annual water balance of the lakes under consideration is shown in Table 3 to understand how the levels of the lakes are fluctuating.

Table 3. Long-term average annual water balance of the studied lakes (mcm)

P_i: precipitation on the lake; R_i: inflow from rivers; G_i: groundwater inflow; S_r: inflow from surface runoff; E_i: lake evaporation; R_o: outflow in river outlets; G_o: groundwater outflow; A: abstraction; Ng: negligible; VH: very high; H: high; M: medium; RO: rare outflow; Mcm: million cubic meter.

Lake	inflow				outflow				Difference (10 ⁶ m ³)
	P _i	R _i	G _i	S _r	E _i	R _o	G _o	A	
Abaya	556	VH	VH	VH	1900	RO	M	-	-
Abiyata	113	230	26.8	15	372	closed	1.2	13	-1.4
Hawassa	106	83.1	H	83.7	132	closed	58	Ng	+82.8
Chamo	406	H	H	H	900.9	RO	H	Ng	-
Langanano	186	212	135.4	VH	463	46	18.9	-	+5.5
Ziway	323	656.5	80.5	48	890	184	14.6	28	-8.6

Source: Tenalem Ayenew (2004)

Much of the evidence for the temporal and spatial changes in hydrology comes from lake level records. Recording of lake levels began for most

lakes in the early 1970s, and was carried out daily using staff gauges. The reference elevation of the position of the staff gauges is not known. Lake levels are expressed only with respect to the bottom of a staff gauge. Most of the lakes do not have a complete record.

Since the lakes have different hydrogeological setup, variable modes of origin and climatic conditions, they possess different physical and chemical characteristics (Tenalem Ayenew, 2009).

4.5 Land use changes

Forest ecosystems contribute greatly to the prosperity and quality of life in the lake regions as well as to cleaning its air and water, and the reduction of soil erosion. Their diversity also provides important habitat to wildlife.

It is well known that land use affects stream water quality. The changes of land use patterns certainly provide many social and economic benefits. However, they also come at the cost of the natural environment (Qin, 1993). One of the major direct environmental impacts of development is the degradation of water resources and water quality (USEPA, 2001 cited in Tenalem Ayenew, 2004). The driving variables that cause land use changes include a variety of social, political and environmental factors, such as distance to transportation, proximity to amenities (such as rivers, lakes, and recreational sites), density of surrounding agriculture, exclusive zones, and population growth.

Clearing of forests, animal grazing and other modifications that reduced the vegetation in the catchment areas of the Ethiopian lakes have expanded considerably (Hillman, 1988 cited in Tenalem Ayenew, 2004). This clearing increases the silt and nutrient load from the catchment. Land degradation and deforestation of lake catchments have both increased surface runoff, ultimately leading to slight rises in lake levels (Geremew, 2000; WWDSE, 2001 cited in Tenalem Ayenew, 2004). Most of the lakes that have undergone considerable changes are those located in terminal

positions. The depletion of vegetation cover not only increases sedimentation in lakes but also decreases canopy and interception losses, which in turn increase the runoff coefficient. Increasing population and expansion of irrigation projects are putting pressure on the vegetation of the Rift Valley Basin. The study made by Huib and Herco (2006) shows that changes in land use and the associated increase in surface water extraction in the Ziway/Abyata catchment have resulted in lower lake water levels and increased salinity and alkalinity of Lake Abyata.

5. Data analysis

5.1 Data Consistency

Hydrometeorological data are vital instruments to assess the hydroclimatic and anthropogenic contributions to the water level fluctuations of the Ethiopian Rift Valley lakes. In spite of this fact, there are problems of data inconsistency with regard to the hydrometeorological records.

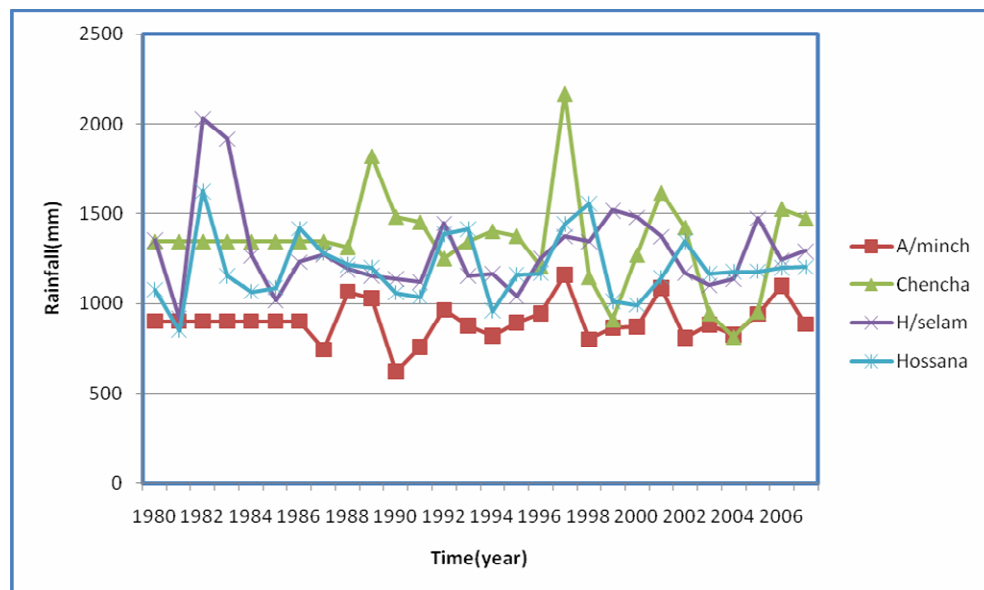


Figure 5. The rainfall values from Arba-Minch, Chench, H/selam and Hossana stations corresponding to Lakes Abaya and Chamo.

As we can see from Figure 5, the rainfall patterns at Arba-Minch, Chench, H/selam and Hossana are not similar and hence averaging all the values from these four stations may not be appropriate. The rainfall patterns at Arba-Minch and Chench; H/selam and Hossana are nearly similar. The averages of the rainfall values from these two groups of stations are correlated with the water levels of Lakes Abaya and Chamo.

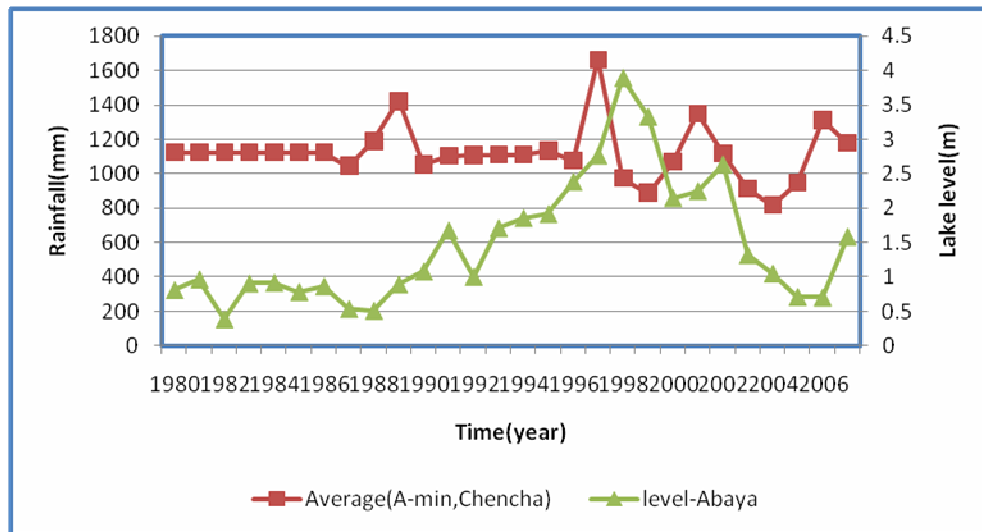


Figure 6. Average of the rainfall values from Arba-Minch and Chencha stations and the water level of Lake Abaya.

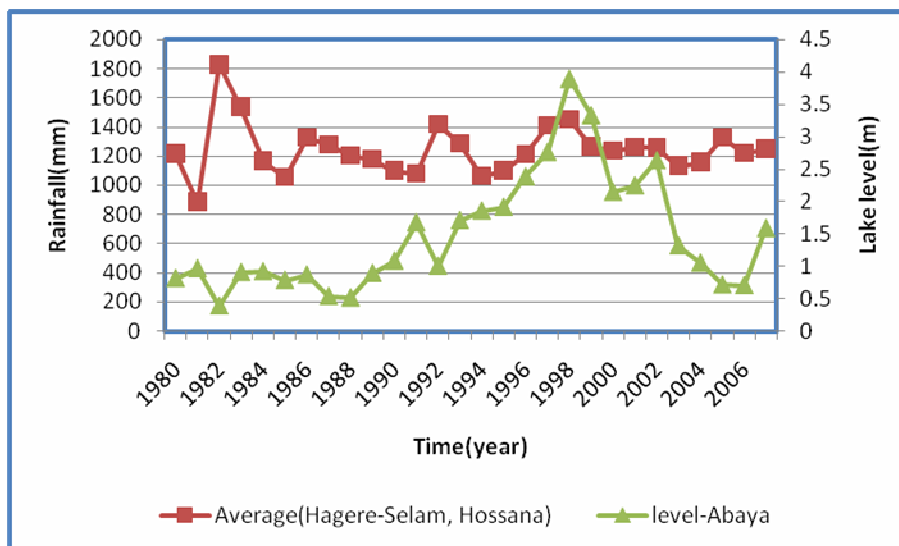


Figure 7. Average of the rainfall values from Hagere-Selam and Hossana stations and the water level of Lake Abaya.

As we can see from Figures 6 and 7, the water level of Lake Abaya is not associated significantly with rainfall.

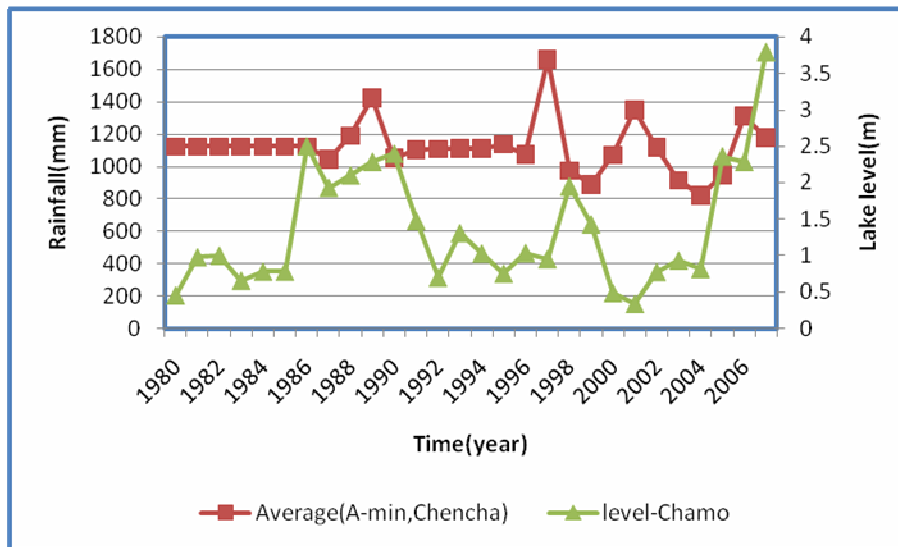


Figure 8. Average of the rainfall values from Arba-Minch and Chencha stations and the water level of Lake Chamo.

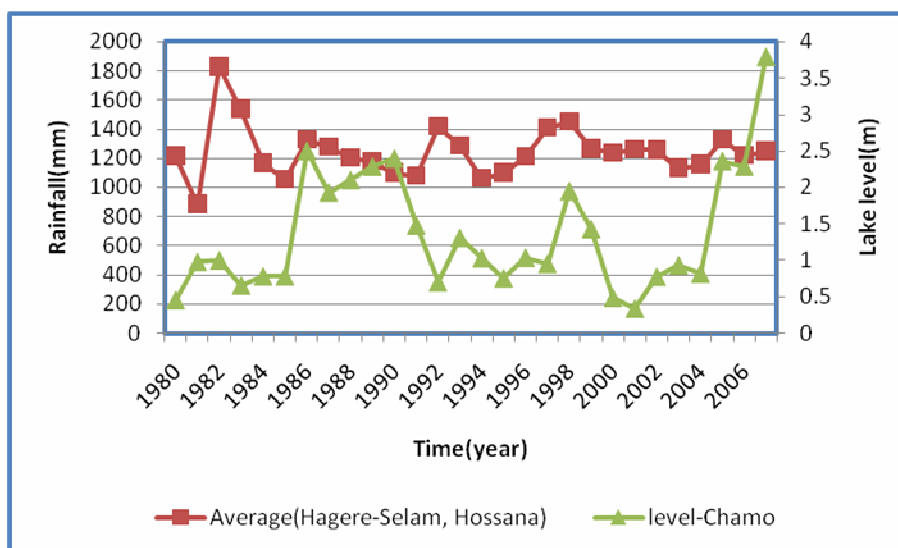


Figure 9. Average of the rainfall values from Hagere-Selam and Hossana stations and the water level of Lake Chamo.

Figures 8 and 9 indicate that the water level of Lake Chamo is not associated significantly with rainfall. For example, as we can see from Figure 9, the rainfall shows increasing trend between 1990 and 1992 while the water level of Lake Chamo shows a decreasing trend during this period. This clearly shows data inconsistency.

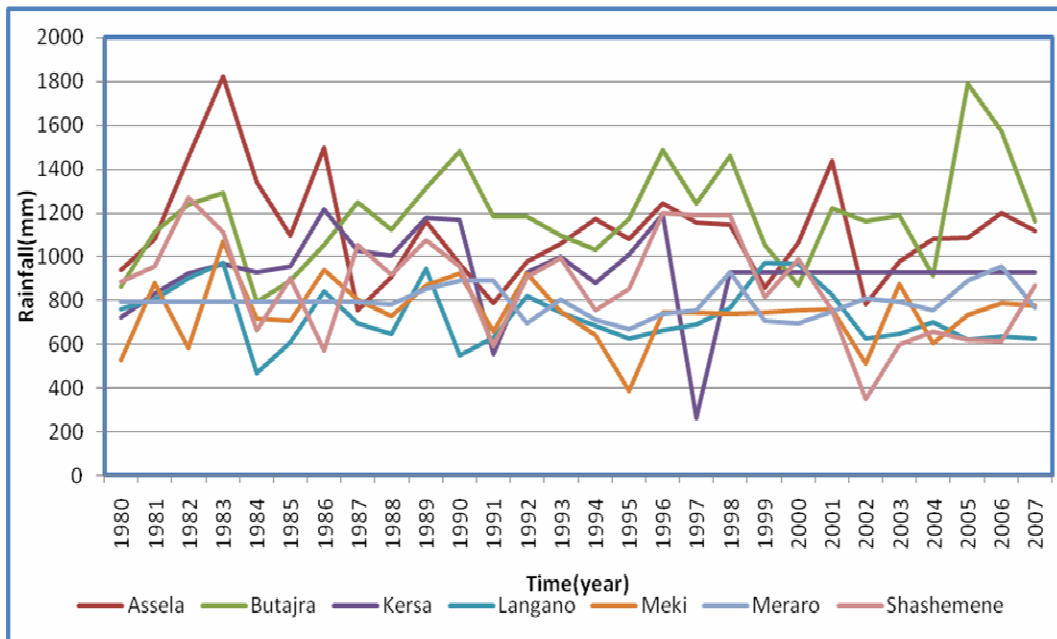


Figure 10. The rainfall values from Assela, Butajira, Kersa, Langano, Meki, Meraro and Shashemene stations corresponding to Lakes Abiyata, Langano and ziway.

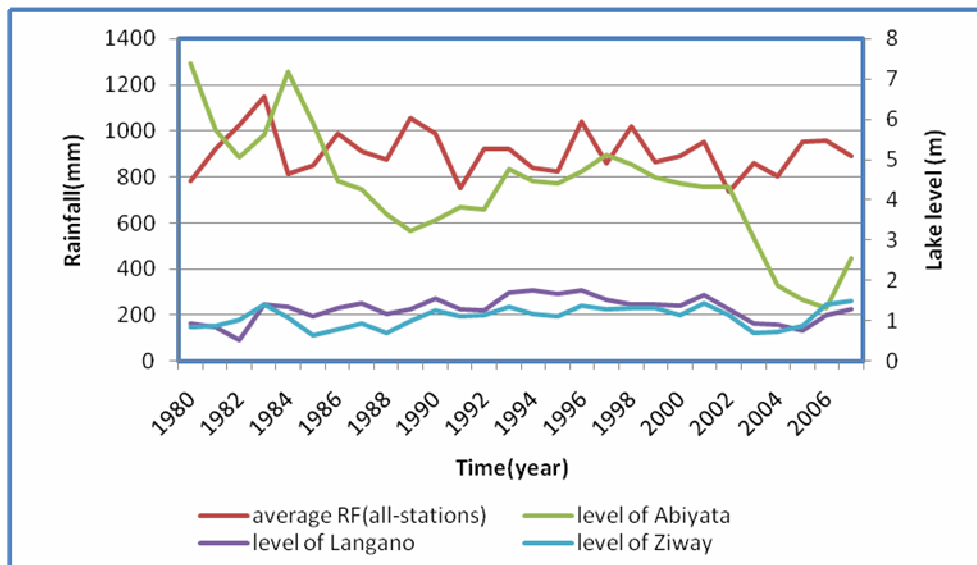


Figure 11. Average of the rainfalls from Assela, Butajira, Kersa, Langano, Meki, Meraro and Shashemene stations corresponding to Lakes Abiyata, Langano and ziway.

We can see from Figure 10 that the rainfalls from the indicated stations do not have similar patterns. The average of the rainfalls from all stations seems to have a similar pattern with the water level trend of Lake Langano.

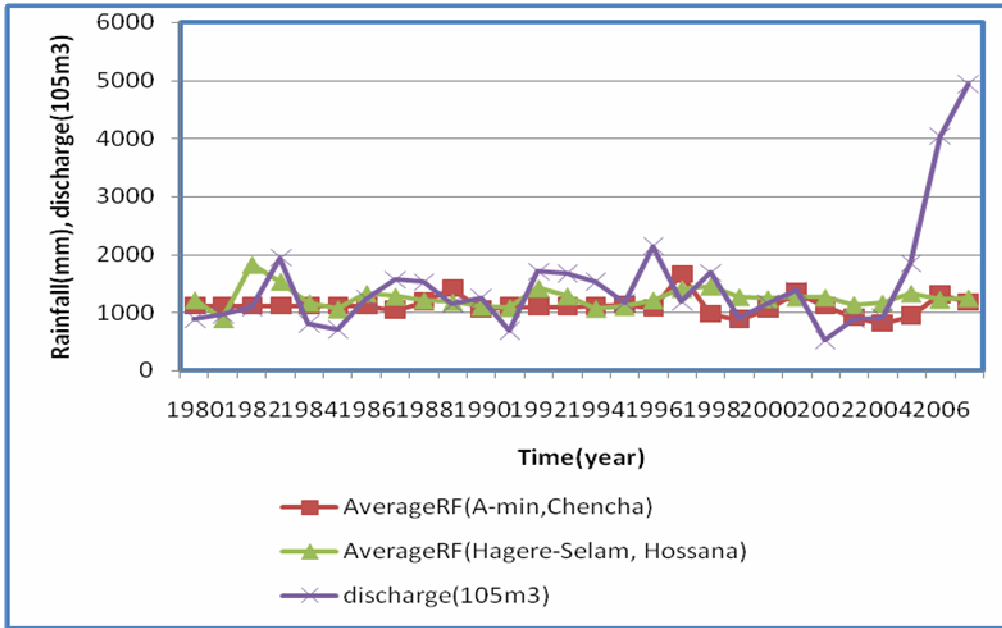


Figure 12. The average rainfalls and the discharge from Bilate River corresponding to Lake Abaya

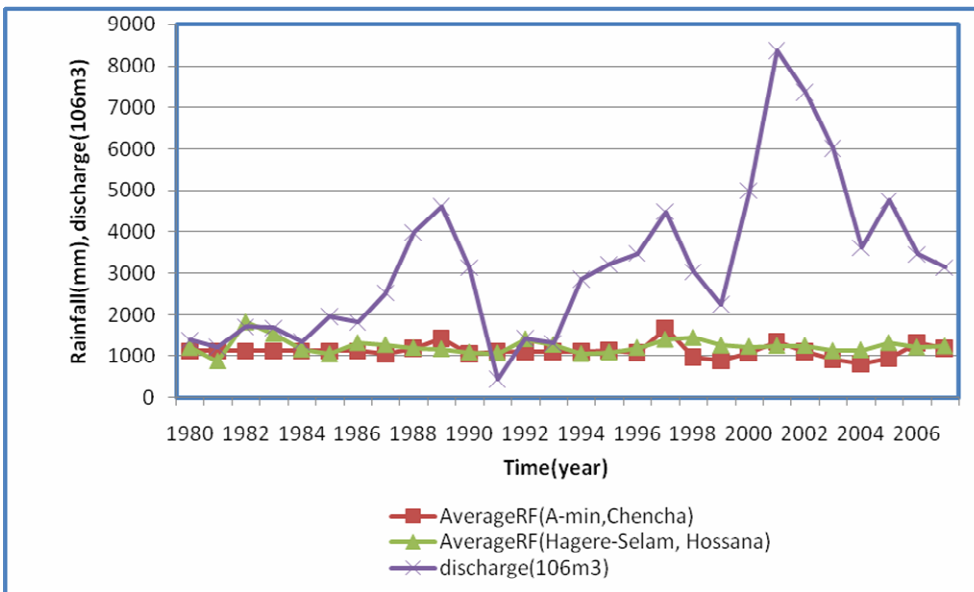


Figure 13. The average rainfalls and the discharge from Kulfo River corresponding to Lake Chamo.

Figures 12 and 13 clearly show that the average rainfalls and the discharges do not show similar trends especially for Lake Chamo indicating data inconsistency. A similar situation is also shown in Figure 11. Due to this problem, more emphasis is given to the analysis of satellite data.

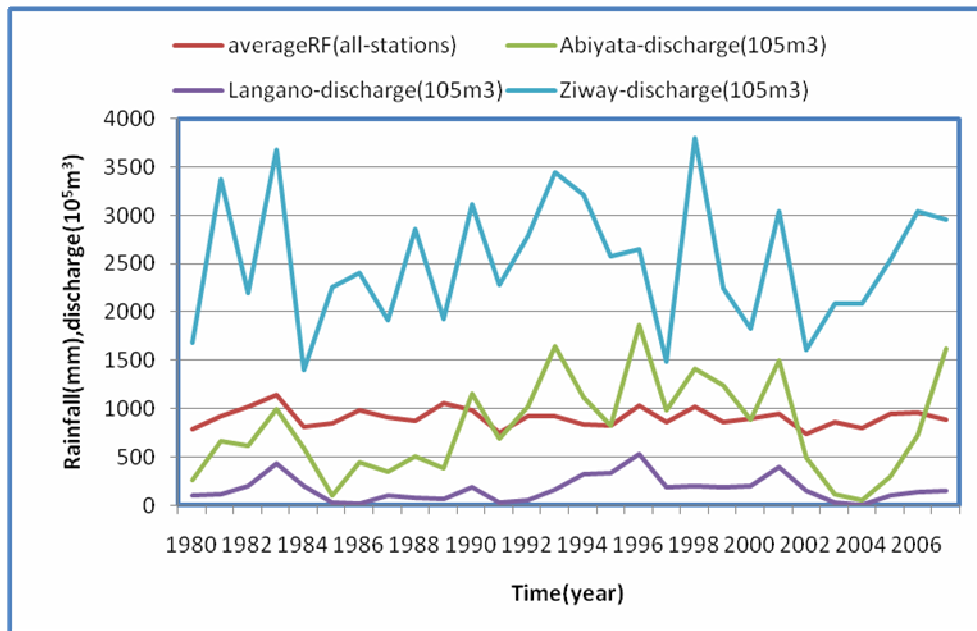


Figure 14.The average rainfall for all stations and the discharges corresponding to Lake Abiyata, Langano and Ziway.

The discharge into Lake Ziway and the average annual rainfall trend show a certain mismatch indicating data inconsistency. Although there are some data inconsistencies especially corresponding to Lakes Abaya Chamo and Ziway, the hydrometeorological data can be acceptable with some degree of tolerance and used to identify the most significant factor(s) that are causing the water level fluctuations. The assessments on the lake fluctuations (rising or declining) and the computations of numerical values indicating the amount of fluctuations were made using satellite image analyses.

Table 4.Correlations of rainfalls with the discharges

Lake	Abaya	Abiyata	Chamo	Hawassa	Langano	Ziway
Correlation coefficient	0.131825	0.379668	-0.00709	0.319599	0.306506	0.052279

As we can see from Table 4, the associations of rainfalls with the discharges have the smallest correlation coefficients for Lakes Chamo, Ziway and Abaya which confirm some degrees of data inconsistency.

5.2 Correlation coefficients and their interpretations

There are always time lags between precipitation events and lake level fluctuations. Moreover, most of the rainfall stations are located on the Graben Shoulder of the Highlands, only few stations are situated in the Rift valley (Stefan et al., 2004) and hence the rainfall records can be less realistic. For this reason, poor correlation coefficients between lake levels and rainfalls have been observed except for Lake Langano with a value of 0.68. Due to the same reason, the correlation coefficients between lake levels and discharges are also very small or negligible except for Lakes Hawassa, Langano and Ziway with values 0.76, 0.57 and 0.40 respectively. There is a significant correlation between water level and evaporation for Lake Abiyata only. The correlation of lake level with rainfall, discharge and evaporation is summarized in Table 5.

Table 5. Correlation of lake level with rainfall, discharge and lake evaporation

Lake	Rainfall	Discharge	Evaporation
Abaya	Not Significant	Not Significant	Not Significant
Abiyata	Not Significant	Not Significant	Significant at 0.01 level $R^2=0.52$, $R= -0.721$
Hawassa	Not Significant	Significant at 0.01 level $R^2= 0.58$, $R=0.758$	Significant at 0.1 level $R^2= 0.14$, $R=-0.372$
Chamo	Not Significant	Not Significant	Not Significant
Langano	Significant at 0.01 level $R^2= 0.47$, $R= 0.684$	Significant at 0.01 level $R^2= 0.33$, $R= 0.573$	Not Significant
Ziway	Not Significant	Significant at 0.05 level $R^2= 0.16$, $R=0.397$	Not Significant

5.3 The significance of the multiple regression equation

Least squares regression equations can be used to predict the values of a dependent variable (lake level in our case) from one or more independent variables (rainfall, discharge and evaporation) with coefficients of multiple correlations indicating the strength of the relationships between the dependent and independent variables. As we can see from Table 6, there are relatively poor or negligible fits between lake level and rainfall, discharge and evaporation data. The possible explanation for this may be due to the time lags between precipitation events and lake level fluctuations or questionable data or both.

Table 6. Curve fitting of lake level with rainfall, discharge and evaporation data. DDNF: data do not fit; RNS: relationship not significant; sig: significant

Y: lake level; X_1, x_2 : independent variable (rainfall, discharge, evaporation)

Lake	Rainfall	Discharge	Evaporation	Multiple Regression equation
Abaya	DDNF (RNS)	DDNF (RNS))	Sig. at 0.01 level Relation type →inverse $R^2 = 0.59, R = -0.77$	$Y = 1.8171 - 51.987x^{-1}$
Abiyata	DDNF (RNS)	DDNF (RNS)	Sig. at 0.01 level Relation type →logarithmic $R^2 = 0.55, R = -0.74$	$Y = 2.2506 - 0.4258 \log x$
Hawassa	DDNF (RNS)	Sig. at 0.01 level Relation type →cubic $R^2 = 0.59, R = 0.77$	DDNF (RNS)	$Y = 1.2735 + 0.00009x + 0.0000005x^2 - 0.000000000x^3$
Chamo	DDNF (RNS)	DDNF (RNS)	Sig. at 0.05 level Relation type →cubic $R^2 = 0.55, R = -0.74$	$Y = 2.5079 - 0.0112x + 0.000024x^3$
Langano	Sig. at 0.01 level Relation type →cubic $R^2 = 0.49, R = 0.68$	Sig. at 0.01 level Relation type →linear $R^2 = 0.33, R = 0.57$	DDNF (RNS)	$Y = 0.0013 + 0.0012x_1 + 0.0144x_2$ X_1 : rainfall X_2 : discharge
Ziway	DDNF (RNS)	Sig. at 0.05 level Relation type →cubic $R^2 = 0.31, R = 0.56$	DDNF (RNS)	$Y = 5.2093 - 0.052x + 0.0002x^2 - 0.0000002x^3$

Table 7. The correlation matrix indicating the association of lake levels with rainfall, discharge and evaporation

Lake	Rainfall	Discharge	Evaporation
Abaya	0.08	0.10	-0.77*
Abiyata	0.37	0.29	-0.74*
Hawassa	0.23	0.77*	-0.37*
Chamo	0.17	0.43	-0.74*
Langano	0.68*	0.57*	-0.01
Ziway	0.26	0.56*	-0.1

Numbers followed by '*' indicate significant correlations.

As we can see from Table 6, the fluctuation in the levels of Abaya, Abiyata and Chamo are related to the variation in the lake evaporation while that of Hawassa and Ziway are related to the variation in the river discharge, with the percentages in the lake level fluctuations explained by the

indicated hydroclimatic factors (evaporation and discharge) being 59%, 55%, 59%, 55% and 31% respectively.

The level of Lake Langano, is correlated to both rainfall and discharge with coefficient of multiple correlation $R=0.78$ and $R^2=0.61$ at a significance level of 0.01. This implies that 61% of the fluctuation in the in the level of Lake Langano is explained by the variation in both rainfall and discharge. Other possible sources for water level fluctuation in the lake are assumed to be neotectonic activities and diversion of tributary rivers in the Arsi Highlands for small-scale irrigation (Tenalem Ayenew, 2009).

Since the hydroclimatic factors (rainfall, discharge and evaporation) interact not only with lake levels but also with themselves, the equations for the regression of lake level on these factors can not significantly predict the lake levels. However, these equations can tell us the strength of the relationships between the factors and lake levels.

5.4 Trend analysis for lake levels, precipitations, discharges and lake evaporations.

Figure 5 shows that the water level of Lake Abiyata is declining drastically while those of Abaya and Hawassa are slightly rising. This is in agreement with the results obtained using Landsat satellite images. The levels of Langano and Ziway seem to have constant trends and that of Chamo shows a rising trend. However, the results obtained using the satellite images show contrasting trends. As shown in table 8, the water level of Lake Abaya was below its long term average between 1980 and 1993, above the long term average between 1994 and 2007. This could be due to increased deforestation of its catchment as indicated by the land use/cover maps (Figure 27 and 28).

The level of Lake Abiyata showed variable trends between 1980 and 2000, and a constant trend (declining trend) after 2000 onwards. More specifically, the lake level has been decreased by about 1.6m from its long term average (about 4.3m) and this shows that very large amount of

water has been abstracted from the lake in addition to the absence of the inflow from Ziway.

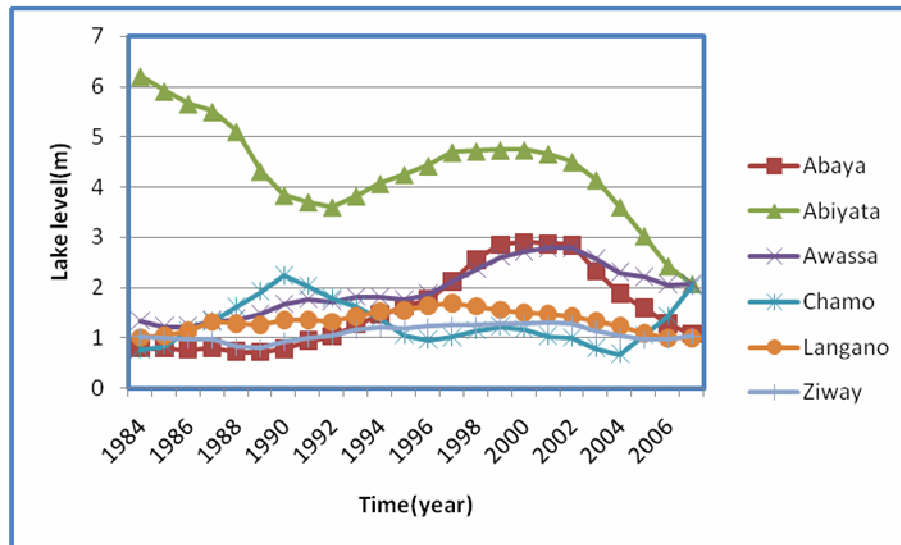


Figure 15 Five Years' moving averages showing the lake levels trends

The level of Lake Hawassa showed declining trends between 1980 and 1993, rising trends after 1994 onwards which may be due to recent neotectonic activities. The levels of Lakes Chamo and Ziway showed increasing trends between 2001 and 2007. This result contradicts with the one obtained using Landsat satellite image analysis. The possible explanation for these contrasting results can be data inconsistency as explained in the previous subsection. The level of Lake Langano is slightly lower than its long term average indicating relatively less anthropogenic contributions to the lake level fluctuation.

Table 8. Seven years' water level trends for the studied lakes

No	Lake	Long term (1980-2007) average(m)	1980-1986 (average)	1987-1993 (average)	1994-2000 (average)	2001-2007 (average)	Reason for the fluctuation
1	Abaya	1.45958	0.699261 Below average	1.059803 Below average	2.613429 Above average	1.465826 Above average	Increased surface runoff, diversion or high groundwater inflow
2	Abiyata	4.283525	5.914493 Above average	3.860681 Below average	4.648305 Above average	2.710621 Below average	Large-scale abstraction of water
3	Hawassa	1.932398	1.272631 Below average	1.744318 Below average	2.476688 Above average	2.235955 Above average	Diversion from nearby water bodies, groundwater inflow
4	Chamo	1.265267	0.725389 Below average	1.743975 Above average	1.092512 Below average	1.49919 Above average	Questionable data
5	Langano	1.288435	1.069915 Below average	1.389686 Above average	1.55971 Above average	1.134429 Below average	Diversion and abstraction of water
6	Ziway	1.088393	0.934722 Below average	1.064988 Below average	1.244583 Above average	1.10928 Above average	Questionable data

The seven years averages are compared with the long term averages to see the pattern of fluctuation with time and also to compare the water levels in the last seven years with the long term averages.

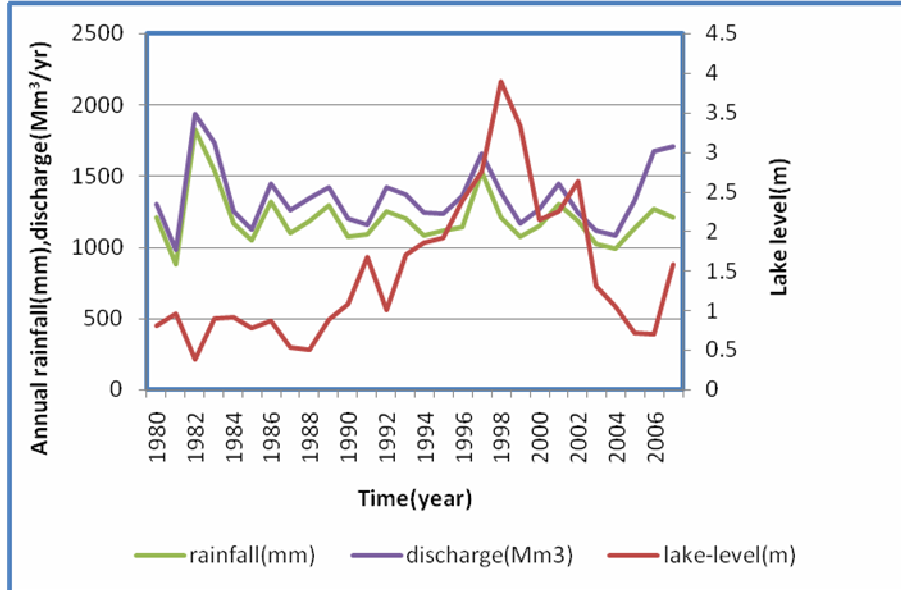


Figure 16. Yearly trends of lake level, rainfall and discharge (Lake Abaya)

We can see from Figure 6 that the rainfall and the discharge corresponding to Lake Abaya seem to have approximate constant trends. Regarding Lakes Abiyata, Langano and Ziway, the rainfalls and the discharges show increasing trends between 1980 and 1998, decreasing trend between 1998 and 2004. These rising and declining trends seem to cancel each other resulting in an overall constant trend.

Concerning Lake Hawassa, the rainfalls show approximate constant trends while the discharges display rising trends which are in agreement with the results obtained using the correlations and least squares regressions. For Lake Chamo, the rainfalls show approximate constant trends like Lake Abaya and the discharges follow rising trends which are in line with the lake levels. Regarding the lake levels, the results obtained from satellite image analysis show contrasting trends. This difference can be due to questionable water level data.

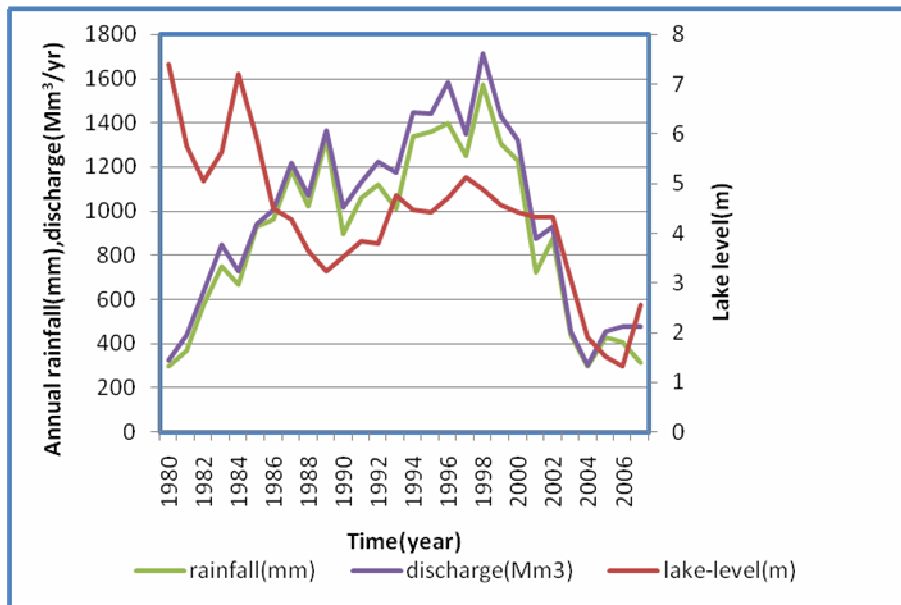


Figure 17. yearly trends of lake level, rainfall and discharge (Lake Abiyata)

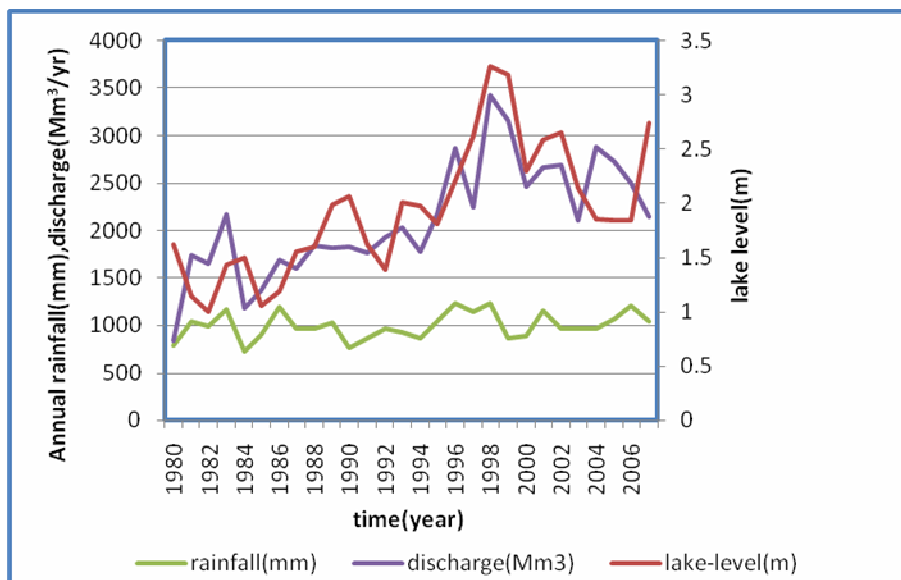


Figure 18. Yearly trends of lake level, rainfall and discharge (Lake Hawassa)

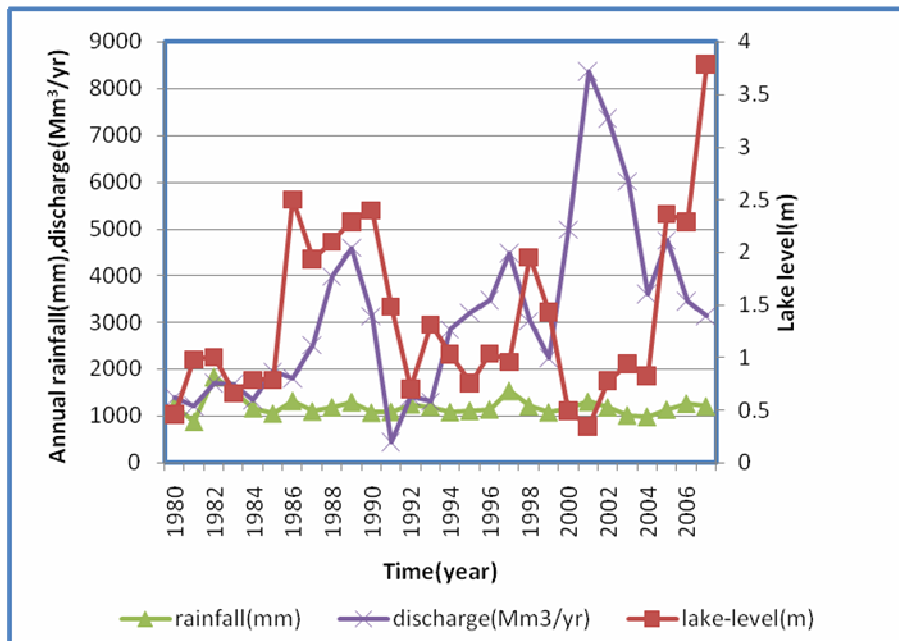


Figure 19. Yearly trends of lake level, rainfall and discharge (Lake Chamo)

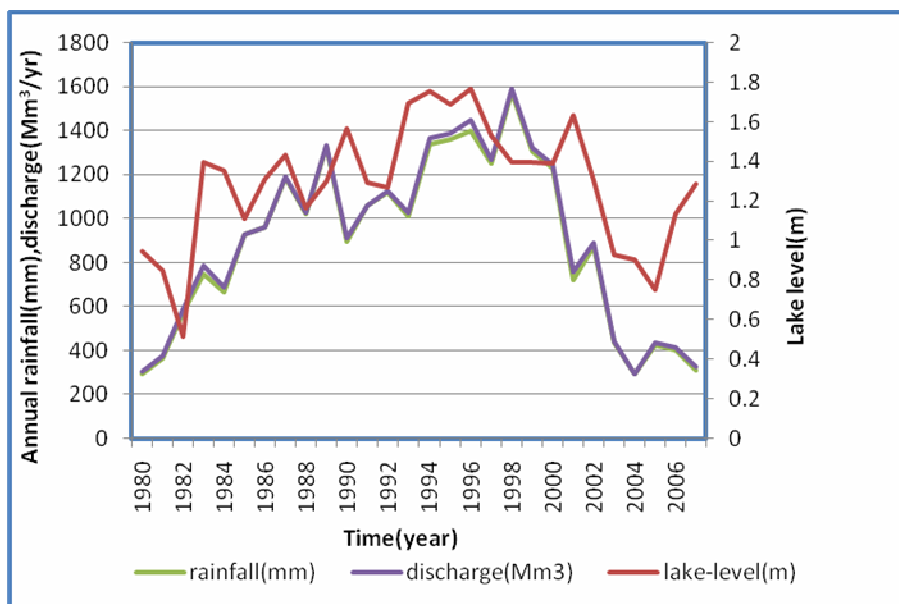


Figure 20. Yearly trends of lake level, rainfall and discharge (Lake Langano)

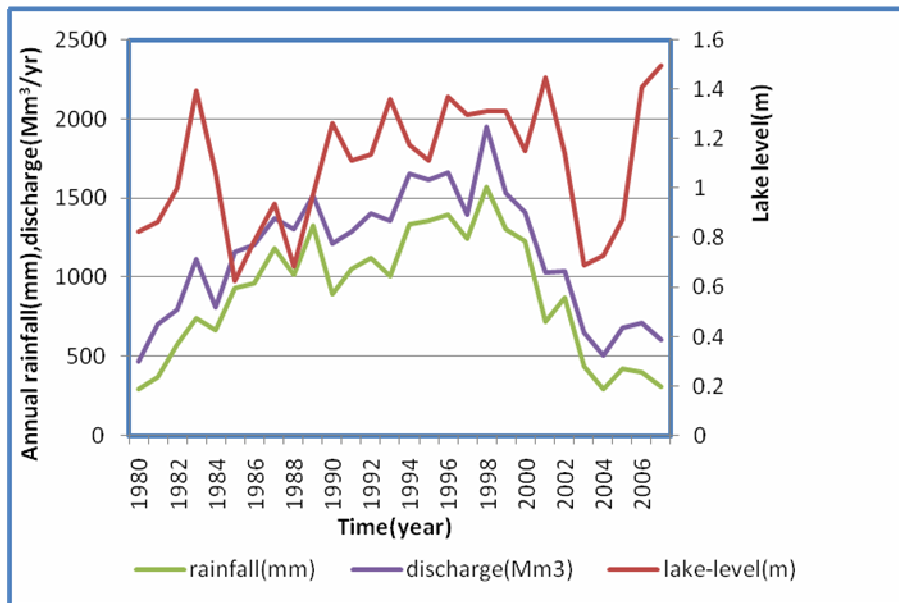


Figure 21. Yearly trends of lake level, rainfall and discharge (Lake Ziway)

Figure 22 and 23 show the evaporation trends in the Lakes Abaya, Chamo and Hawassa. There is a rising trend in the Lakes Abaya and Chamo and decreasing trend in Lake Hawassa. One reason for the rising trend in the level of Hawassa is the decreasing trends in the lake evaporation. The rising evaporation trends for Lake Chamo can be one reason that led to the declining water level trends in the lake.

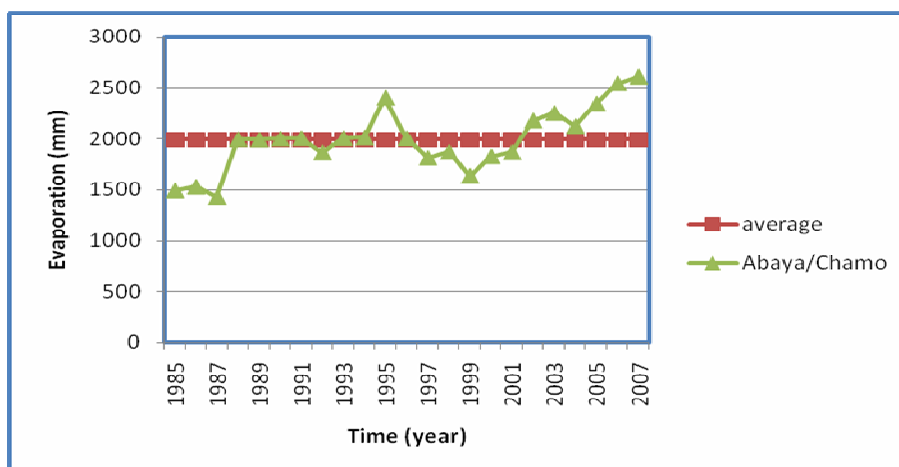


Figure 22. Evaporation trends in the Lake Abaya/Chamo

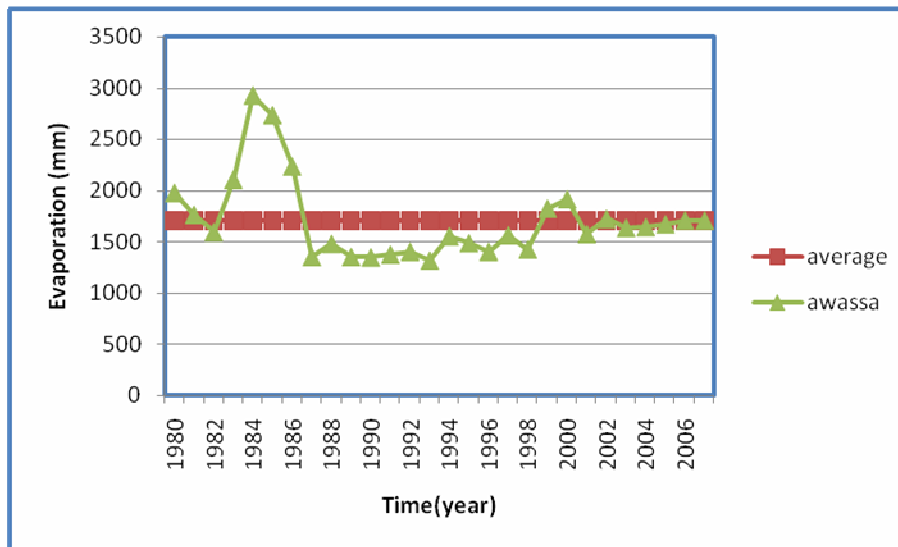


Figure 23. Evaporation trends in the Lake Hawassa

5.5 Analysis of multi-temporal satellite images of the lakes

The analysis of the Land sat images (with acquisition years: 1986, 2000 and 2010) indicated that Abiyata, Chamo, Ziway and Langano are declining while Hawassa and Abaya are rising. The decline of Abiyata is very drastic (nearly 28% of its area in 1986) and the decline of Chamo is about 11% of its area in 1986. Table 8 summarizes the fluctuation in the size (area) of the lakes under consideration.

Table 9. Areas of the lakes (km²) from Land Sat images

Lake name	Year			Change (%) b/n 1986 & 2010
	1986 (jan-21)	2000 (jan-05)	2010 (jan-31)	
Abaya	1102	1111	1111	+0.8 → Rising Trend
Abiyata	162	164	117	-27.8 → Declining Trend
Hawassa	91	96	94	+3.3 → Rising Trend
Chamo	331	312	295	-10.9 → Declining Trend
Langano	229	228	224	-2.2 → Declining Trend
Ziway	424	420	412	-2.8 → Declining Trend

Note:-acquisition dates are given in the brackets

The reductions in the sizes of Lakes Abiyata and Chamo are shown pictorially in figure 24 and figure 25 respectively. The size of Lake Hawassa has increased by 3.3% of its area in 1986. This is pictorially shown in Figure 26. The following three figures are created by overlapping the lake images corresponding to 1986, 2000 and 2010.

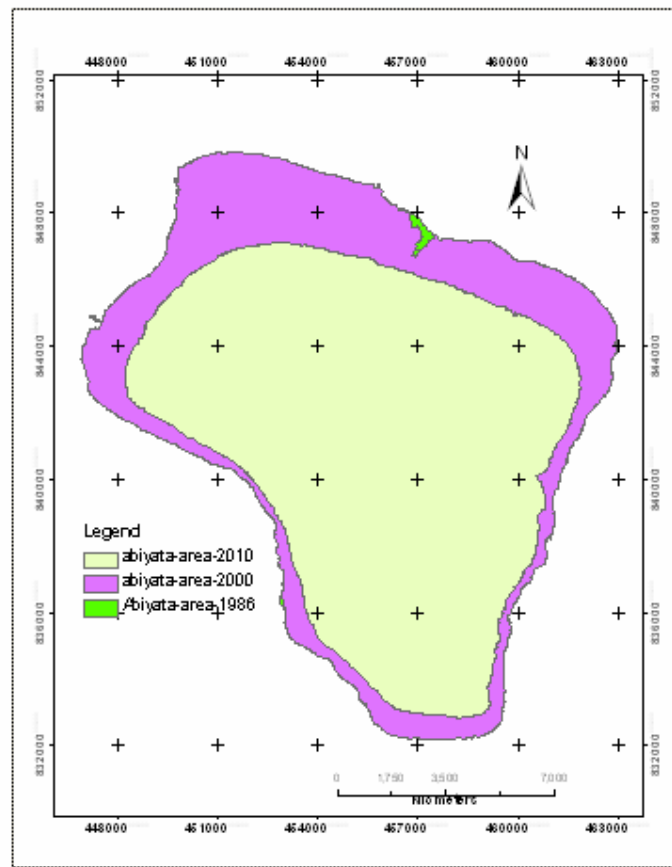


Figure 24. The size of Lake Abiyata during 1986, 2000 and 2010

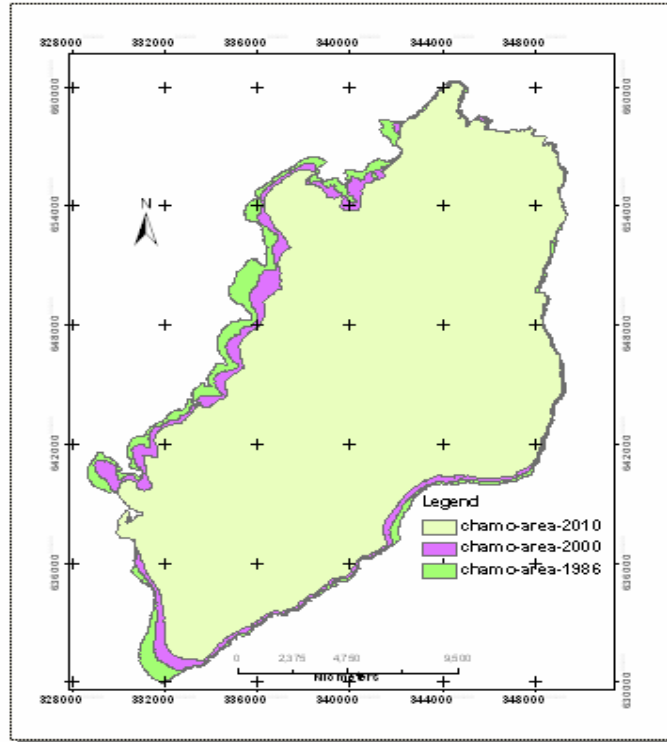


Figure 25. The size of Lake Chamo during 1986, 2000 and 2010

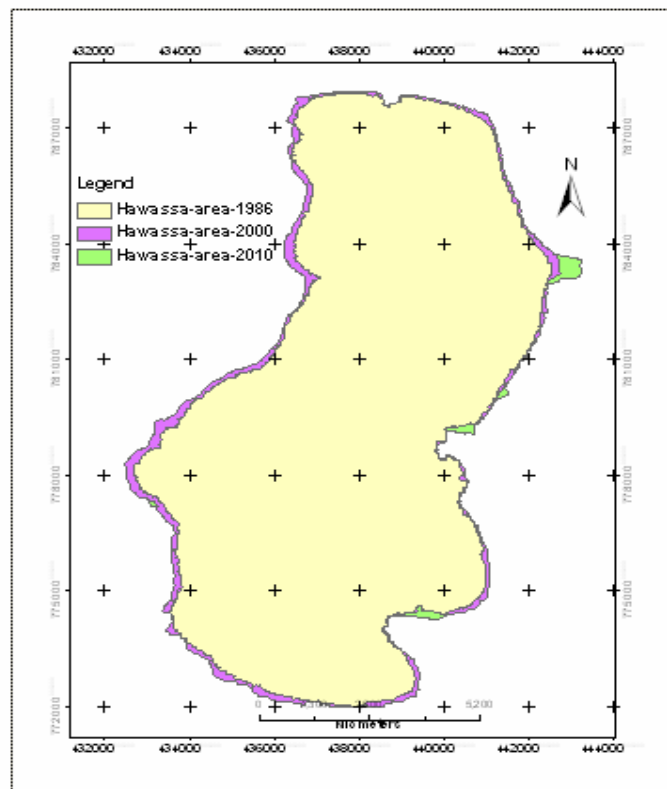


Figure 26. The size of Lake Hawassa during 1986, 2000 and 2010

5.6 Analysis of land use/cover changes in the Rift Valley Basin

The lakes under consideration are included in the Rift Valley Basin. The major land use/cover types in the basin are indicated in Table 10. Figures 17 and 18 show the change in the land use/cover of the basin and the quantitative description is summarized in Table 10. Cultivated land and bareland have been increased by 90% and 75%, vegetation cover and grassland have been decreased by about 80% and 68% respectively between 1997 and 2008. This could imply slight rise in the level of the lakes. However, other factors also contributing to the fluctuations and the levels are actually declining except for Lakes Abaya and Hawassa.

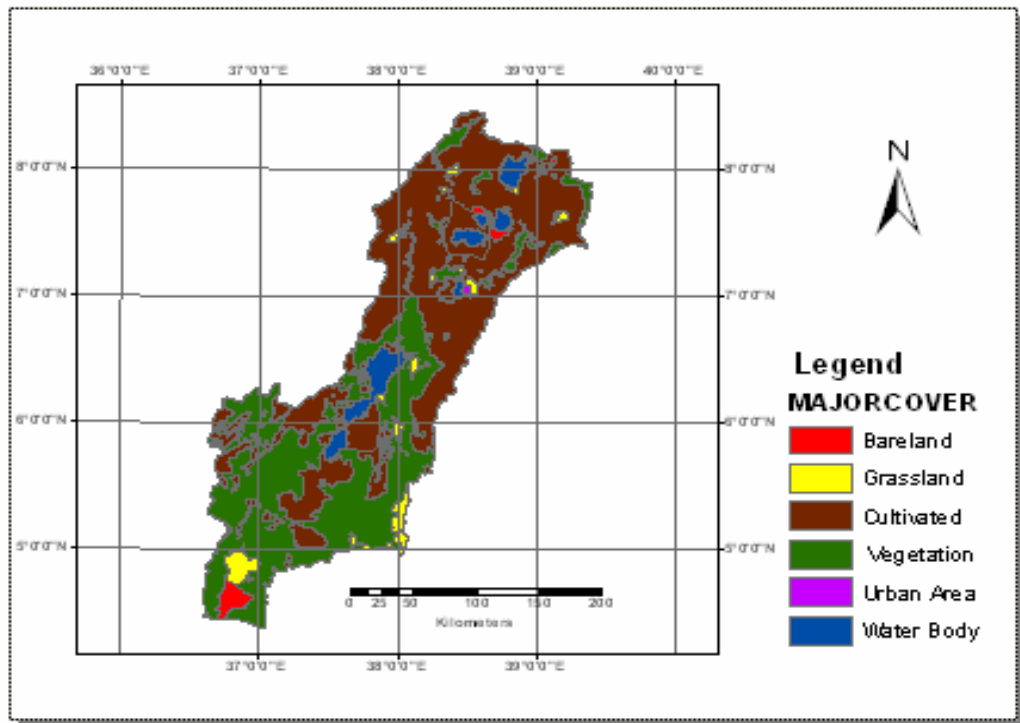


Figure 27. Land use land cover map of the Rift Valley Basin (FAO, 1997)

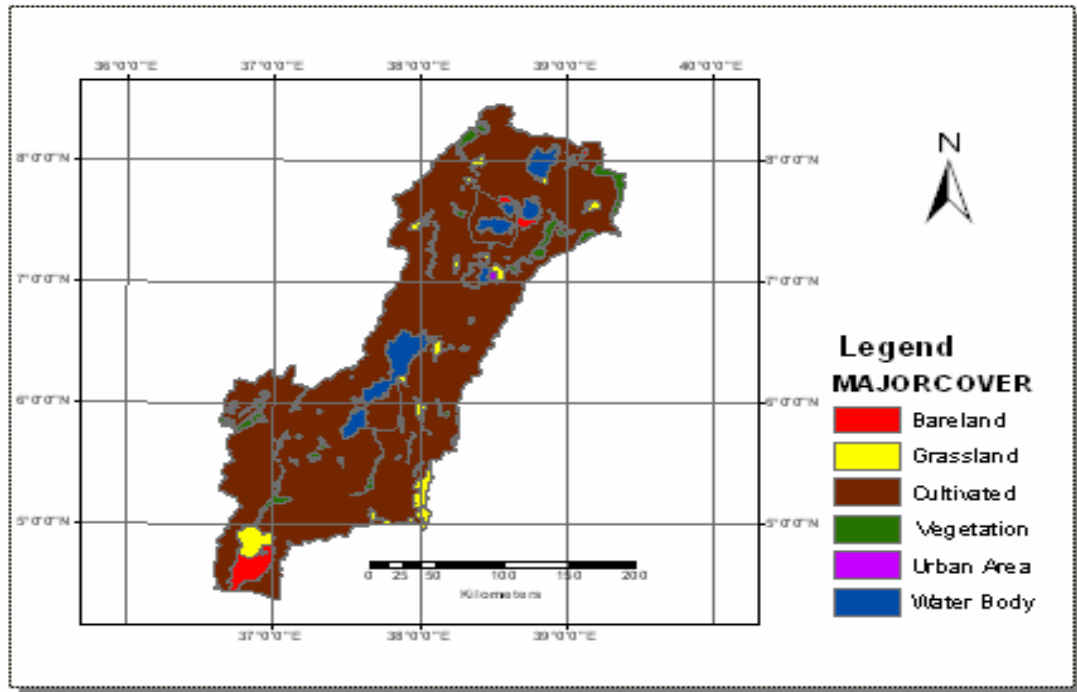


Figure 28. Land use land cover map of the Rift Valley Basin

Source: Ministry of Water Resources (2008)

Table 10. Change in area (km²) of the land use/cover types for the Rift Valley Basin

No	Land use type	Data From FAO (1997)		Data From Ministry of Water Resources (2008)		Change (%)
		Value(km ²)	%	Value(km ²)	%	
1	Cultivated land	22938	43.25	43796	82.58	+90.94
2	Vegetation	20772	39.18	4142	7.81	-80.07
3	Grassland	6291	11.86	1596	3.00	-67.76
4	Water body	3023	5.70	2619	4.94	-0.13
5	Bareland	9	0.02	808	1.52	+75
6	Urban area	1	0.002	73	0.14	+69
	total	53034	100	53034	100	

Table 10 shows how fast the vegetation is being depleted in the basin which can result in a slight rise in the lake levels.

5.7 Synthesis

The results of the correlations and least squares regressions indicated that lake level fluctuations are not associated with rainfall variability for most of the studied lakes (except Langano). The reasons for these weak associations can be time lags between rainfall events and lake level fluctuations, less realistic lake level or rainfall data (few rainfall stations available near the lakes), and dominant anthropogenic contributions to lake level fluctuations among many others.

The associations of the lake levels with the river discharges are significant only for Lakes Hawassa, Langano and Ziway. According to the study made by Tenalem Ayenew (2006), the level of Hawassa is rising (increased discharge) due to neotectonism and considerable deforestation of the lake basin which in turn resulted in increased surface runoff. The change in land use in the Rift Valley Basin, as summarized in Table 10, also confirms this result. The decline in the water level of Lake Ziway can be attributed to the large-scale abstraction of water for irrigation (Tenalem Ayenew et al., 2006; Huib and Herco, 2006) and the decline in the level of Lake Langano can be related to the decrease in discharge caused by neotectonic activities and diversion of the tributary rivers in the Arsi Highlands for small scale irrigation (Tenalem Ayenew, 2009) in addition to the slight decline in average annual rainfalls (after 1998) as indicated in figure 20.

The fluctuation (decline) in the water level of Lake Abiyata is not significantly associated with rainfall and discharge variability indicating extremely high anthropogenic contributions (large-scale abstraction of water for soda ash extraction and diversion of the tributary rivers for irrigation). The level of the lake showed a declining trend between 1980 and 1998 while the rainfall and discharge showed increasing trends during the same period of time. This clearly shows very significant anthropogenic contributions towards the shrinking of the lake. As indicated in Figure 17,

the rainfall and the discharge show declining trends between 1998 and 2004. This situation, together with the large-scale abstraction of water, resulted in serious decline in the level of Lake Abiyata. Other reasons for the decline may include the increased evaporation rates (although there are no sufficient evaporation data) and the decrease in overflow from Lake Ziway (Tenalem Ayenew, 2004; Huib and Herco, 2006).

The decline in the level of Lake Chamo can be connected to the increase in evaporation rates and may be to the diversion of Feeder Rivers for irrigation. Another possible reason may be due to groundwater outflow from the lake to the surrounding aquifers. This reason seems realistic since the lake water is more saline as compared to that of Lake Abaya.

The slight rise in the level of Lake Abaya can be related to very high groundwater inflow from the surrounding aquifers (Tenalem Ayenew, 2009) and may be to considerable deforestation of the lake catchment leading to increased sedimentation and siltation. This is evidenced by the different color in the northern portion of the image of the lake. The following Table summarizes the most significant factors that led to the lake level fluctuations.

Table11. Ordering the hydrometeorological, geological and anthropogenic factors

Lake	Most significant factor for lake level fluctuation.
Abaya	Groundwater inflow, evaporation, sedimentation and siltation (Land use change)
Abiyata	Abstraction of water, evaporation, decreased overflow from Lake Ziway
Hawassa	Increased discharge due to neotectonic activities and land use changes, evaporation
Chamo	Evaporation, diversion of feeder rivers, groundwater outflow
Langano	Rainfall, river discharge, diversion of tributary rivers, neotectonic activities
Ziway	Abstraction of water, river discharge

6. Conclusions and recommendations

6.1 Conclusions

The results of the study revealed that much of the fluctuations in the lake water levels are caused by human activities especially for the lakes in the Central Ethiopian Rift (CER).

Lakes Abiyata, Chamo, Ziway and Langano are declining while Abaya and Hawassa are rising. This is also confirmed by the long-term average annual water balance of the studied lakes as indicated in Table 3, except for Lake Langano with a positive difference between inflows and outflows.

Among the studied lakes, Abiyata is drastically reduced in size (about 28% of its area in 1986) due to both human activities (most dominant ones) and natural factors. The other seriously affected lake is Chamo with about 11% reduction in its area between 1986 and 2010.

Lake Abaya was found to be relatively stable during the indicated period (showed only a 0.8% increase in its area).

As indicated in Table 3, groundwater flow into Lake Abaya is very high and the flow into Lake Chamo is high. Regarding Lake Abaya, surface water and groundwater flow into the lake exceeds the increase in evaporation rates plus the effects of anthropogenic factors (the variation of rainfall and discharge being negligible) leading to the slight rise in the level of the lake. As to Lake Chamo, the increases in the lake evaporation rates plus abstraction of water dominate the groundwater inflow which resulted in the decreasing trend of the level of the lake.

Lake Hawassa is rising due to the increased discharge and slight decline in evaporation. About 59% of the variation in the lake level is due to the

variation in the discharge and about 14% of the variation is due to the variation in evaporation rates.

The water level of Lake Abiyata is declining drastically due to large scale-water abstraction, decreased inflow from Ziway and increased evaporation. The significant association of the level of Lake Abiyata with evaporation seems to be realistic since the lake is closed from surface water point of view and is located at a terminal position in the CER.

The size of Lake Ziway is also reduced slightly due to abstraction of water for irrigation and the variation in discharge (about 16% of the lake level fluctuation is due to the variation in the river discharge). The lake level does not associate significantly to rainfall and evaporation indicating considerable anthropogenic contributions to the level fluctuation.

The size of Lake Langano is reduced slightly. The lake level is associated with rainfall and river discharge. About 61% of the lake level fluctuation is caused by the variation in both rainfall and discharge. This comparatively large value could imply relatively less (as compared to the other lakes in the CER) man-induced contributions to the fluctuation in the level of Lake Langano.

The lakes under consideration in order of decreasing magnitude of the degree of fluctuation are: Abiyata, Chamo, Hawassa, Ziway, Langano and Abaya.

6.2 Recommendations

- Concerned bodies need to work in harmony to manage water use in the Ethiopian Rift Valley lakes, particularly Abiyata and Chamo.
- Since Lake Abiyata is seriously affected, special attention is needed to replenish the water in the lake by controlling the use of water and save the lives of many endemic animals including the flora and fauna.

- Further studies need to be made on the Ethiopian Rift Lakes to accurately identify the prevailing factors that are causing lake water level fluctuations, especially in the Lake Abaya-Chamo Basin.

- Educations on the consequences of excess water use and on how to protect the water resources need to be given to some representatives of the community living around the lakes.

7. References

Alexander,S. and Habteselassie Redeat (2010). Fish faunas of the Chamo-Abaya and Chew Bahir basins in southern portion of the Ethiopian Rift Valley: origin and prospects for survival, Aquatic Ecosystem Health & Management. Russian Academy of Sciences, Institute of Ecology and Evolution, Moscow.

URL: <http://dx.doi.org/10.1080/14634980903578506>

Azeb Belete (2009). Climate Change Impact on Lake Abaya Water Level. Unpublished MSc. Thesis, Addis Ababa University, Addis Ababa.

Ebrahim Esa (2008). Analysis of the Impacts of Soda Ash Mining on Abiyata and Shalla Lakes Subwatershed: The Main Ethiopian Rift System. Unpublished MSc. Thesis, Addis Ababa University, Addis Ababa.

Grove, A.T., Alayne, F.S. and Goudie, A.S.(1975). *Former Lake levels and climatic changes in the rift valley of Southern Ethiopia. The Geographical Journal*, **141**:177-194. Blackwell Publishing, England.

URL: <http://www.jstor.org/stable/1797205>

Habtom Gebremichael (2007). Modeling and Forcasting Hawassa Lake Level Fluctuation. Unpublished MSc. Thesis, Addis Ababa University, Addis Ababa.

Heathwaite, A. L. and Burt, T.P. (1991). Predicting the Effect of Land Use on Stream Water Quality in the Uk. University of Sheffield, Department of Geography, Uk.

Huib, H. and Herco, J. (2006). *Agricultural development in the Central Ethiopian Rift valley: A desk-study on water-related issues and knowledge to support a policy dialogue*. Plant Research

International B.V., Wageningen, the Netherlands. URL:
<http://www.ewnhs.org.et/Agr.%20Dev%20in%20CRV-WUR%20Feb%2006.pdf>

Keddy, P.A. and Reznicek, A.A.(1986). Great Lakes Vegetation Dynamics: The Role of Fluctuating Water Levels and Buried Seeds. Department of Biology, University of Ottawa, Ottawa.

Kinshiro, N. (1974). *Hydrological Regime on the Regulation of Lake-level, A Contribution to the Paleolimnological Study of Lake Biwa*. Department of Geophysics, faculty of Science, Hokkaido University, Hokkaido. URL:

http://www.journalarchive.jst.go.jp/english/jnlabstract_en.php?cdjournal=pjab1945&cdvol=50&noissue=9&startpage=665.

Murimi, S.K.(1994). *Falling Water-levels in Saline Lakes of the Central Rift Valley of Kenya: the case of Lake Elmenteita*. Geography Department, Kenyatta University, Nairobi. International Journal of Salt Lake Research **3**:65-74.

Niko, P. and Bardhyl, A.(2009). A Method to Estimate Buna River Discharge, Albania. Tirana University, Faculty of History, Philology and Geography, Tirana.

Qin, B.(1993).The Hydrological Characteristics and Water Budget of Qinghai Lake Drainage Basin, China. Nanjing Institute of Geography and Limnology, Academia, Sinica, Nanjing.

Ramsis, S., Elise, B., Daniel, P., Lorraine, B., John, B., Wayne, H., Gerald, W. and Greg, B.(2002). Hydrological Response Units of the Ord Stage I Irrigation Area and the Dynamic Filling of the Aquifers of the Ivanhoe and Packsaddle Plains. Technical Report 7/02, CSIRO Land and Water Private Bag No 5, Western Australia.

- Shewadeg Molla (2008). Decision Support Tool for Estimating Lake Water Balance with Particular Emphasis to Lake Abiyata. MSc Thesis, Addis Ababa University, Addis Ababa, Ethiopia.
- Sousounis, P.(2000). The Potential Impacts of Global Warming on the Great Lakes Region. University of Michigan and Patty Glick (National Wildlife Federation), Michigan. URL: <http://www.climatehotmap.org/impacts/greatlakes.html>
- Stefan, T. and Gerd, F. (2004). Water Resources Assessment in the Bilate River Catchment-Precipitation Variability. Lake Abaya Research Symposium 2004-Proceedings.URL: <http://www.koubou.com/keywords/MI>
- Susanne, B. and Brigitta, S. (2004).Character of Lake Floor Sediments From Central Lake Abaya, South Ethiopia. Lake Abaya Research Symposium-2004 Proceedings. URL: <http://www.uni-siegen.de/fb10/fwu/ww/publikationen/volume0405/blumberg.pdf>
- Tang, Z., Engel, B.A., Pijanowski, B.C. and Lim, K.J. (2004). Forecasting land use change and its environmental impact at a watershed scale. *Journal of Environmental Management*, Department of Agricultural and Biological Engineering, Purdue University, Purdue. URL: www.elsevier.com/locate/jnlabr/jenvman
- Tenalem Ayenew (1998). The hydrogeological system of the Lake District basin: Central Main Ethiopian Rift. Ph.D. Dissertation, Free University of Amsterdam, Amsterdam. URL: http://www.itia.n...sj_47_03_0493.pdf
- .(2002). Recent changes in the level of Lake Abiyata, central main Ethiopian Rift. Department of Geology and Geophysics, Addis Ababa University, Addis Ababa.URL: http://www.itia.ntua.gr/hsj/47/hysj_47_03_0493.pdf

-----.(2004).Environmental implications of changes in the levels of lakes in the Ethiopian Rift since 1970. Department of Geology and Geophysics, Addis Ababa University, Addis Ababa. URL: <http://www.springerlink.com/content/0xxwlxkaycvlyv4c/>

-----.(2006). Vulnerability of selected Ethiopian lakes to climatic variability, tectonism and water use. Global Change System for Analysis, Research and Training. URL: <http://start.org/download/gec05/ayenew-final.pdf>

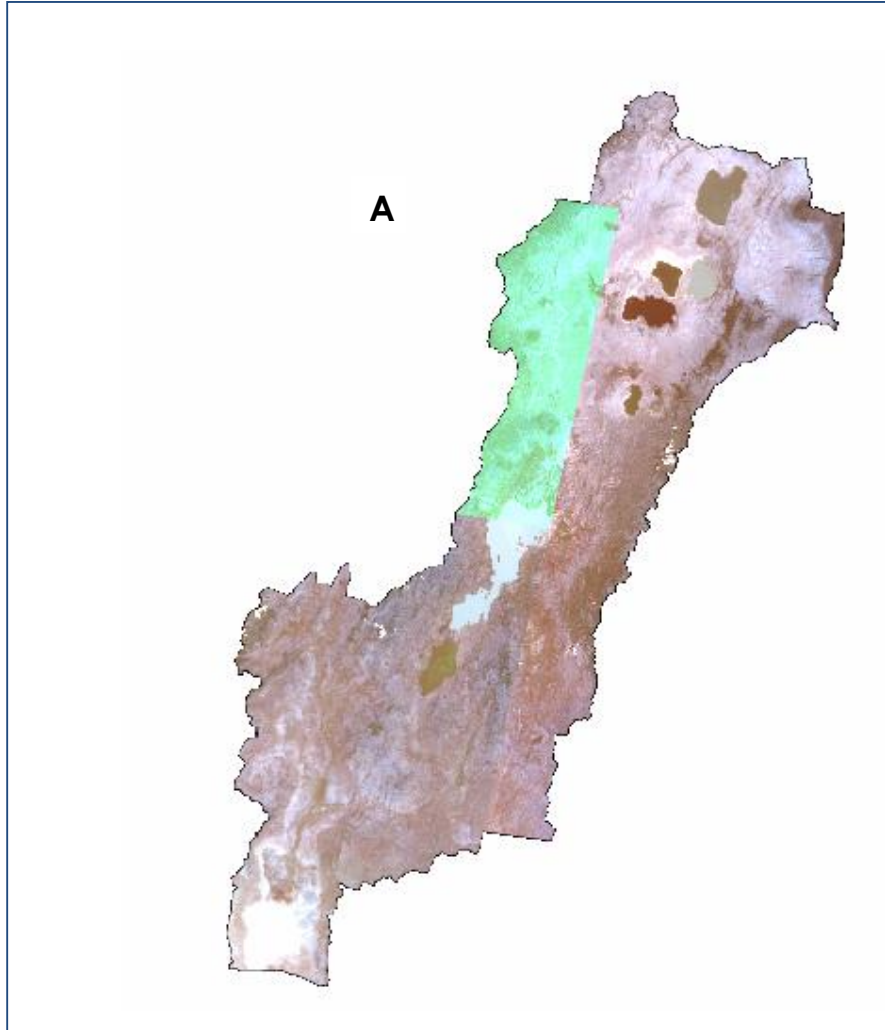
----- . (2009).*Natural Lakes Of Ethiopia*. Addis Ababa University Press, Addis Ababa.

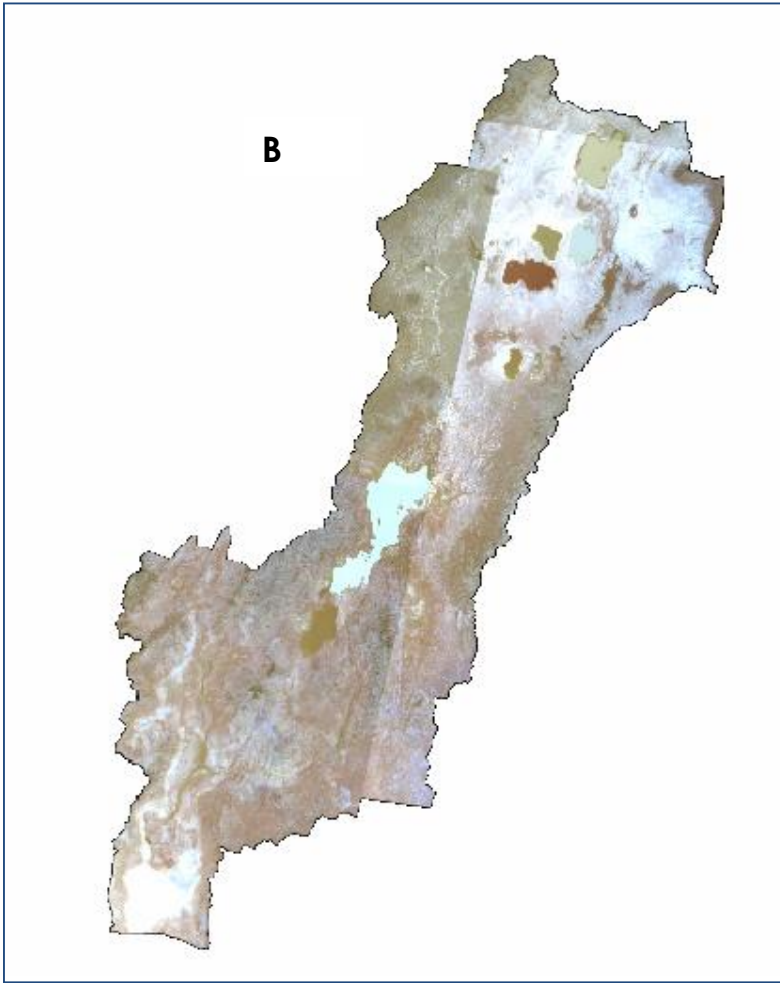
Tenalem Ayenew and Yemene Gebreegziabher (2006). Application of a spreadsheet hydrological model for computing the long-term water balance of Lake Hawassa, Ethiopia. Department of Earth Sciences, Addis Ababa University, Addis Ababa. URL: <http://www.informaworld.com/smpp/ftinterface~db=all~content=a918691315?tab=references>.

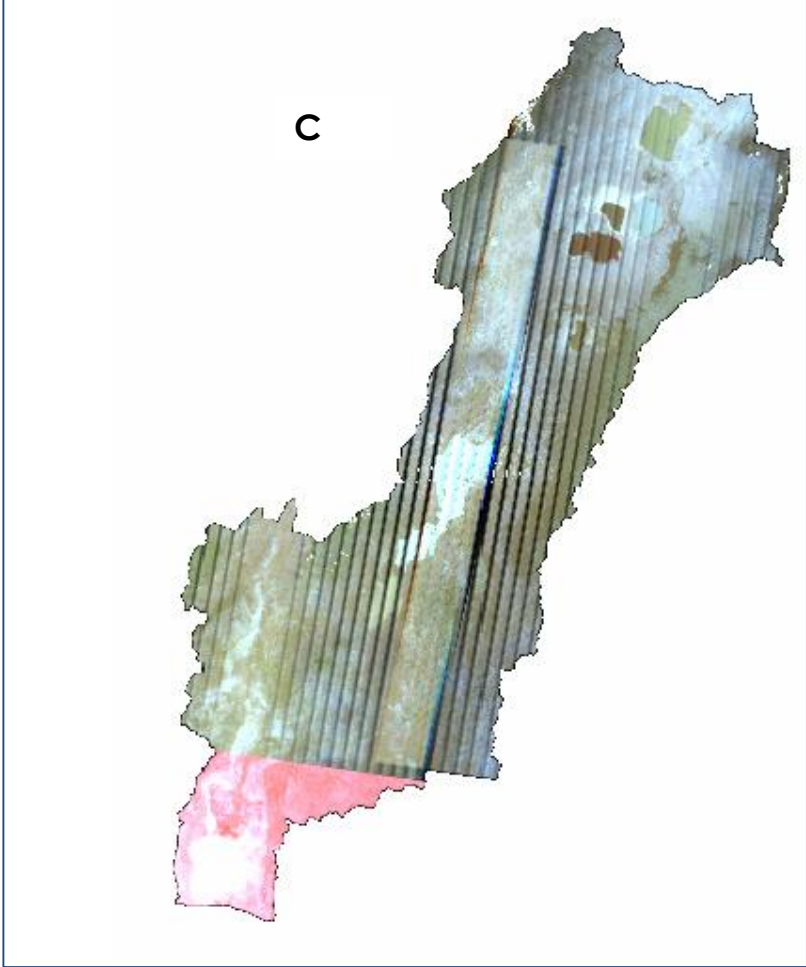
Thompson, F. and Turk, J. (2005).*Earth Science and the Environment, 3rd edition*. Books/Cole, a division of Thompson Learning Inc., 10 Davis Drive, Belmont.

URL: <http://www.climatehotmap.org/impacts/>

Appendix 1. Raw satellite images of the lakes acquired during 1986(A), 2000(B)and 2010(C)

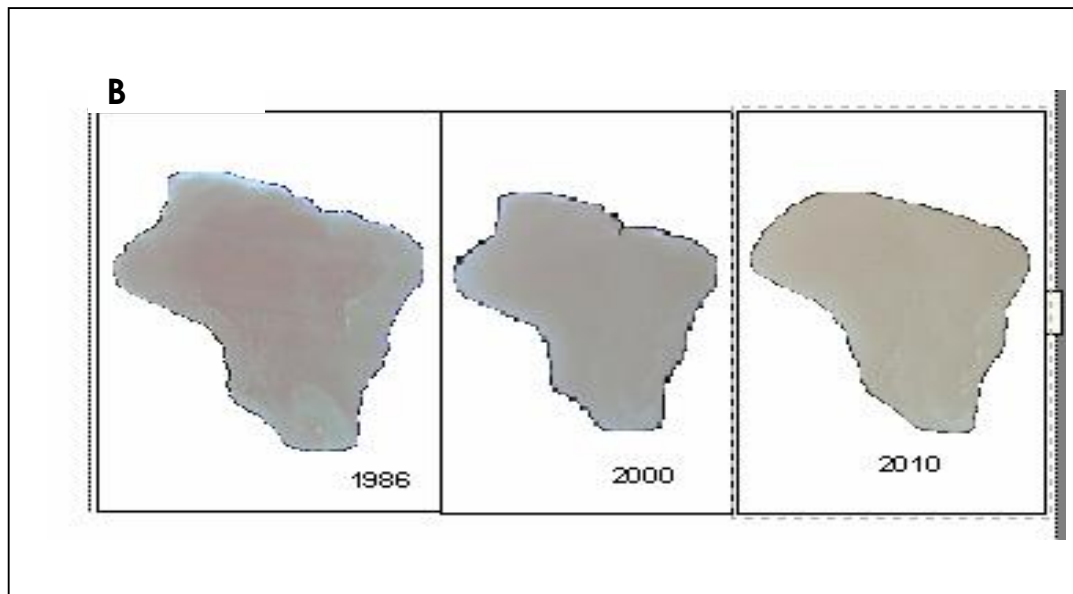
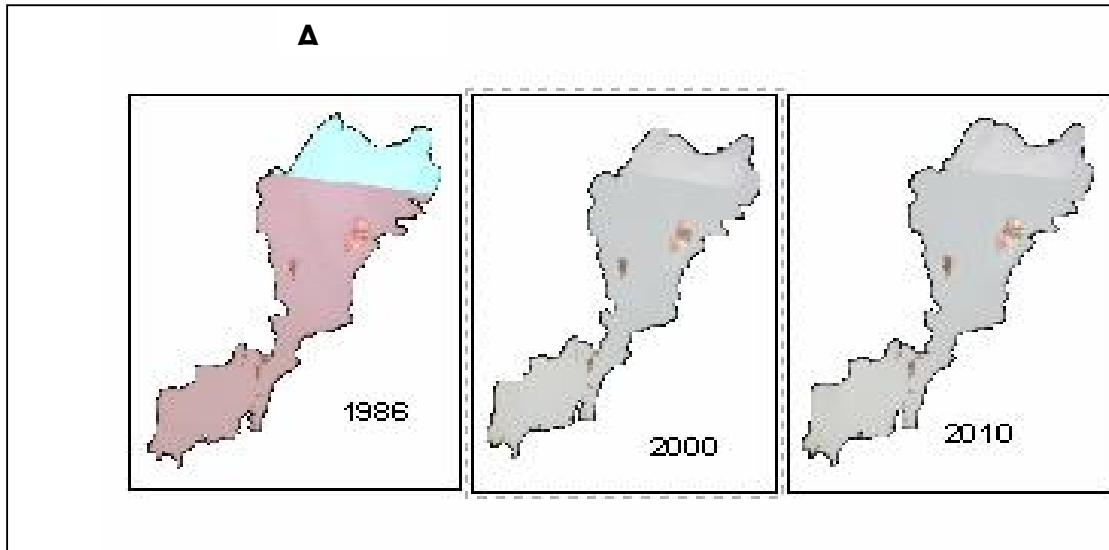


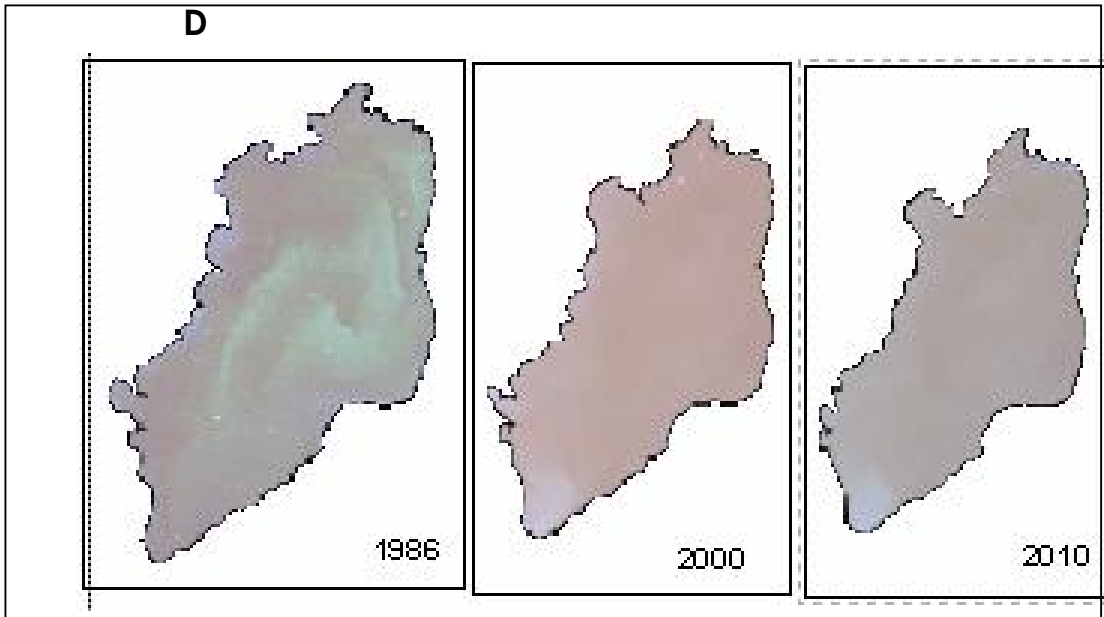
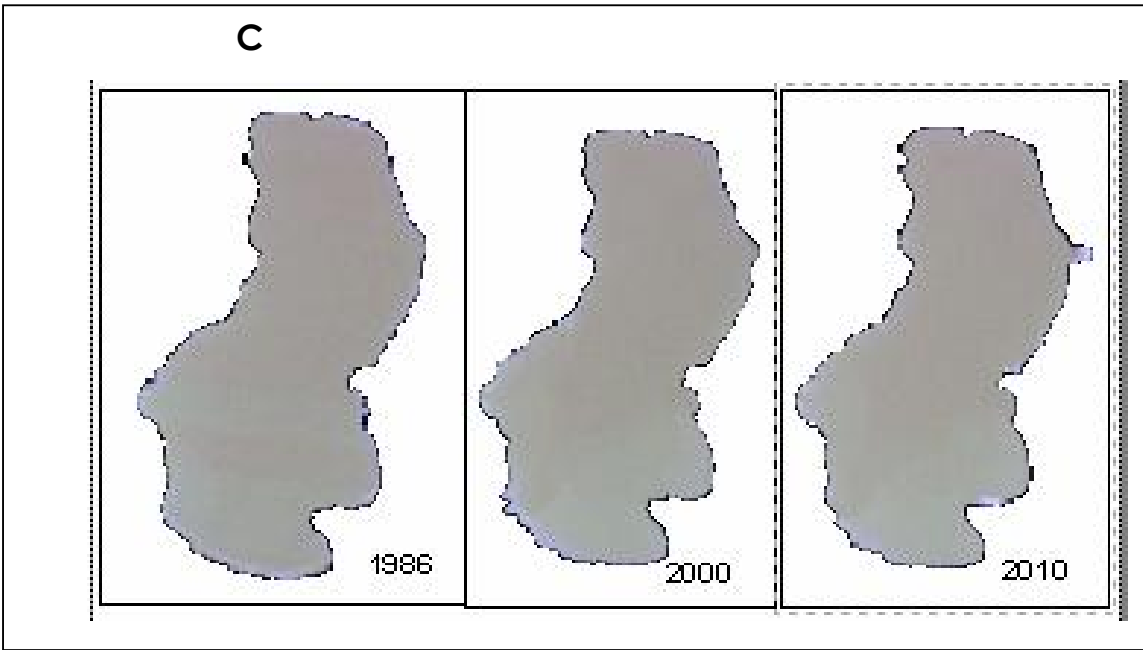




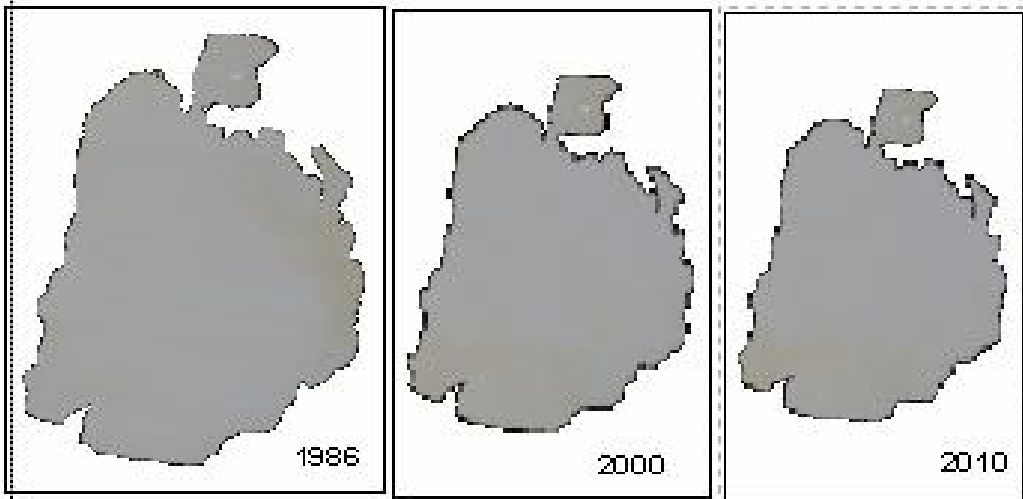
Appendix 2. Clipped satellite images of the lakes :

Abaya(A), Abiyata(B), Hawassa (C),Chamo(D),Langano(E),Ziway(F)

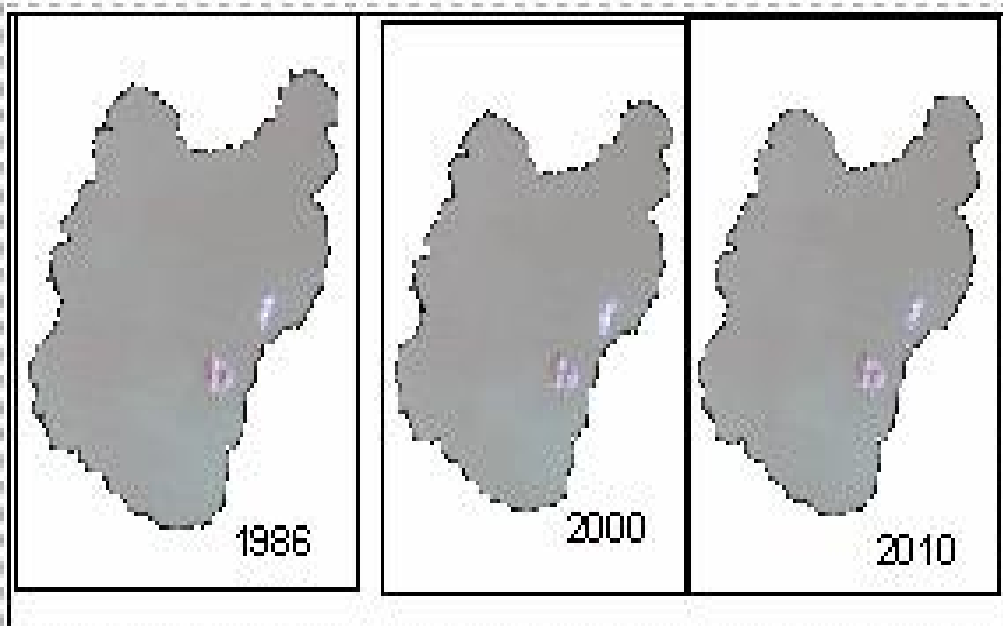




E



F



Appendix 3. Long-term average annual lake level(m)

year	Abaya	Abiyata	Hawassa	Chamo	Langano	Ziway
1980	0.812667	7.391	1.614583	0.45725	0.944	0.822333
1981	0.967445	5.74021	1.13625	0.980064	0.852427	0.859917
1982	0.387333	5.054919	0.99625	1.002578	0.515892	1.00075
1983	0.907417	5.635299	1.432583	0.659033	1.39697	1.3905
1984	0.918583	7.18975	1.498667	0.782878	1.35506	1.060083
1985	0.784551	5.907167	1.050417	0.783128	1.112969	0.624167
1986	0.867392	4.483107	1.179667	2.50025	1.312083	0.785301
1987	0.537333	4.275501	1.552333	1.931327	1.431535	0.935667
1988	0.512917	3.65185	1.600917	2.10125	1.167208	0.684083
1989	0.894	3.230083	1.987083	2.288083	1.29875	0.973583
1990	1.082833	3.513083	2.063083	2.396833	1.568917	1.259917
1991	1.676189	3.82525	1.614583	1.479172	1.295167	1.11125
1992	1.003417	3.776833	1.389309	0.700417	1.271583	1.133917
1993	1.711931	4.752167	2.002917	1.310743	1.694639	1.3565
1994	1.857417	4.45725	1.977417	1.030417	1.752167	1.174333
1995	1.915833	4.407417	1.807583	0.757	1.687333	1.111333
1996	2.384917	4.716667	2.202167	1.037333	1.76675	1.366583
1997	2.7635	5.109049	2.61475	0.954	1.529327	1.2955
1998	3.894833	4.878	3.262417	1.950167	1.394667	1.309167
1999	3.3305	4.554667	3.181167	1.42975	1.398917	1.307167
2000	2.147004	4.415083	2.291318	0.488917	1.38881	1.148
2001	2.248444	4.328083	2.585333	0.340083	1.63325	1.443917
2002	2.635167	4.316083	2.64625	0.777163	1.302583	1.137667
2003	1.318272	3.060833	2.143312	0.934711	0.931	0.687374
2004	1.051981	1.891333	1.849568	0.821033	0.904793	0.726167
2005	0.714167	1.5175	1.842583	2.361939	0.752313	0.86975
2006	0.705333	1.316917	1.843809	2.287844	1.132359	1.406083
2007	1.587417	2.543596	2.740833	3.790228	1.284707	1.494002

Appendix 4. Long-term average annual rainfall (mm)

year	Abaya	Abiyata	Hawassa	Chamo	Langano	Ziway
1980	1213.95	298.2716	784.4769	1213.95	298.2716	298.2716
1981	881.8	368.7841	1039.7	881.8	368.7841	368.7841
1982	1827.55	574.2165	991.6	1827.55	574.2165	574.2165
1983	1539.728	747.5045	1159.8	1539.728	747.5045	747.5045
1984	1168.802	669.1092	724.5	1168.802	669.1092	669.1092
1985	1054.085	930.6477	901.7	1054.085	930.6477	930.6477
1986	1323.97	962.1174	1192.1	1323.97	962.1174	962.1174
1987	1099.981	1182.853	958.7	1099.981	1182.853	1182.853
1988	1188.328	1019.722	957	1188.328	1019.722	1019.722
1989	1299.7	1326.555	1030.3	1299.7	1326.555	1326.555
1990	1074.6	897.9738	756.7	1074.6	897.9738	897.9738
1991	1091.629	1059.231	866.9	1091.629	1059.231	1059.231
1992	1252.376	1121.026	962.3	1252.376	1121.026	1121.026
1993	1199.826	1009.818	928.4	1199.826	1009.818	1009.818
1994	1086.487	1336.369	861.5	1086.487	1336.369	1336.369
1995	1116.6	1357.474	1034.436	1116.6	1357.474	1357.474
1996	1142.616	1394.863	1224.628	1142.616	1394.863	1394.863
1997	1535.559	1248.317	1144.679	1535.559	1248.317	1248.317
1998	1212.307	1571.421	1226.6	1212.307	1571.421	1571.421
1999	1078.622	1305.983	862.7	1078.622	1305.983	1305.983
2000	1154.51	1228.497	882.5	1154.51	1228.497	1228.497
2001	1303.875	722.8243	1156.25	1303.875	722.8243	722.8243
2002	1186.825	876.358	959.1	1186.825	876.358	876.358
2003	1021.205	441.0286	967.1	1021.205	441.0286	441.0286
2004	989.221	296.6966	964.4	989.221	296.6966	296.6966
2005	1137.237	427.0536	1067	1137.237	427.0536	427.0536
2006	1266.813	405.0473	1199.236	1266.813	405.0473	405.0473
2007	1209.363	312.0212	1032.103	1209.363	312.0212	312.0212

Appendix 5. Long-term average annual discharge($1 \times 10^6 \text{m}^3$)

year	Abaya	Abiyata	Hawassa	Chamo	Langano	Ziway
1980	2671.56	773.2288	1607.82	41768.91	284.2556	5058.33
1981	2893.37	2016.025	20970.15	36364.71	324.5981	10133.09
1982	3265.634	1841.661	19583.76	51266.73	601.41	6597.9
1983	5831.49	3008.383	30456.6	50400.99	1302.21	11029.92
1984	2415.12	1779.87	13500.12	40336.04	582.66	4219.937
1985	2134.23	306.93	14113.65	58457.24	64.56	6768.724
1986	3715.08	1336.863	15037.04	54232.53	32.74875	7231.576
1987	4698.78	1037.696	19137.9	75611.4	311.5763	5745.197
1988	4568.88	1509.42	26585.64	119521.2	213.48	8561.01
1989	3471.87	1142.88	23564.13	137852.3	193.14	5788.53
1990	3772.92	3462.071	32208.18	94073.11	553.59	9359.193
1991	2061.33	2070.27	26884.38	13273.83	97.47	6868.83
1992	5125.92	3070.358	28942.29	42912.42	161.58	8357.675
1993	5028.78	4944.874	32903.28	39188.52	486.9638	10328.04
1994	4620.99	3347.929	27522.12	85612.23	982.0088	9644.656
1995	3532.47	2494.98	33898.71	96428.43	1022.61	7742.075
1996	6438.18	5610.668	49430.76	104203.6	1604.46	7945.642
1997	3549.6	2956.089	33070.47	134447.7	545.6494	4483.524
1998	5067.6	4231.62	65936.22	90998.16	587.49	11396.34
1999	2695.95	3723.716	68786.67	67561.17	558.1163	6756.78
2000	3470.76	2679.758	47194.95	149467.6	615.4875	5485.2
2001	4158.48	4520.82	45090.84	250995.5	1196.1	9135.143
2002	1573.95	1483.41	51745.38	220725.8	450.9	4825.89
2003	2670.93	342.9	34108.19	180165.8	93.99	6286.746
2004	2723	164.67	57354.37	108425.9	4.74	6274.898
2005	5540.37	895.92	49733.19	142567.6	309.24	7638.192
2006	12115.53	2175.548	39104.09	103662.3	429.9975	9143.608
2007	14822.7	4882.689	33168.14	94073.11	458.3794	8868.515

Appendix 6. Monthly Lake Evaporation Data(mm):

Hawassa(A);Abaya and Chamo(B); Abiyata, Langano and Ziway(C)

A

year	i	ii	iii	iv	v	vi	vii	viii	ix	x	xi	xii
1980	229.5	242.5	227	180.6	141.6	124.3	98.2	107.1	103.9	156.1	158.8	209.1
1981	289.5	235.2	126.5	87.1	116.6	126.5	92.6	87.1	69.4	126	175.5	231.8
1982	173.1	182	268.5	108	127.2	110.2	93.9	108.4	91.4	107.7	96.6	128.1
1983	181.2	192.3	252.6	146	118.5	134.6	141.1	125.3	142.7	172	227.6	270.9
1984	340.6	370.2	396.9	379	201.2	233.1	186.8	155.2	123	117.38	242.3	182
1985	352.8	364.8	397.6	148.6	166.8	111.4	130	161.3	127.5	203.9	245.4	324.3
1986	327.1	327.1	290.2	151.2	153.6	114.6	136.7	141.9	122.1	144.9	176.8	148.5
1987	173.3	170.2	97.2	83.7	78.7	80.6	87.2	86.5	86.2	88.5	140.4	181.5
1988	160.3	164.8	219.7	127.1	123.1	96.5	67	66.6	64.7	77.2	139.9	173.8
1989	169.7	143.2	159.9	89.1	121.2	92.2	77	85.8	62.8	108	138.9	104.7
1990	151.9	96.7	85.8	94	77.4	117.4	95.2	84.7	83	123.5	160.8	178.2
1991	174.5	121.1	126.9	119.5	88.9	86.1	69.4	73.3	69.6	120	172.9	153.7
1992	164.4	121.5	178.1	142	105	114.3	86.4	74.8	67.8	82.2	126.5	141.5
1993	125.1	91.9	190	101.5	77.1	82.6	94.8	82	71.4	93.5	135.6	171.3
1994	216.6	190.3	166.1	139.7	84.6	89.9	69.2	76.5	74.1	137	146.2	165.4
1995	197	172	149.4	99.8	120.2	119.5	77.2	80.6	72.3	111.6	142.3	145.6
1996	119.6	178.1	119.2	91	79.5	77.1	88.7	84.1	71.3	122.9	169.8	202.1
1997	184.4	234.5	197.1	93.3	126.7	97.4	95.2	99.6	101.2	103.2	90.1	143.2
1998	120	119	126.3	143.6	102.7	116.5	97.3	91.8	80.1	75.4	146.1	207.1
1999	282.9	251.9	142	145.9	133.4	129.2	96.7	106.2	92.4	86.7	166.7	189.9
2000	247.8	287.8	293.1	156	104.6	130.4	104.6	104.2	83.7	86.6	135.3	181.3
2001	201.4	189.7	140.3	117.5	108.7	93.6	85.2	96.3	77.5	99.2	170.6	195.2
2002	174.2	216.4	126.8	133.6	143.5	102.8	165.5	91	85.5	124.8	211	148.5
2003	173.5	205.7	187.9	122.9	120.4	97	77.5	87.2	75.2	130.8	187.4	171.9
2004	162.7	172.8	208.6	98.7	139.3	117.8	100	97.1	73.9	140.2	166.5	167.2
2005	183.4	209.5	150	158.5	77.5	99.8	94	118	91.4	112.7	161.4	216
2006	202.9	202	193.2	133	116.8	111.4	100.3	98.95	87.08	117.38	162.75	182
2007	202.9	202	193.2	133	116.8	111.4	100.3	98.95	87.08	117.38	162.75	182

B

year	i	ii	iii	iv	v	vi	vii	viii	ix	x	xi	xii
1985	208.3	191.4	186.8	139.4	131.6	137.6	137.9	154.8	160	200.5	2002.9	237.3
1986	265.1	238	255	155.5	165.1	97.4	162.8	194.2	164.4	157.8	157	141
1987	250.7	241.3	82.9	141.4	129.9	152.8	208.7	290.8	263.8	181.3	196.2	239
1988	259.9	301.1	314.8	184.5	142.8	156.9	121.4	119.6	121.5	121.7	163	217.4
1997	185	294.2	284	120.9	114.7	117.8	106.6	138.7	144.9	121.75	228.06	122.4
1998	111.2	117.2	156	145.6	102.1	113.3	101.8	100	134.4	83.6	143.3	221.1
1999	219.8	262.4	157	139.2	120.5	146.2	99.05	134.4	131.9	99.25	172.55	188.2
2000	262.6	279.4	290.1	195.9	112.8	119.5	123.5	119	117.7	94.3	123.65	157.5
2001	145.8	174.5	146	132.4	81.55	80.95	100.5	92.7	98.7	111.6	149.4	180.4
2002	152.9	218.5	166.9	143.2	103.9	109.4	115.1	118.1	128	140.79	259.56	158.2
2003	169.4	195.9	193.5	131.2	130.3	109.4	98.07	113.4	114.5	146.99	247.56	176.8
2004	154.8	169	203.1	144.5	129	123.2	118.7	111.7	112.2	140.4	127	103.2
2005	174.5	225.7	184.8	163.4	83.65	104.9	115.8	139.4	116.7	139	180.65	240.3

C

year	i	ii	iii	iv	v	vi	vii	viii	ix	x	xi	xii
2001	168	223.1	99.3	120.7	117.9	67.6	63	53.5	97.3	117.6	151.9	178.6
2002	182.2	249.6	130.5	120.4	157.6	91.9	80.9	62.5	102.8	136.6	189.6	109.4
2003	160.4	207.5	232	144.8	182.5	102.2	43.6	52.5	75.1	125.9	166.1	162.6
2004	161.5	212.3	171.9	73.6	181.3	88.7	44.4	56.17	91.73	96.8	112	131

D E C L A R A T I O N

I hereby declare that the thesis entitled "**Hydrodynamics of selected Ethiopian Rift Lakes**" has been carried out by me under the supervision of Prof. Tenalem Ayenev Department of Earth Sciences, Addis Ababa University, Addis Ababa during the year 2010 as a part of Master of Science program in Computational Science. I further declare that this work has not been submitted to any other University or Institution for the award of any degree or diploma.

Kassaye Bewketu Zellelew

Signature: _____

Place: Addis Ababa

Date: June, 2010

CERTIFICATE

This is certified that the dissertation entitled “**Hydrodynamics of selected Ethiopia Rift Lakes**” is a benefited work carried out by Kassaye Bewketu Zellelew under my guidance and supervision. This is the actual work done by Kassaye Bewketu for the partial fulfillment of the award of the Degree of Master of Science in Computational Science from Addis Ababa University, Addis Ababa, Ethiopia.

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