Assessment of the Water Balance of Lake Awassa Catchment, Ethiopia.

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by

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Abstract

Lake Awassa is located in a closed catchment in the Central Main Ethiopian Rift Valley. Its level is rising progressively during the past 2 decades. Despite its economic and social importance to the community within the catchment, its rise poses a frequent flooding problem to the town of Awassa that is established adjacent to the lake. It is a fresh water lake while other closed lakes in the region are alkaline. For better management of the lake water, the hydrologic components which play a significant role in the lake level fluctuations need to be understood. The possible causes for the rise of water level need to be identified and the behaviour of the catchment at large must be understood: For that a water balance study is crucial.

Thornthwaite and Mather soil water balance procedure and spreadsheet model have been used in the catchment and the lake water balance studies for the period of 1981-1998 respectively.

The spreadsheet model uses monthly evaporation, surface runoff, and precipitation as an input and groundwater component is treated as net groundwater flow. Based on the simulation results it is found that evaporation, rainfall, surface runoff and constant groundwater outflow from the lake constitutes 131, 106, 83 and 43 Mm^3 of the annual average lake water balance respectively. The freshness of the lake water is attributed to the constant groundwater outflow from the lake.

Computer program WTRBLN developed on basis of Thornthwaite and Mather soil water balance procedure is used for the catchment water balance calculation. Long-term average monthly climatic variables (rainfall, reference potential evapotranspiration), crop coefficient and water capacity of the root zone are inputs to the model. Using ILWIS/GIS environment, catchment factors like soil type, land use and rooting depth, the water holding capacity of the root zone is defined. Incorporation of land use and climatic variables in the soil water balance program serves to assess the impact of different land use and climatic changes on the catchment runoff. Results of the catchment water balance shows that long-term mean annual values of rainfall, actual evapotranspiration, and catchment runoff (surface and sub-surface runoff) constitutes 1398, 916 and 482 Mm^3 respectively.

The results of the lake and catchment water balance analysis shows that the combined effect of climatic and land use changes during the past 25 years most likely resulted in an increase of the catchment runoff and so the lake level.

Acknowledgements

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This work is dedicated to
My Late father
Gebreegziabher Gebrehiwot
&
My mother
Abadit Abraha

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1. Introduction

1.1. Back ground

The study has been conducted on the Lake Awassa catchment located within the Central Main Ethiopian Rift Valley (MER) in central Ethiopia. Lake Awassa is a fresh closed lake playing an important role in the lives of many people in the region. It is the source of commercial fishery and used for recreation with great potential for future agricultural development. Despite its importance in a wide spectrum of purposes, the water balance of the lake is poorly understood. Proper assessment of the components of the hydrological cycle in terms of water balance is extremely essential for any future water resources development.

The town of Awassa, the regional capital of the Southern Regional State is located right on the eastern shore of the lake. The existence and protection of the lake is very critical to the town and the population residing within the entire catchment. The total population of the catchment was estimated to be 360,555 growing annually by 2.9% as of 1995,(Dessie 1995). Most of the population depends on agriculture that is directly or indirectly related to the water resources of the catchment including Lake Awassa, feeder rivers and groundwater.

The lake water frequently floods the town of Awassa during extreme wet seasons. The lake level rise poses problem not only to the town but also will have potential impact on the farms confined within the wide plains surrounding the lake.

Any future sustainable utilization of the water resources of the catchment and proper mitigation measures of the existing problems (related to lake level rise) demands the establishment of a proper conceptual hydrologic and hydrogeologic model of the catchment. In this regard, a water balance is one of the most important components of such a study. The research basically has focused on the water balance issues for the lake catchment and the Lake Awassa; with supporting evidences from conventional field hydrogeological surveys.

1.2. Main Objective

The main objective of the study is to quantify the water balance components of the Lake Awassa and its catchment on monthly bases and assess if the lake level rise could be attributed to natural or anthropogenic factors.

1.2.1. Specific objectives

- Estimate the various water balance components of the catchment and the lake, such as Evapotranspiration, surface runoff, Precipitation, evaporation, net groundwater flow and Abstraction.
- Assess the relation of lake levels with catchment factors (climatic, land use, etc.)
- Understand the flow pattern of the groundwater system.
- Identify recharge areas and mechanisms of recharge.

1.3. Research Problems

Despite its importance in the lives of millions of people in the region the water balance of Lake Awassa and its catchment is poorly understood, like many other Ethiopian rift lakes. Lake Awassa is also important from scientific viewpoint. There are at least the following problems to be solved:

1. For the last 25 years the lake is rising progressively fig (1). The cause of lake level rise is not clearly established and as such it is unclear whether it is related to natural (climatic or tectonic) or anthropogenic factors (land use change).

2. From surface water point of view Lake Awassa is closed. Many closed lakes in the Ethiopian rift are alkaline while lake Awassa is fresh which signifies the presence of groundwater outflow, which was previously reported by some authors (Tenalem 1998);. However, the total groundwater inflow and outflow terms are not well understood.

In addition to these basic scientific problems, there are the following practical issues.

3. Any plan by the regional government to construct flood control structures to protect the town of Awassa requires information on the temporal variation of lake levels, which in turn requires a detailed assessment of the various components of the hydrologic cycle.

4. The lake water would potentially be used in the future for agricultural purposes. For utilizing the lake water or any water from its catchment (spring, well or river) requires baseline study so that there will be no grave consequences on the fragile rift valley environment.

These issues demand proper hydrological and hydrogeological studies.

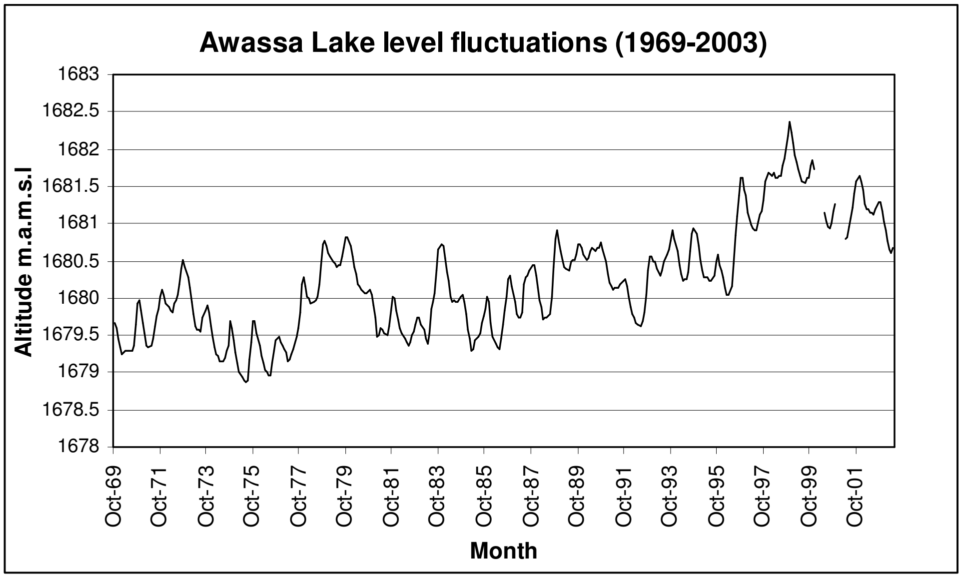


Figure 1 Awassa lake level fluctuations (1969-2003)

1.4. Research Questions

- What are the dominant components of the hydrological cycle controlling the hydrological behaviour of the lake and the catchment at large?
- Can the raise of Awassa lake level be explained in terms of climatic or anthropogenic factors?
- How does the interaction of the surface and groundwater in the catchment look like (i.e. where does the groundwater flows to and what are the springs, surface drainage systems and structures which affect the movement of water on the surface and sub-surface etc?
- What is the hydrologic relation of Lake Awassa with the adjacent catchment?

1.5. Materials and Methods

The methodology adopted is as follows.

- Select satellite images suitable for background map, for land use identification and image processing;
- Collect relevant secondary data from all sources and assess previous studies conducted on the area;
- Collect primary data from the site on land use, groundwater, water quality and geophysical and relevant hydrometeorological data (i.e. Rainfall, evaporation, temperature, wind speed, Relative humidity, river discharge, lake level) from respective offices;
- Data organization, data Pre-processing, producing relevant maps (i.e. DEM, drainage, catcment and sub-catchmnet area boundaries from DEM and soil map and land cover maps from relevant hard copy maps);
- Application of Spread sheet lake water balance model, used by (Armstrong 2002) and estimate the water balance components of the lake;
- Compare the lake water balance terms and understand the dominant component on the lake level fluctuation;
- Land use classification from Satellite images;

- Application of WTRBLN a computer program, developed by (Donker 1987), based on Thornthwaite and Mather soil water balance, to calculate the water balance of the catchment;
- Estimate the water balance of the catchment based on long term mean monthly hydrometeorological data and assess the magnitude of the effect of land use change on the water balance components and their role on the lake water level rise at different land use and climatic scenarios;
- Understand from previous studies and present interpreted data (geophysical survey, hydrochemistry, piezometric map, and the water balance), the groundwater component leaving the lake catchment and the direction of outflow.

1.5.1. Pre-field work

As part of preparation for the field work and collection of available secondary data from different sources, land sat and Aster satellite images were acquired for 1994, and 2004 from personal collection and through ITC Remote sensing and geo-data base respectively. These images were selected, because these were images possible to get cloud free for image processing purposes and possible to classify based on the recent field work observations.

1.5.2. Field and Post field work

A field trip has been organized to collect secondary data from different sources and primary data from the study area. The source of most relevant meteorological data (rainfall, relative humidity, pan evaporation, temperature and wind speed) is National Meteorological Services. Groundwater level, river discharge, lithological logs and water quality data are obtained from previous study reports. Soil map, Bathymetry map and land cover map are obtained from Water works construction and supervision Enterprise and topographic map from National Mapping Agency. Land use ground truth points, water samples for additional water quality analyses, depth to groundwater, and geophysical survey on selected sites was undertaken on the study area. All raw hydrometeorological data was pre-processed as indicated in the following sections.

1.6. Literature review

1.6.1. General

Uncertainties in water balance estimates

Water balance estimates of a catchment or a lake involves different parameters and variables recorded in hydrometeorological stations and some times obtained from model calibrations. Human or instrumental errors are associated with such estimates. A comprehensive analysis with regard to uncertainties in estimating the water balance of lakes is presented by (Winter 1981), as follows;

Estimates of precipitation can have a wide range of error, depending on the gage placement, gage spacing, and areal averaging technique. Errors in measurement of individual storms can be as high as 75 percent. Errors in short term averages are commonly in the 15-30 percent range, but decrease to about 5 percent or less for annual estimates. Errors in estimates of evaporation can also vary widely depending on instrumentation and methodology. The energy budget is the most accurate method of calculating evaporation; errors are in the 10-15 percent range. If pans are used that are located a distance from the lake of interest, errors can be considerable.

Annual pan-to-lake coefficients should not be used for monthly estimates of evaporation because they differ from the commonly used coefficient of 0.7 by more than 100 percent. Errors in estimates of stream discharge are often considered to be with in 5 percent.

Effect of land use change on hydrology

The concept of different aspects of an effect of land use change on hydrology at local, regional and global scale is discussed in detail by (Maidment 1993). Land use changes that could have an effect on decrease or increase of the quantity of water input to the Lake Awassa is selected from Maidment's expanded description and is presented in Appendix (1).

In the same source impacts of Urbanization on storm water runoff is discussed separately as:
Urbanization increases surface storm runoff and modifies its quality. As land urbanizes, it is covered by impervious surfaces such as paved roads, parking lots and roofs which prevent rainfall or snowmelt from infiltrating into the ground.

A change in land use is likely to alter the availability of water at the evaporating surface through changes in:

- The surface area of free water surfaces in streams and lakes
- The availability of soil water to plants (for example, When short-rooted agricultural crops replace deep-rooted trees, the availability of water will be reduced in dry periods or when drainage reduces soil moisture content in the rooting zone)
- Replacement of crops with different total leaf area per unit ground area (leaf area index, LAI), different stomatal resistance, and different stomatal responses to soil water and atmospheric humidity deficits.

A model for predicting the effects of a land-use change should have:

1. Input data requirements which can be satisfied;
2. A range of application which covers the problem being considered;
3. Sufficient complexity to give the required prediction accuracy- use the simplest model which will give a sufficiently accurate result, (Maidment 1993).

Thornthwaite and Mather soil water balance procedures

Thornthwaite and Mather soil water balance procedure which is used in the Lake Awassa catchment is complimented in literatures for its applicability in long-term water balance estimation. This type of monthly water-balance models are lumped conceptual models that can be used to simulate steady state seasonal (climatic average) or continuous values of watershed or regional water input, snow pack, soil moisture, and evapotranspiration, (Dingman 2002). It uses long-term average monthly precipitation, long-term average monthly potential evapotranspiration and soil and vegetation combined characteristics to calculate water balance. Long-term average monthly evapotranspiration is estimated using long-term average monthly air temperature as an index of the energy available for evapotranspiration, by assuming that air temperature is correlated to the integrated effects of net radiation and other controls of Evapotranspiration, and the available energy is shared in fixed proportion between heating the atmosphere and evapotranspiration (Thornthwaite and Mather 1957).

Therefore these types of water balance methods are useful for areas where adequate hydro-meteorological data of daily time series is not available. Whenever the basic metrological data is obtained making use of modified Penman-Monteith equation to calculate the reference crop evapotranspiration will reduce the uncertainties that could occur by only considering temperature. This model can give basic information for regional and sub-regional base line type study, where as other physically based complex models require more data on daily bases, which are difficult to get for the study area.

In spite of their extremely simple structures, models of the Thornthwaite type generally estimate monthly runoff values reasonably well (Calvo 1986, and Alley 1984, cited in (Dingman 2002a). This correspondence suggests that their estimates of actual evapotranspiration are likely to be generally reasonable. Therefore, having the basic hydrometeorological data required by the model on monthly bases and giving that the model assumes catchment soil and land cover properties and is applied in different catchments a choice has been made to make use of it on Awassa catchment.

Recent environmental and land use changes in Ethiopia

With respect to recent environmental and land use changes, (Nyssen et al. 2004) states that temporal rain patterns, apart from the catastrophic impact of dry years on the degraded environment, cannot explain the current desertification in the driest parts of the country (Ethiopia) and the accompanying land degradation elsewhere. Causes are changing land use and land cover, which are expressions of human impact on the environment. He has noted also that not land use changes in the highlands, nor changes in the seasonality of rain has never been taken in to account by most Authors, but changes in precipitation depth as a cause for lake level and river discharge changes, while both can lead to a change in runoff coefficients. In the present study an attempt is made to address the effect of land use and climatic changes in generating catchment runoff and its implications on lake level rise specific to Lake Awassa catchment. Comparison is also made between runoff values generated by rainfalls of seasonal variation.

1.6.2. Previous study on the area

Researchers have discussed different aspects of the Lake and the catchment as a whole at different times. Some of the aspects addressed by the research are as follows.

1.6.2.1. Land use of the lake catchment

The land use of Lake Awassa catchment has been changed in the last few decades. The rise in the lake level has been explained in terms of increase in the runoff as a result of excessive deforestation (W.W.D.S.E 2001). In a study conducted on Ketar watershed which is part of the Ziway-Shalla basin north of Lake Awassa, (Legesse et al. 2003) have investigated the impact of climatic and land use change on water resources in data scarce tropical Africa. In the study distributed rainfall-runoff model has been used to simulate runoff from a catchment under different climatic and land use scenarios. The study revealed that land use change of present day cultivated/grass land by wood land in the area would decrease the discharge at the outlet by about 8%, which could have an effect on the level of Lake Ziway.

1.6.2.2. Hydrology of the lake catchment

Telford developed a steady state water balance for Lake Awassa and suggests that direct precipitation accounted for 56% of the total input and 44% of runoff. Evaporation dominates losses from the lake (93%) but there is some ground water seepage (7%). The fresh nature of the closed lake Awassa is explained in terms of groundwater outflow (Telford 1998, Lamb et al. 2002).

Lakes Awassa and Shallo (Cheleleka), situated in Awassa caldera, were united as a single lake last century (Mohr 1971, Tadesse and Zenaw 2003). However, recent terraces are much less preserved in the Awassa catchment than Ziway-Shalla lakes to the north, the reason may lay in the wetter climate of the Awassa region. The existence of terraced pumiceous lacustrine sediments both sides of the fresh transverse faulting which limits the present lake Awassa basin to the north suggests that in pluvial times this basin was connected to that of Ziway-Shalla. They were separated by post pluvial block faulting and tilting.

Lake sediment related to ancient Awassa lake level was encountered in borehole located north of the lakeshore at 1700 elevation, which shows a drop around 30 m to the present lake level. If the level of hyaloclastite, rocks formed by granulation of the lava front due to quenching when lava flows in to or beneath water, at 1725m is taken, the present day level of Awassa has dropped by 40m.

The surface area of Lake Cheleleka was about 12 km^2 in 1972 but currently it is completely disappeared as a result of siltation. The lake floor, which once was covered by water, is now filled by sediment transported from the eastern highland as a result of deforestation that has taken place over the last 30 years. Prior to filling up of the basin with silt, Lake Cheleleka used to serve as a sediment trap for Tikurwuha River that flows in to Lake Awassa. As a result of losing its function as sediment trap, water and sediment load to Tikurwuha is now directly going in to Lake Awassa. Tall papyrus like grasses grow in the swampy area indicating that the deposition of transported sediment from the uplands has been in a continuous process of filling the natural reservoir of lake Cheleleka (W.W.D.S.E 2001).

1.6.2.3. Hydrogeology

The study conducted to assess the groundwater potential and quality at Shallo farm area, (North east of Lake Awassa) shows that the main aquifers are unconfined lacustrine sands with thickness ranging from slightly more than 10m to over 60m The piezometric map prepared during this study showed that the groundwater flow feeds the TikurWuha river (the main river that brings water to the lake from the sub-catchment) and lake Awassa evidencing an interaction between surface water and groundwater(W.W.D.S.E 2001).

In 1999 with the objective of determining variations in lithology and groundwater depth with in the lake basin and determining the existence of concealed tectonic structures that may serve as groundwater flow channels towards or away from the lake basin, geophysical survey has been conducted in the northern and south-western side of the lake by water works design and supervision enterprise (W.W..D.S.E). Although getting geophysical data collected during the study was not possible the following conclusion has been given with regard to features which affect the groundwater flow system.

The study has outlined numerous NNE-SSW trending structures (faults), one east-west trending structure in the north-western part of the area and second approximately north-south trending fault/contact in the central part of the area.

With regard to the south-western side of the lake where the recent fissures are created the study concludes the following. "On the basis of the apparent resistivity map for both the short (AB/2=30m) and long (AB/2=100) current electrode separations, two linear tectonic structures, interpreted to be faults cross profile Vm1 (fig.2). The fault lines traverse in an approximately NW-SE to E-W direction. On the other hand the result of the VES survey in both Muleti village (profile Vm2) and Dore Bafano(profile Vm7) area indicates the apparent resistivity maps for AB/2=30 and 100m discern fault structures that cross profile Vm2. The trend and occurrence of these two fault zones in Muleti and Dore Bafano probably suggest that one is a continuation of the other (W.W.D.S.E 2001).

Note must be taken that during the present study Derba pond which was located in the village Muleti (sub-catchment Muleti) was dried. Thus possibility of draining the pond water to Lake Awassa through these concealed structures was expected.

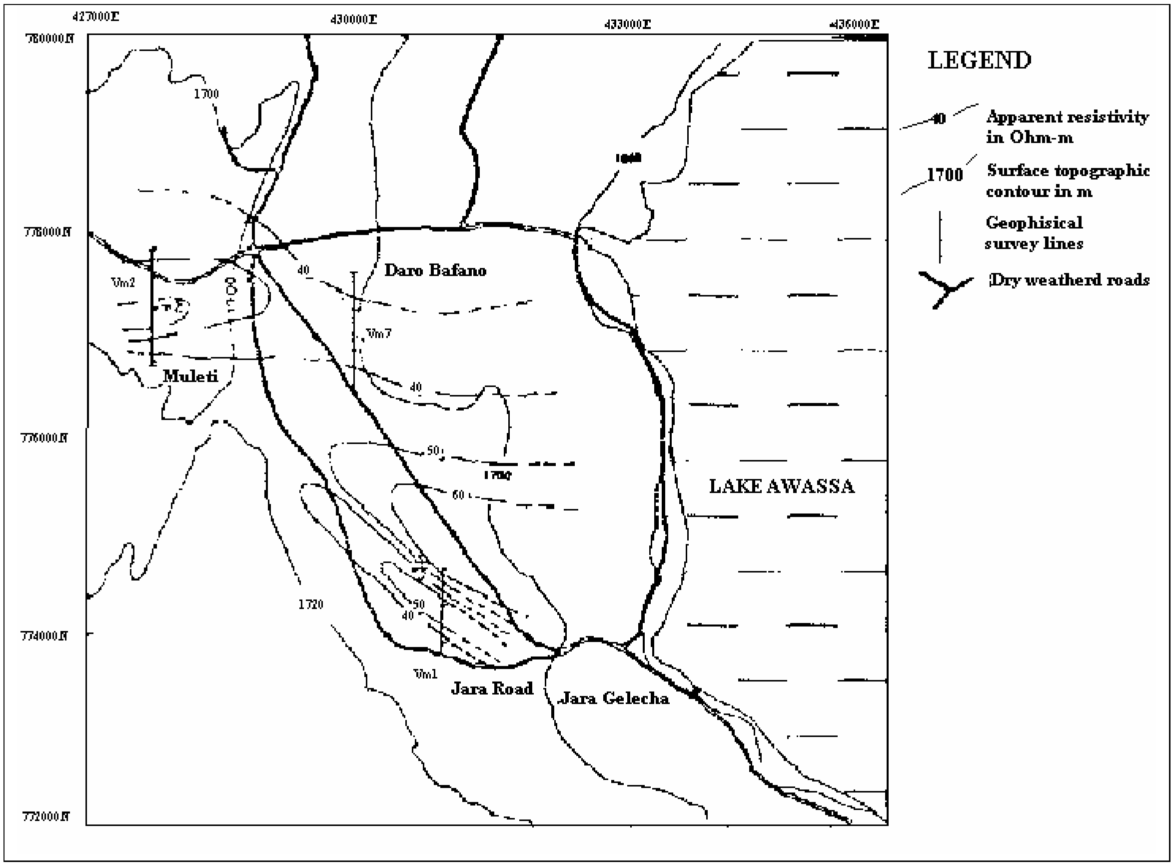


Figure 2 Apparent resistivity map for current electrode separation (AB/2) =100m (Adopted from W.W.C.S.E, 2001).

2. Description of the study area

2.1. Location and accessibility

The study area lies between $6^0$49'N-$7^0$15'N latitude and $38^0$17'E-$38^0$44'E longitude, 275 km south of Addis Ababa, with elevation range of 1680 m.a.s.l at Awassa lake and 2940 m.a.s.l at Kululu Ridge, south east of the catchment. The lake is situated in the Main Ethiopian Rift Valley system surrounded by flat to slightly slopping lands, escarpments and hills. The area is accessed through the Addis Ababa-Moyale main road and to different parts of the catchment through the network of dry weathered roads fig (3).

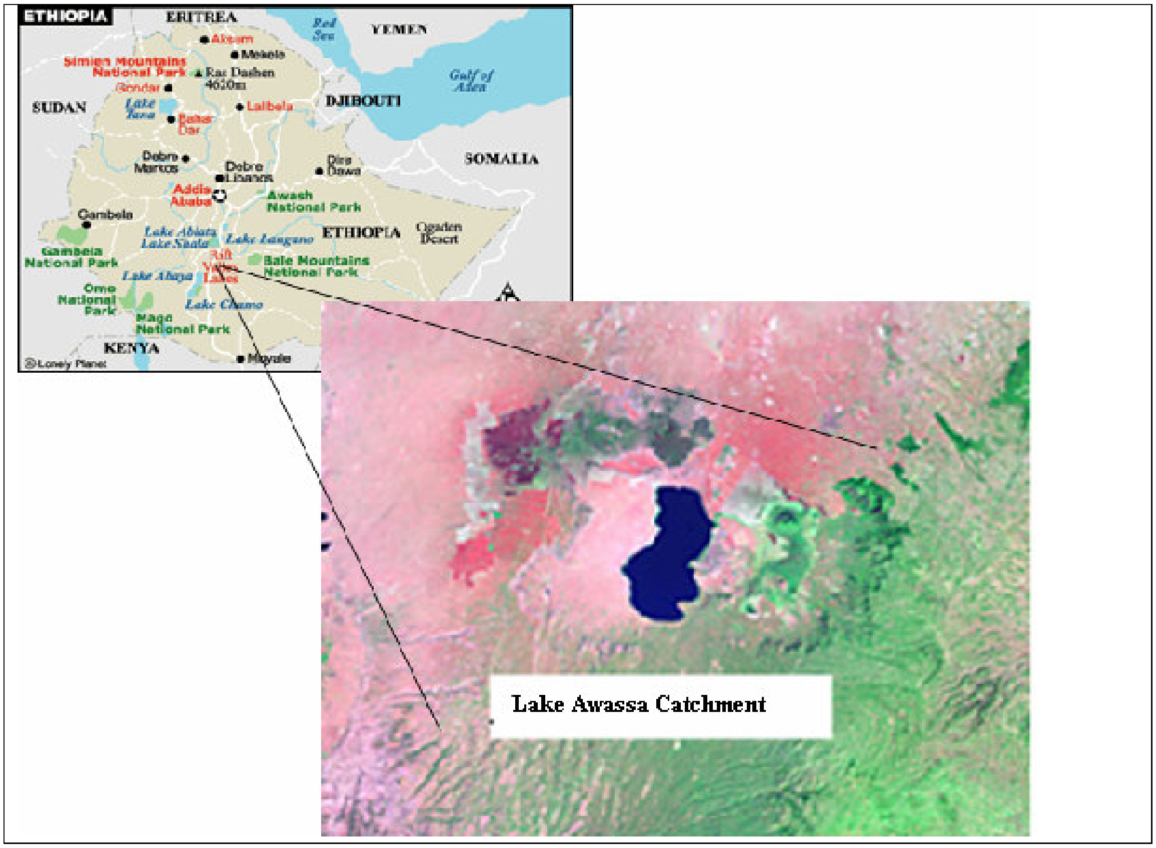


Figure 3 Location map of the study area

2.2. Phisiography and drainage

The catchment has a total area of 1455 km^2 of which 93.6 km^2 is the Lake surface area as obtained from digitized October 2004 Aster image. Lake area increases up to 99.3 km^2 in extremely wet year like in the case of 1996-1998. The Lake has a maximum depth up to 21m at an average level at the northern part of the lake.

Lake Awassa is a Closed-catchment Lake with no surface water outflow. The lake is fed both by few ephemeral streams on the north-west and western side of the catchment and by the TikurWuha River, which is the only perennial river, enters Lake Awassa draining the Cheleleka swamp on the north-east side. Cheleleka swamp receives surface runoff from the head waters of the eastern rift escarpment and from groundwater upstream.

Lake Awassa is the smallest and the highest of the major MER lakes (1680 m.a.s.l) between the Ziway-Shala lakes to the north and Lakes Chamo and Abaya to the south. The lake lies within a nested caldera complex and is predominantly underlain by highly faulted ignimbrites and other silicic pyroclastic deposits (Kazmin 1979).

When we compare the elevation of Lake Awassa (1680 m) with lakes Ziway (1636 m), Langano (1585 m), Abiyata (1578 m), Shalla (1550 m) and Abaya and Chamo (~1180m) it is possible for water from the Awassa lake catchment to flow to lower laying lakes through the subsurface when hydrogeological condition permits. Their relative position with respect to altitude is shown in fig (4).

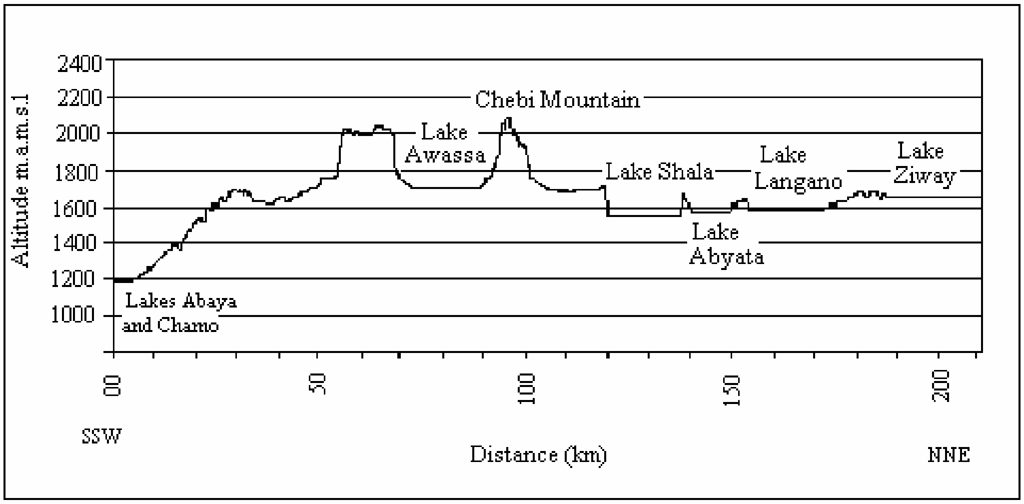


Figure 4 Cross-section along the Ethiopian Main Rift valley Lakes (extracted from SRTM)

The lake catchment mainly is characterized by a flat-lying topography with scattered small hills. The elevation of the rift escarpments and ridges in the east and west range from 2000 to the maximum of 2940 m.a.s.l.

It is known that the uplands on either side of the flat lowlands are deforested and denudated. The steeply sloping and deforested uplands are likely to produce high runoff to the lowlands shortly after individual storms. But still the eastern rift escarpment especially is a potential source of sustained hillside spring waters that feed not only the swampy areas of cheleleka but also the lake Awassa. The tectonic effect might have created fractures which serve as storage and preferential pathways for the sub-surface water emerging as springs from these highlands. The continuous erosion process on the eastern highlands have resulted on filling Cheleleka Lake with sediment load and transformed it to a swamp.

The drainage density and pattern mainly depend on climate, rock and soil formations, topography and surface and sub-surface fracture intensities. The highly eroded and most deforested western part of the catchment has relatively flat toped topography and is massive in nature made of coarse un-welded pumicious pyroclastic rocks has no significant drainage system. It is different from the eastern side which is covered with fractured ignimbrites and tuffs. It can be seen from the drainage map that no interconnected and long river channel reaches the lake from the western uplands. This However necessarily does not mean that there is no run off from this side of the catchment. The overland flow is not channelized but it occurs in the form of dissipated overland flow. The flat laying thick and fertile agricultural land with slope range of 0-8% but dominantly 0-2% (W.W.C.S.E, 2001) composed of fine to medium texture soils infiltrates the dispersed overland flow from the highlands. The fact that most of the runoff produced from the South-western and North-western highlands ends up on the closed sub catchments of Muleti, 91.6 km^2 and Wondokosha, 114 km^2 and due to the flatness of the plain agricultural land west of the Lake no significant surface runoff can be expected to enter the lake. The absence of significant river channels crossing the low laying plains is another indication of less importance of surface runoff from the northern and western side on the lake level rise. Thus water input to the lake from these sub-catchments is mainly through groundwater inflow provided that the hydrogeologic condition of the subsurface is conducive. In addition to that there should not be a sedimentation problem on the lake due to land use change on the closed sub catchments.

The eastern and south-eastern portion, which is characterized by dense drainage system, has streams flowing separately and in a radial pattern, which is the common feature of volcanic area. Some of the rivers like Wedesa, Gomesho, Wetera, Werka, Wesha, are perennial feeding the catchment floor and all ends up in the Cheleleka swamp, where TikurWuha River gets its waters from fig(5).

Large part of the low land is intensely cultivated. The low land also includes the vast marshy land east of Awassa town that includes the Cheleleka swamp and the Derba pond in the Muleti sub-catchment to the west of the lake, which is also dried and transformed in to a grass land.

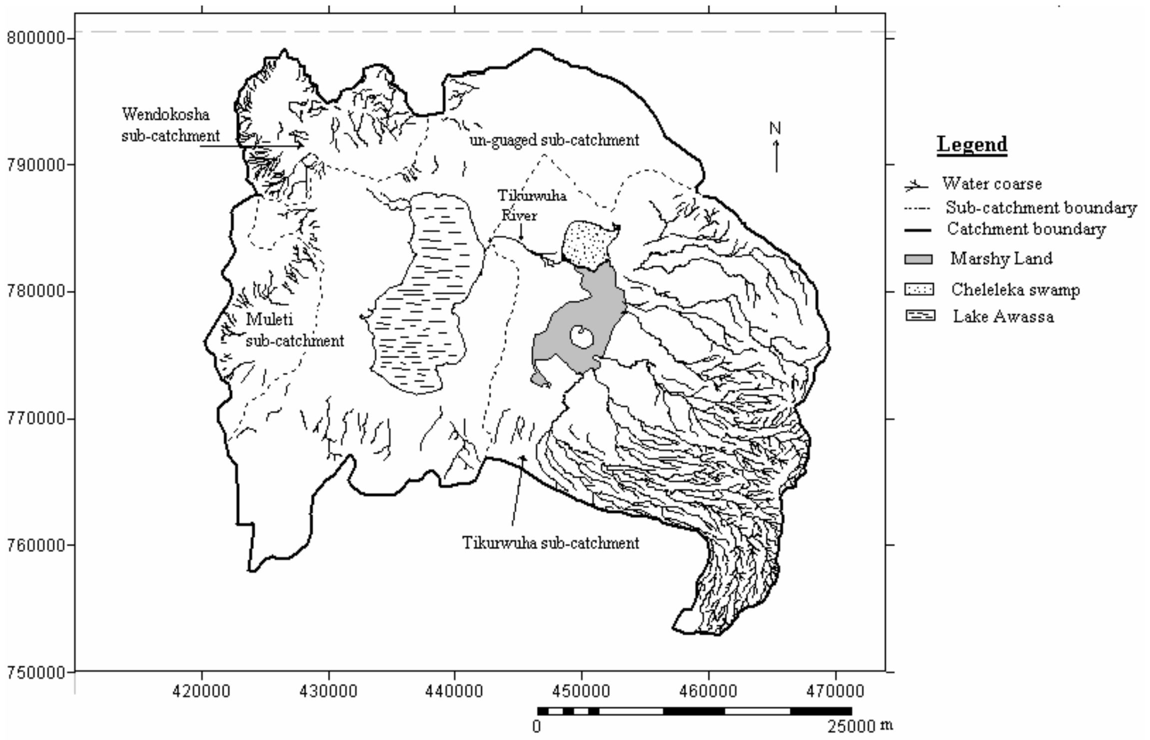


Figure 5 Drainage system of the Lake Awassa Catchment

2.3. The lake

2.3.1. Lake Ecosystem

Lake Awassa is a fresh closed lake inhabited by different birds and fish. The seasonal increase and decrease of the lake level favours development of long grass along its shores. It has been used also for drinking by the communities surrounding it.

2.3.2. Lake morphology

Lake Awassa stretches 16 km NE-SW (the longest axis) and 6 km NW-SE (the shortest axis) with a maximum depth of 21 meter at its NE part and decrease in depth to the shores. From the bathymetric contour line the lake bottom topography follows the orientation of the Lake Surface; oval shaped with its elongated structure oriented NE-SW and flat bottom at its deepest part.

2.4. Climate

The moisture for precipitation in the area originates from south-west equatorial air stream, which moves northwards with intertropical convergence zone (ITCZ), (W.W.D.S.E 2001). Ethiopia is located in the region where June through September is the main rainy season. Lake Awassa catchment however has even extended period of wet season (March-October with mean monthly rainfall varying from 85 to 133mm). June to September rainfall contributes 44% to the mean annual precipitation in the catchment.

The climate in the area is dry to sub-humid according to the Thornthwaite's system of defining climate or moisture regions, (Dessie 1995). The mean annual rainfall on bases of 12 to 30 years of record of 5 rainfall stations that contribute to the catchment is estimated to be 1028mm.

Both the amount and seasonality of the rainfall shows some variability. The wettest months are April, May and September fig (6). Though there is no other station in the catchment that records temperature to compare with, it can be concluded from Awassa station that the lowland part of the catchment annual temperature ranges from 9 to 29 ^{0}C, while mean monthly temperature is 19.7 ^{0}C.

The long term Mean monthly potential evapotranspiration estimated using FAO Penman-Monteith for the catchment based on the climatic variables recorded at Awassa meteorology station ranges from 39 mm in July to the maximum of 100 mm in January. Relative humidity records show the mean monthly value of 66.3% with mean minimum monthly of 53.9 in February and reaches maximum 77.3 in September. Generally the wet season on the catchment have mean monthly relative humidity values of more than 70%. Wind speed has decreased with time according to the records found at Awassa station. Wind speed records of 27 years shows that a decrease of average annual wind speed from 1.47ms^{-1} in 1973 to 0.79ms^{-1} in 2003 with some fluctuations in between. Long-term mean monthly values of climatic variables are presented in the following figures.

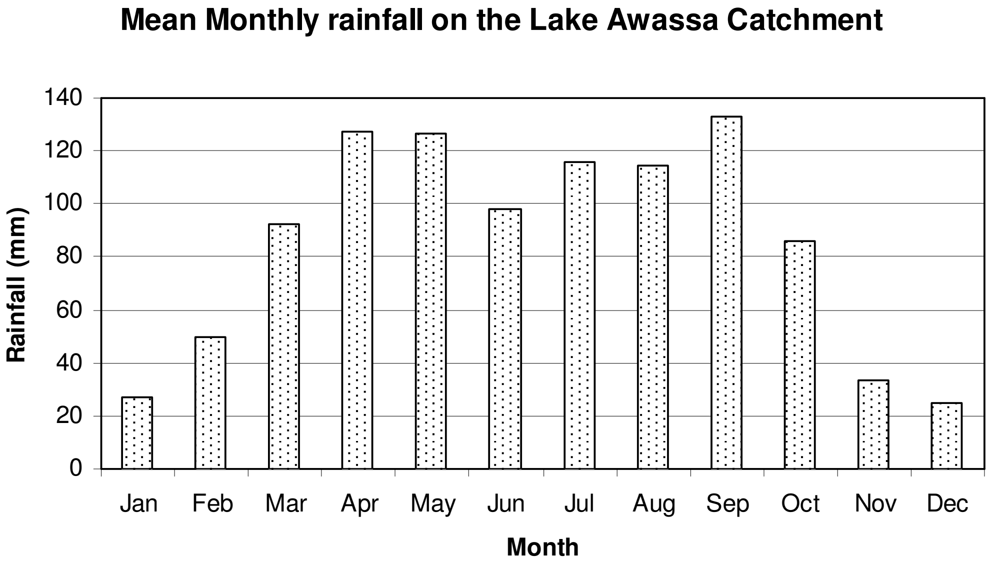


Figure 6 Mean monthly rainfall on Lake Awassa Catchment

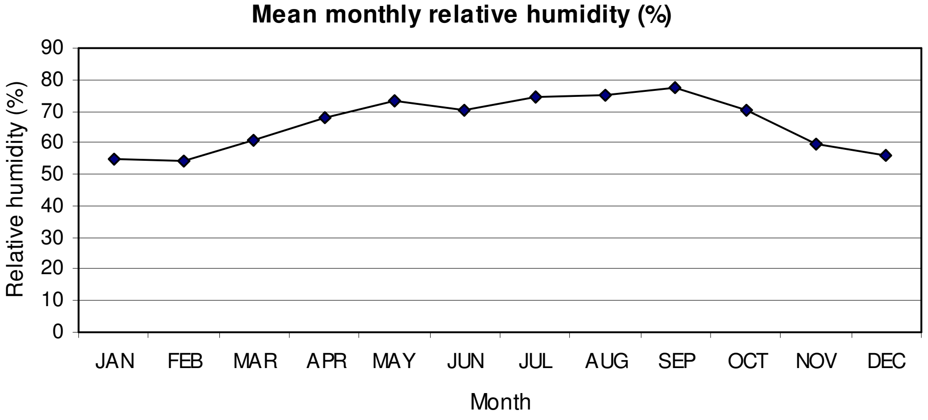


Figure 7 Long-term mean monthly relative humidity of Lake Awassa catchment

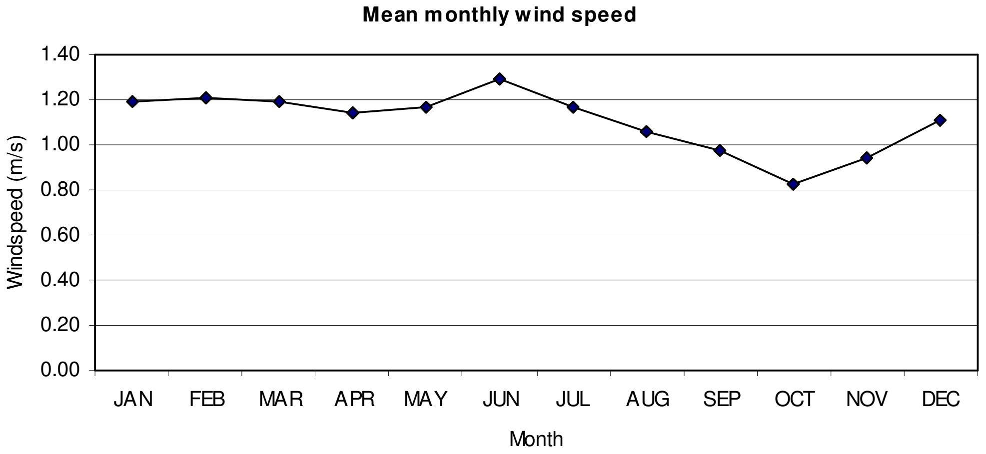


Figure 8 Long-term mean monthly wind speed of Lake Awassa catchment

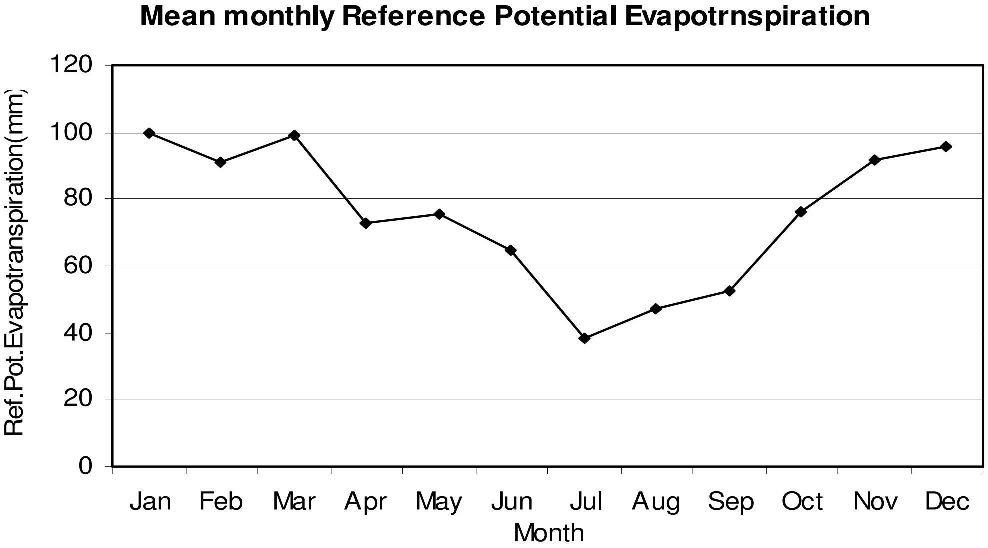


Figure 9 Long-term mean monthly reference crop potential evapotranspiration of Lake Awassa catchment

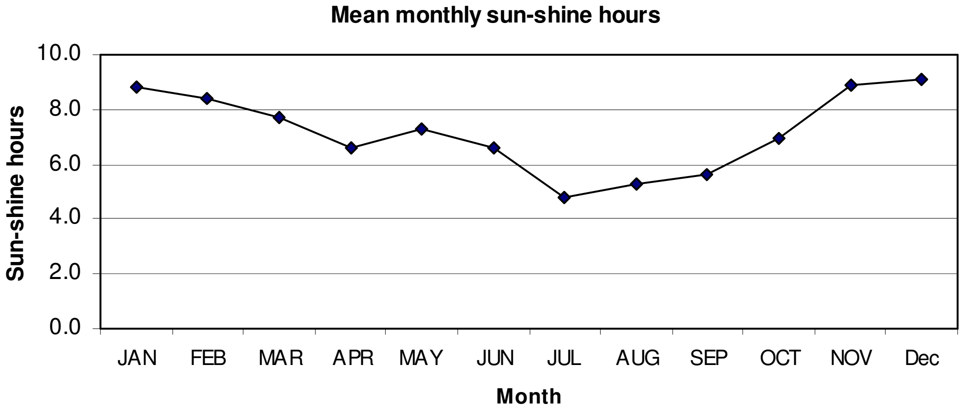


Figure 10 Long term mean monthly sunshine hours on Lake Awassa catchment

2.5. Landuse and Vegetation

The eastern highlands are moderately vegetated and the lowlands close to the foot of the escarpment are relatively well covered with mixed type vegetation, while the poorly drained western part of the catchment is devoid of vegetation and it is severe in the high lands. The North West mountainous area formed of obsidian rock formation is covered with dense bush.

Remotely sensed images are vital in land use/land cover classification specially when dealing with large and inaccessible study areas. The land cover study of the catchment area is made based on October 2004 satellite images and field observations. GPS location of the main land cover types on the catchment has been collected to support the supervised image classification. Water works construction supervision enterprise has also prepared a land cover map of 1965 and 1998 based on 1965 and 1975 areal photograph interpretations and ground survey. For some part of the eastern escarpment which is not covered with the satellite image land cover map of 1998 is retained assuming no significant land cover change with in 5 years time. According to the maps of 1965 and 1998 the catchment has revealed considerable land use change. The situation in 1998 has identified that dense wood land and bushy wood land have been changed to open bush land, open grass land, and cultivated land by about 70% as compared to the situation of the lake watershed in 1965. This condition is believed to have come due to increase in population and demand for firewood and construction materials, according to the report of W.W.D.S.E, [2001]. As a result degradation of natural vegetation and erosion become evident.

To be consistent to the definition and characterization of land use types identified by (W.W.D.S.E 2001), in the present survey cultivated land covered with various types of cereals, grass land, shrubby grass land, bush land, bushy woodland, swampy grassland, lake area, built-up and bare rock are considered to be the major land cover units in terms of the area they cover and their relative significance in the computation of evapotranspiration from the lake catchment. For computational convenience land cover types of similar rooting depth and growth stage are combined to one and when there is considerable difference in rooting depth and if the area covered for specific type of vegetation is considered to be large disaggregating of land cover types is made. Thus under cultivated land all cereals are grouped together as they are in similar range of rooting depth. Grassland and shrubby grass land are also merged in to one grassland unit. However the swampy grass land needs to be treated separately as the long grass and papyrus plants are grown fully on a swamp where water is available throughout the year, so the actual evapotranspiration in this land use could be equal to the potential evapotranspiration.

Since there was an overlap of spectral reflectance between different land cover units like built-up with bare rock, manual modification has been made to come up to the generalized land use map of 2004. Land cover maps 1965, 1998 prepared by W.W.D.S.E and 2004 from image classification are presented in fig (11), fig (12) and fig (13) respectively and are used in the catchment water balance.

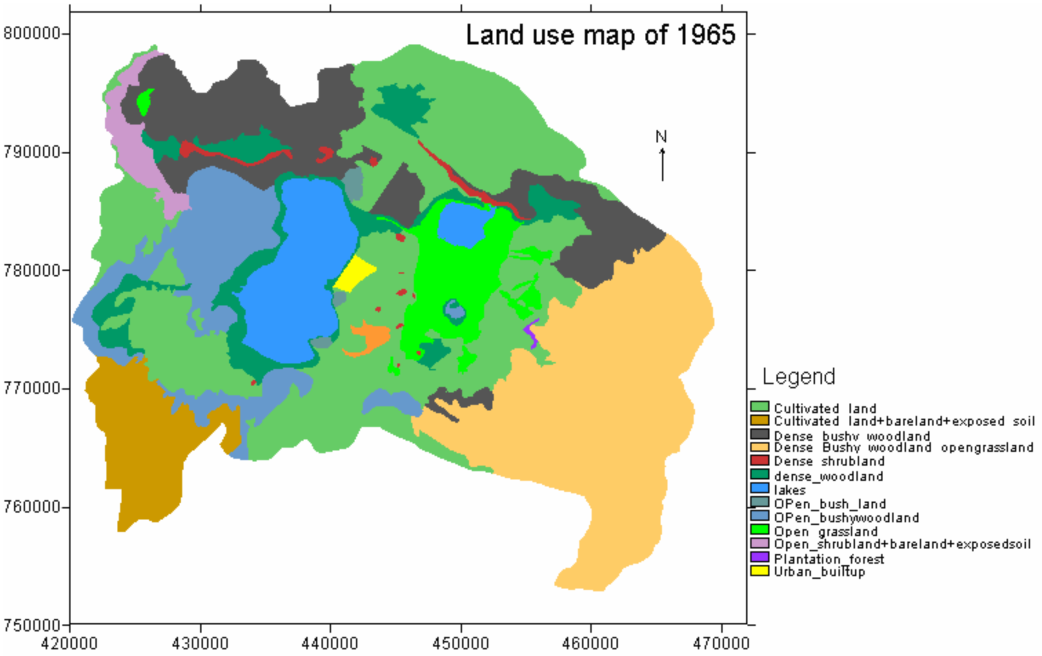


Figure 11 land use map of Lake Awassa catchment-1965 (adopted from W.W.D.S.E, 2001)

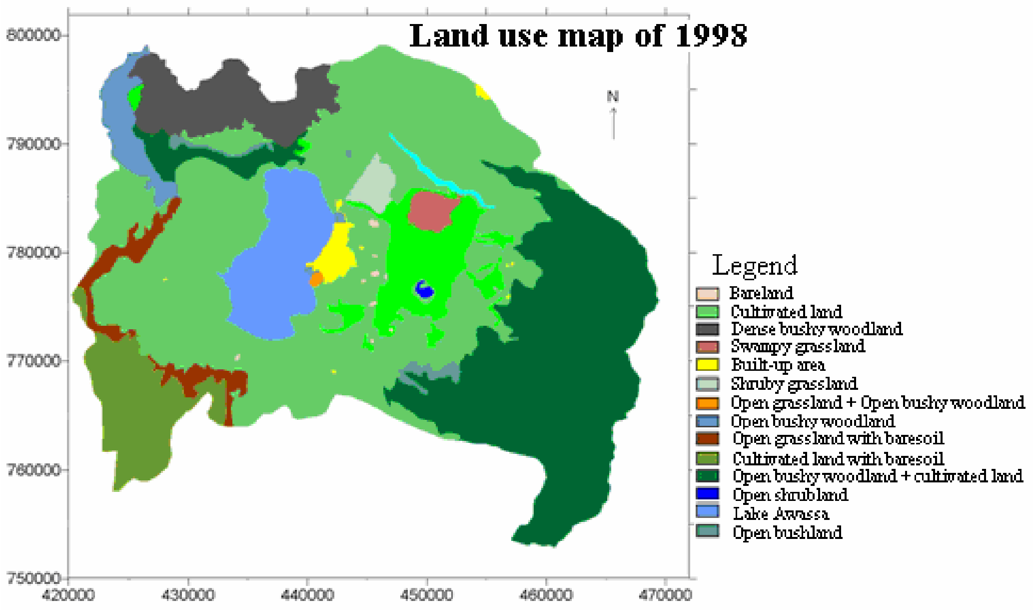


Figure 12 Land use map of Lake Awassa catchment-1998 (adopted from W.W.D.S.E, 2001)

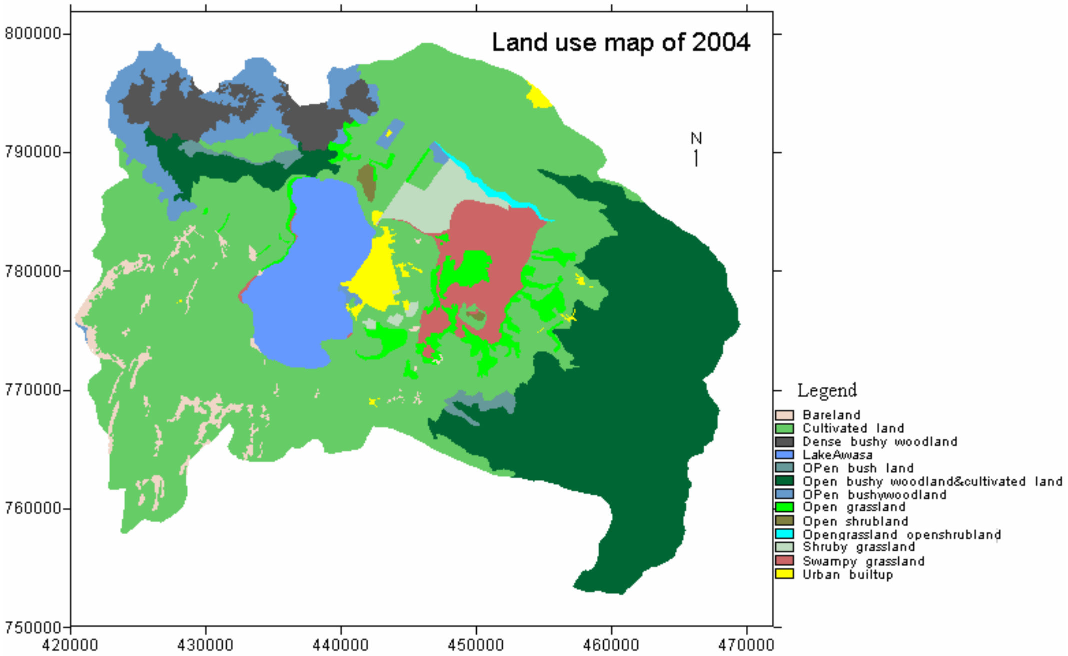


Figure 13 Land use map of Lake Awassa catchment -2004

2.6. Soil classification

Soil map of the catchment is obtained from Water Works Design and Supervision Enterprise in a hard copy form. As it is explained in the Enterprise's document classification is based on the physical and chemical characteristics which include depth, colour, structural development, texture and evidence of profile development such as presence of diagnostic horizons, reaction to 10%HCL, pH value and others. Accordingly 19 soil mapping unites were identified and soil map has been produced. Some of the soil types described in the document with respect to their position in a different relief intensity and slope are Cambisols, Andosols, Vertic cambisols, Vertic luviosols, Regosols, Gleysols, Alisols, and Leptosols.

The broad divisions of soil types in to different families as used in calculations of available water capacity of the root zone and suggested in Thornthwaite and Mather of soil texture and vegetation combination, fine sand, fine sandy loam, silt loam, clay loam and clay are mentioned. Accordingly the soil classification given in the W.W.D.S.E report is reclassified to this general soil family classification based on the soil texture fig (14).

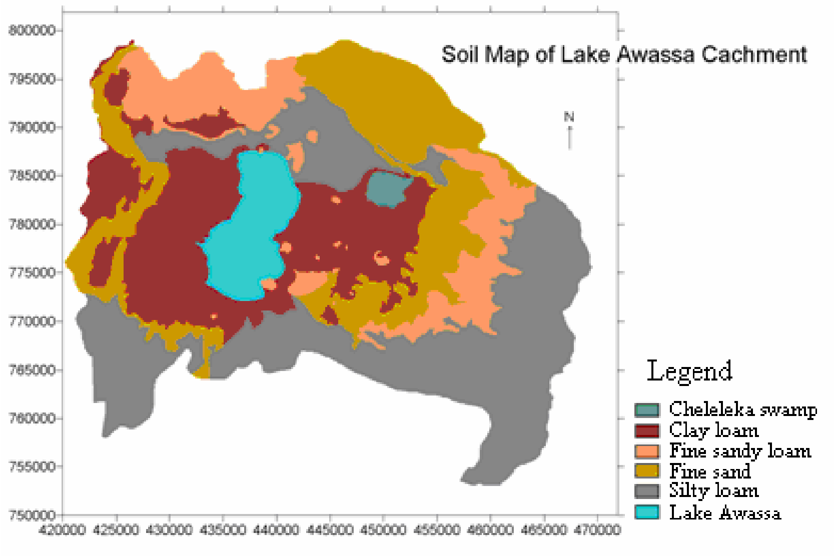


Figure 14 Soil map of Lake Awassa Catchment (modified from W.W.D.S.E, 2001)

3. Geomorphology and Hydrogeology

3.1. Geology

The main Ethiopian Rift Valley is divided based on structural features in to three geographic areas; represented by the northern(Fentale Nazret), Central (Nazret Awassa) and southern (Awassa-Konso) sectors. The central sector, where the Awassa lake basin belongs to is a symmetric rift basin where both sides of the rift margins are fully defined except in the region between guraghe and Sodo of the western escarpment and the Shashemene area of the eastern margin, (Tadesse and Zenaw 2003).The closed basin of the nested Awassa-Korbetti caldera complex is a giant elliptical depression 30-40kms wide.

The Korbetii caldera, which is found northwest of Lake Awassa, is nested caldera with in Awassa caldera. It has two volcanic centers of Urgi and Chebbi. The Urgi centre is a source for the formation of pumice in the vicinity and Chebbi is a center of formation of obsidian, which covers the Chebbi Mountain.

(Dessie 1995), stated the main formations in the area subdivided in to four lithologic units as follows;

1. Volcano lacustrine deposits, which cover most part of the floor of the depression, composed mostly of volcanic origin (tuff, pumice, ash) with small amount of diatomite;
2. Recent acidic volcanics, which covers large part of the north and north-western part of the catchment where glassy rhyolitic rocks superimposed and form massive domes and thick obsidian flows;
3. Basaltic lava flows, scoria and hyaloclastites, which are observed sprinkled on the flat catchment floor forming conical shapes.
4. Ignimbrite of the rift floor and the rift scarp, which is common rock type for the region and covers the east, southwest and the southern part of the catchment where the top few meters of the rock is weathered and fractured in places with columnar joints.

3.1.1. Geological structures

There are a number of rift system faults with north and northeast trend along which the longest axis of Lake Awassa is oriented. These faults are expansions (normal faults) forming step faults. They are mainly dominant to the south and south west of the lake. The volcanic collapse structure (caldera) forms nearly circular structure around Lake Awassa basin. The collapse shifts some of the MER fault systems showing that the collapse has taken place subsequent to the rifting. In the Awassa caldera a line of young faults affect the rift floor. These faults shattered the rift floor in to several relatively small horst and grabens. Lakes or swamps occupy the more depressed areas, (Tadesse and Zenaw 2003).

Ground cracks are observed in the Muleti sub-catchment south west of Lake Awassa. Hydrologically these cracks appeared to be important since they are situated in the depressed closed sub-catchment, with no streams connecting to the lake. The approximately NNE-SSW striking cracks could convey water from the sub-catchment to the lake when intercepted by East-west running faults.

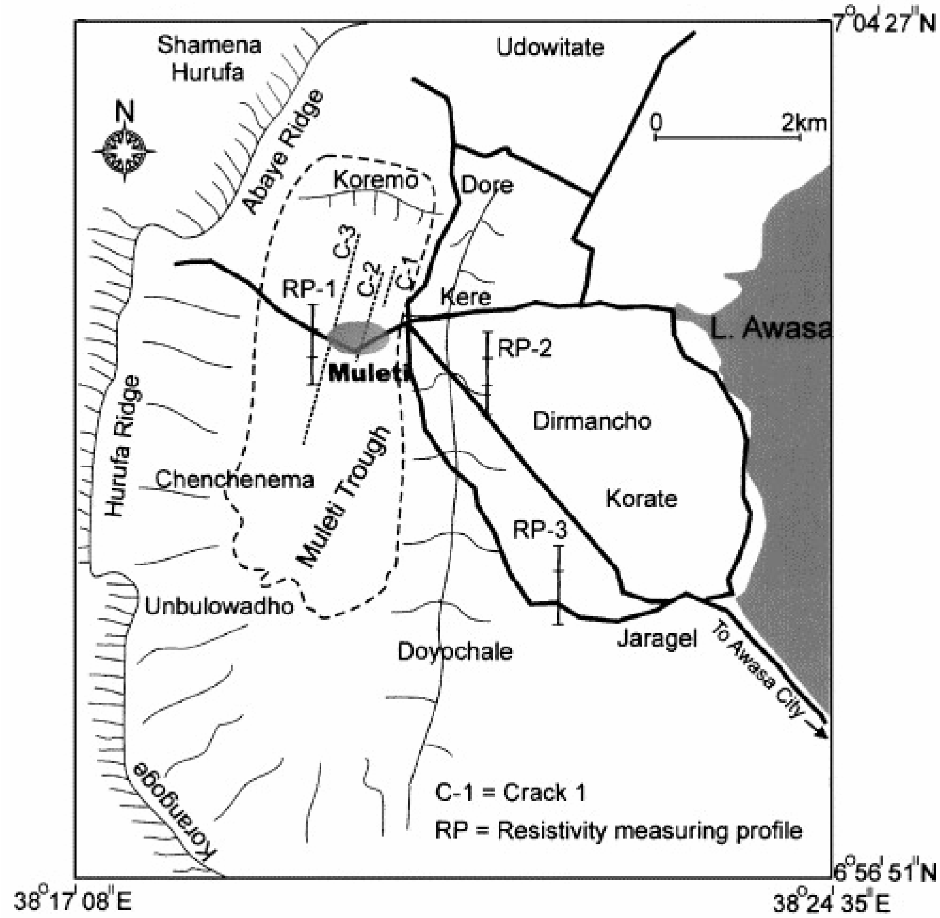


Figure 15 Map showing the location of recent cracks (After Ayalew et al 2004)

It is indicated by (Ayalew et al. 2004) that such type of cracks are not only present in Muleti area but also around Lake Shala (approaching the lake from northeast), and Adamitulu area both located north of Lake Awassa in a different catchment. They conducted an investigation to find out a reason for the cause of ground cracks in Ethiopian Rift Valley and their mechanism of formations based on information compiled largely from field surveys and geophysical investigations.

Ground Cracks, fig(15), 1, 2, have been created in 1996, 1997 and crack 3 in 1996 but widened 1998 respectively one after the other when the region was inundated by massive flood after above normal precipitation and developed in length and width gradually since April 1996, (Ayalew et al. 2004). The cracks have varying dimensions ranging from 2.5 to 12 meter wide and 150 m to 2.4 km length. The cracks have been described by Ayalew, et al. as having similar strike direction to the general trend of the Ethiopian Rift Valley and have neither vertical offsets nor horizontal displacements.

As a conclusion the possible cause of the surface cracking is indicated as aseismic elastic strain, which originates at depth and propagates upward through sediments without the formation of bedrock faults. This in turn favours soil piping and hydrocompaction as the hydraulic gradient between the Muleti sub-catchment and Lake Awassa promotes to such mechanisms.

Whatever the cause of the newly developed ground cracks may be, these are important hydrologic features that facilitates easy passage of surface water in to the aquifer and then to the lake provided that groundwater from the sub-catchment flows toward the lake. Although not conclusive on bases of the piezometric map of the area, there is an indication however that the groundwater outflow direction from the lake is towards the northern part of Muleti sub-catchment and north ward to Lake Shalla. Therefore what is flowing from the lake and from the ground cracks is probably flowing out of the catchment through subsurface structures towards neighbouring catchments. The extent of the ground cracks can be seen on fig (16).

Figure 16 Some of the recent ground cracks (1996-1998) on lake Awassa catchment (Muleti area)

3.2. Hydrogeology

Hydrogeological study conducted by Tesfaye Chernet, pointed out that Awassa Lake Catchment is covered by highly permeable lacustrine sediments, moderately permeable acidic volcanic (rhyolites, tuffs, pumice and obsidians) and low permeability ignimbrites and tuffs. Acidc volcanics are highly permeable when sorted and ignimbrites are highly permeable when they are jointed, (W.W.D.S.E 2001).

Quaternary sediments are dominantly distributed with large stretches at the eastern and western side of the lake and they overlay the ignimbrites. They consist of alternating fine and coarse sand beds, but they are predominantly fine to medium grained. The transmissivity of the lake sediments become higher when there is a higher proportion of coarser material like pumice sand beds.

Based on borehole data and field observation the lacustrine sediments have medium to high transmissivity values ranging from 100 to over 1000 m^2/day. The groundwater is generally unconfined. Average thickness of the lake sediments is estimated to be about 40 to 50 meters. The temperature of the groundwater varies from 21 to 32 ^{0}C and conductivity from 230 to 1900 μS/cm, (W.W.D.S.E 2001). Cold springs with varying temperature range of 20 to 28 ^{0}C and conductivity of 175 to 232 μS/cm and hot springs with temperature varying from 70 to 90 ^{0}C and conductivity of 1500 to 2000 μS/cm have also been reported. During the current field work 175 to 1500 μS/cm for shallow groundwater, 200 μS/cm for cold springs, 790 μS/cm for the lake water, 930 to 1700 μS/cm for the hot springs has been measured. The lake water appears to be fresher than some of the aquifers around.

Among the prominent springs worth mentioning are the hot springs (60 – 70^{0}c) situated some in the lowlands and others at the hillsides of the eastern escarpment, like the Wondogenet hot spring and other cold springs that are important water sources for rural and urban water supply and for recreational purposes. Loke cold spring which seems to be fault controlled is situated at the junction of the major fault running North-South and Lake Awassa. Before it has been developed and connected to Awassa water supply and to rural water supply since 2001 around 20 l/s water was entering in to Lake Awassa from this spring.

Groundwater depth increases as a function of distance away from the lake in the south and southwest of the lake. The groundwater depth between Lake Awassa and Cheleleka swamp varies according to surface elevation, i.e. on the surface water divide the groundwater depth reaches up to 67 meters and decrease to 6.3 meters close to Lake Awassa and 10.3 meters near to Cheleleka. (W.W.D.S.E 2001).
The groundwater flow pattern indicated in the peziometric map was prepared by interpolation of observation points obtained from previous reports fig. (17).

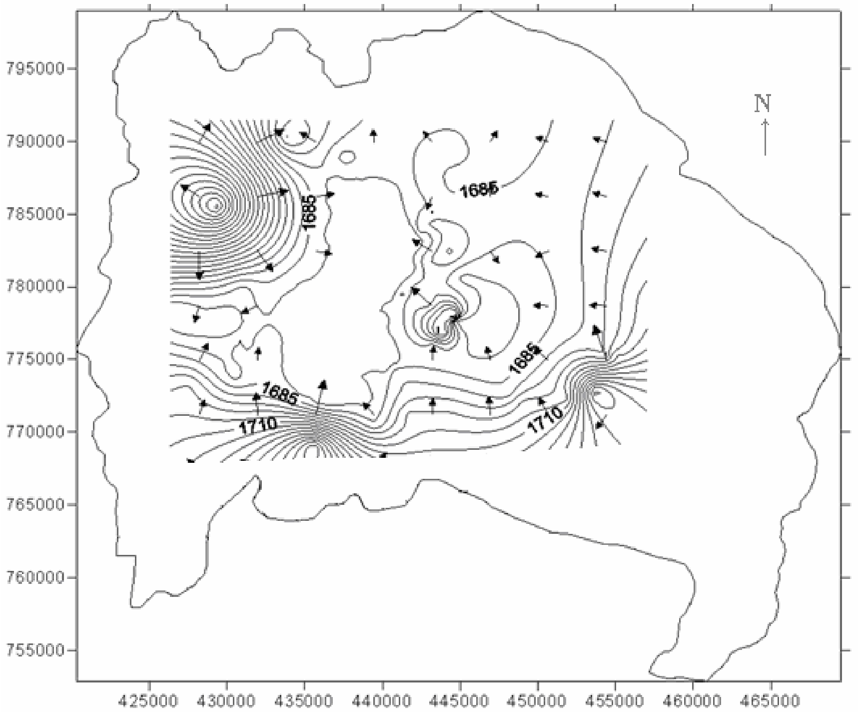


Figure 17 Piezometric map of Lake Awassa Area (interpolated in Surfer, Observation points from W.W.C.S.E, 2001)

As discussed above the range of permeability values of the lacustrine sediments is large. Similar hydraulic properties have been recorded in the formations of adjacent Ziway-Shalla catchment. However large spatial variation in the permeability of rocks is common feature of fractured volcanic terrain due to differences in the degree of fracturing. In contrast to geological bodies which are frequently determined by their stratigraphic characteristics and/or lithologic composition, spatial variations of hydrological bodies (aquifers and aquitards) can be partly or entirely independent of lithologic properties in a highly fractured environment, (Krasny 1997, cited in Tenalem 1998).

Thus it may be difficult to estimate ground water terms of the lake water balance on bases of observed wide range hydraulic property of the sediments contributing in the groundwater outflow and inflow from/to the lake.

3.2.1. Geophysical investigation

In the present study, aiming at confirming with additional evidence to previous conclusions on the groundwater outflow from Lake Awassa catchment towards Lake Shalla, Vertical Electrical Soundings were conducted north of the lake. From the geophysical response of different subsurface formations it was expected to obtain the relative depth to water bearing rocks and the gradient of the groundwater flow system along the inferred fault lines. The VES stations were selected in positions where comparison is possible to lithological logs of previously drilled boreholes. The orientation of electrode spread of VES 1, 4, 5 and 6 are NS and VES 2 and 3 are EW direction Appendix(6). However as it can be seen on the modelled curves the data points collected could not help achieve the objective of the survey. Different reasons could have caused the irregular readings. The fact that irregularities occurred usually at wider electrode spacings appears systematic difficulty of getting proper recording due to geological properties or other technical problems which can not be explained by only analysing the plots. It is not possible therefore to interpret the Vertical Electrical sounding curves as a layer model.

3.2.2. Recharge and discharge areas

The western side of the lake catchment and specifically the Muleti sub-catchment where the recently developed ground cracks appear is potential recharge area for the groundwater from which Lake Awassa might have been fed through groundwater inflow provided that the gradient of the flow is towards the lake. The swampy area located 5 km east of Lake Awassa could be considered as discharge area for the eastern high lands since the groundwater level of the foot of the escarpment is higher than the level of the swamps. At the same time the swamp recharges the groundwater system downstream as the groundwater level is below the level of the swamps. The swamp gets water not only from the groundwater but also from the seasonal and perennial streams that drain the eastern highlands. From the piezometric map above it is possible to see that the southern, eastern and north-western uplands are the recharge areas while the northern and the south western part of the catchment are the discharge areas for the lake in the form of groundwater.

3.3. Surface hydrology

A. Streams and gullies

Perennial rivers are concentrated only in the eastern side of the catchment emerging from the highlands and end up in the Cheleleka swamps from which Tikurwuha River carries the water to Lake Awassa. Tikur Wuha River is the only one which has been gauged since1981. TikurWuha River drains a total catchment area of 636 km^2.

B. Lakes/swamps

Lake Awassa

The surface area of the lake was about 88km^2 in 1976, as interpreted from topo-map and 99 km^2 in 1998, i.e. about 11 km^2 expansion in 22 years. In 2004, as it is obtained from Aster satellite image the lake area drops to 93km^2.

But still when it is compared to 1976 lake area an increase of 9 km^2 is observed.

Cheleleka swamp

Lakes Awassa and Cheleleka, situated in Awassa caldera, were united as a single lake last century (Mohor, 1970, cited in Tadesse and Zenaw 2003). Cheleleka gradually transformed in to a swamp is fed with around 11 perennial rivers emerging from the eastern highlands. Although not intensive, part of these rivers is being used for micro scale irrigation and town water supply systems (i.e. water diverted to Shashemene town water supply service from Wosha River). In addition to the Cheleleka swamp, large part of the wetlands that extends to the south until the hot springs is covered with long grass.

Derba dried pond

This is a small pond, SW of lake Awassa, created in 1970(local information) as a result of enormous volume of runoff coming from adjacent escarpment. The lake is 2m deep and covers 5 km^2 area. It is located in Awassa catchment but has no surface connection with Awassa Lake, (Tadesse and Zenaw 2003). The above mentioned pond did not exist any more since 2001/2002 (local information). It is clear that the then water bearing pond and now grass land has existed till the early inception of the report by Taddese and Zenaw. Although not confirmed with different source it has been learnt from the local people that the lake has disappeared as widely opened ground cracks were formed as a result of repeated earth quake. However, as indicated in the previous study (section 3.1.1) the earth quake has been ruled out from the cause for ground crack formation in the pond area.

C. Un-gauged catchment

The part of the catchemnt referred as un-gauged in this study is a sub-catchment adjoined to Lake Awassa but has never been gauged. This area includes west, southwest and north and some part of eastern side of the lake. The closed sub-catchments Muleti and Wondokosha located 5 to 10 km away towards west and north-west of the lake cover 15% of the land surface surrounding the lake. Therefore an area of 205.8km^2 that is covered with these sub-cacthments should not be accounted in the estimation of surface runoff. Thus 38% of the total land surface (517 km^2) that is needed to be considered to determine surface water input to the lake turns out to be un-gauged.

3.4. Digital elevation model

Four sub sheets of topographic maps covering different parts of the catchment were glued and digitized to prepare the digital elevation model of the area. The boundaries of the study area and the sub-catchments are derived from the Digital Elevation model and the river networks. Thus delineation of sub-catchments that do not have surface contact to Lake Awassa and therefore estimating the total catchment area and sub-catchments that should be excluded from surface runoff computation has been possible. Accordingly the study area was divided in to 5 geomorphologic units, such as sub-catchment Tikurwuha which is gauged, sub-catchment Muleti and sub-catchment wondokosha which are closed sub-catchments, un-gauged sub-catchment which includes the western south-western and northern flat lands and the lake itself. Although the surface elevation obtained using Etrix summit GPS and from the Digital elevation model shows a difference of plus or minus 7 meter on top of the error associated with digital elevation model processing and instrument error on the GPS it is used to estimate the groundwater level elevation on the boreholes from which piezometric maps were prepared. Ilwis and Arcview/GIS were used on the procedure.

4. Hydrometeorological data analysis

4.1. Discharge data

As stated in the previous sections the only perennial river from which discharge records of 1981 to 1998 was found is Tikurwuha River. River discharge data gauged at Dato village some 4 km upstream of the lake on Tikurwuha River is used in the water balance calculations. Due to reasons mentioned under section 2.2 the surface runoff contribution of the un-gauged catchment is considered insignificant and lamped to the groundwater flow component. The mean monthly discharge data from Tikurwuha River is presented on table (1). The Available time series discharge data is presented in Appendix (3).

Generally the river discharge has increased over the recorded period of time fig (18). Increase of rainfall, change in seasonal distribution of rainfall and land use changes are reasons for increase of river discharge of a certain catchment. One of the main land cover changes on the Lake Awassa catchment which could lead to an increase of river discharge is the transformation of the lake Cheleleka to a swamp. Cheleleka is a sink for the surface runoff from the eastern escarpment of the catchment and groundwater discharge from the aquifer upstream. It has gradually transformed in to a swamp due to siltation and covered with grass as explained in the previous chapters.

The decrease in storage capacity of Lake Cheleleka due to siltation leads to transfer additional water in to Lake Awassa.

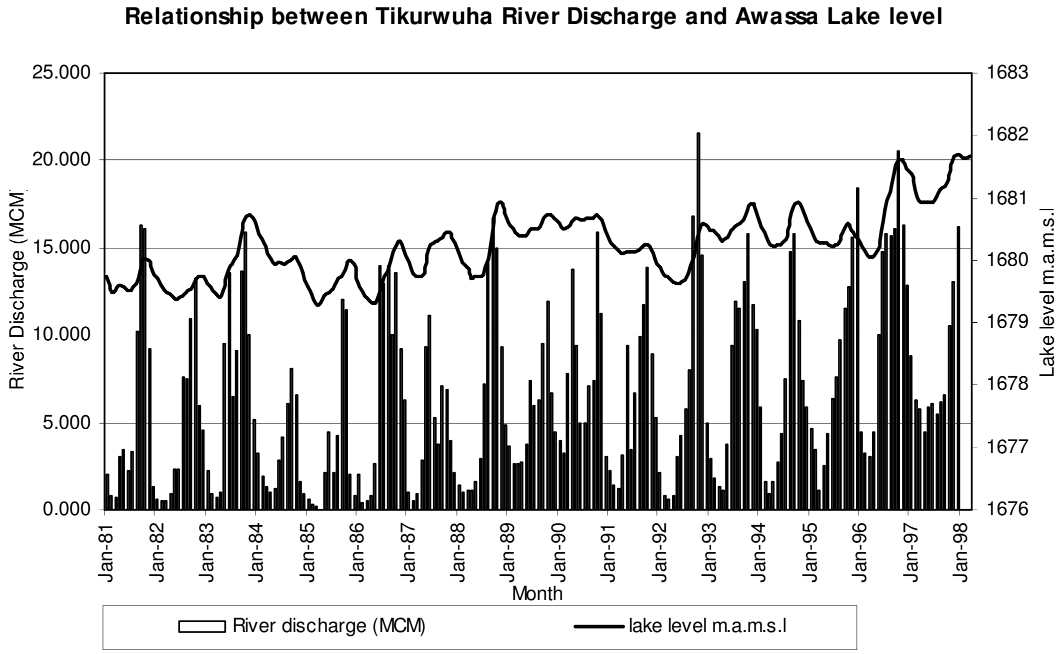


Figure 18 Relationship between discharge of Tikurwuha River and the Awassa lake level

Month	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Mean Discharge on Tikurwuha river (Mm^3)	3.8	2.6	2.2	2.7	5.2	7.3	7.7	9.6	12.1	14.1	9.4	6.4

Table 1 Mean monthly discharge on Tikurwuha River (Dato gauging station)

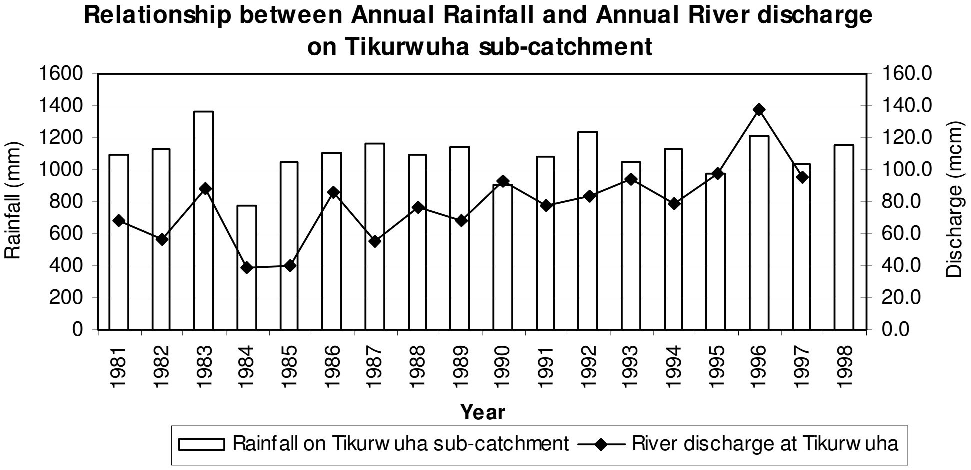


Figure 19 Relationship between Annual rainfall and annual river discharge at Tikurwuha sub-catchment

Apart from the very high rainfall that was recorded for Tikurwuha sub-catchment in 1983 and the driest year of 1984, rainfall in the area was fluctuating around the long-term average rainfall value. There is an indication that the highest peaks in the lake level correspond to the highest rainfall in 1983, 1992 and 1996. However the decrease and increase of catchment runoff does not coincide sometimes to the decrease or increase of annual sub-catchment rainfall fig(19). The discharge generated from annual rainfall of 1366 mm in 1983 is 88Mm3 where as in 1996 a river discharge of 137Mm3 is recorded from annual rainfall input of 1215mm. Variation in Seasonal rainfall distribution, high runoff generation due to land use change, antecedent moisture condition of the catchment or discharge measurement errors in either of the variables are some of the possible reasons for such inconsistency in rainfall runoff relationship. As it can be seen in fig (20) even though the seasonal rainfall distribution of both years varies to a large extent the higher rainfall of April and May 1983 would have yielded to a higher runoff values where as the graph shows the opposite. Unless further variations of seasonal rainfall storms are investigated at shorter time scale (daily basis) the reason of seasonal rainfall distribution could be ruled out. River discharges of 1996 are high both in the wet and dry season. The preceding years to 1983 and 1996 had similar annual rainfall amount so it is less likely that antecedent moisture is a reason. The transformation of Lake Cheleleka in to a swamp may have contribution to the attenuation of surface runoff and increasing the base flow and so the dry season discharge. Therefore land use change seems to have contributed to the increase of the river discharge.

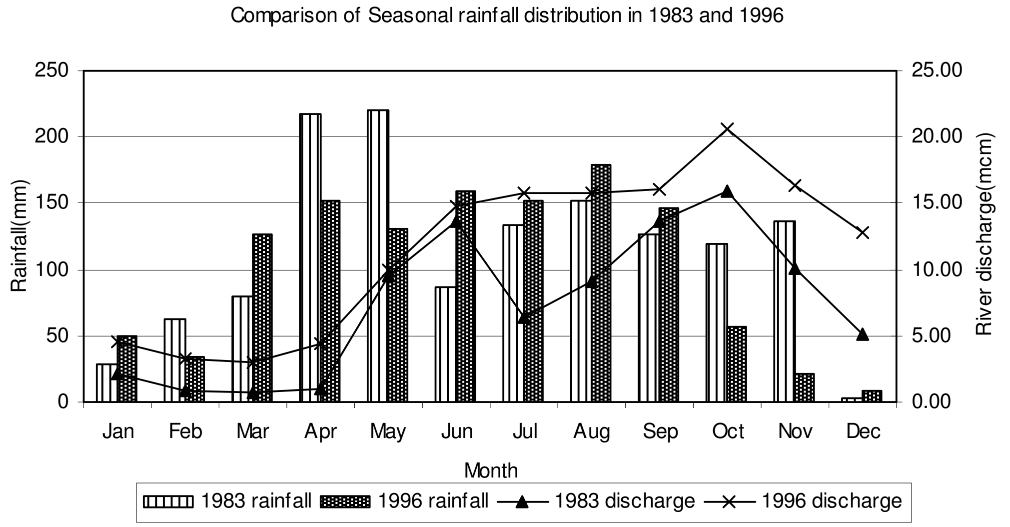


Figure 20 Comparison of seasonal rainfall distribution and river discharge from Tikurwuha sub-catchment

4.1.1. Baseflow Separation

There is much uncertainty for monthly flow volumes to be used for base flow separation purposes, as the information on short-term flow variability has been lost. While it can be concluded that it is possible to determine regionalized parameters from monthly data separation that are useful, further information on the processes involved would be of great value to validate the methods and parameter value (Hughes et al. 2003).

An estimate of base flow is made by plotting the hydrograph on semi-logarithmic paper, fitting a straight line to the end of hydrograph recession and projected backward in time under the peak. This projected line is transferred on to arithmetic graph paper and a smooth line is sketched connecting it to the end of the preceding recession fig (21). The direct runoff determined from this base flow separation process is used as input to the soil water balance model.

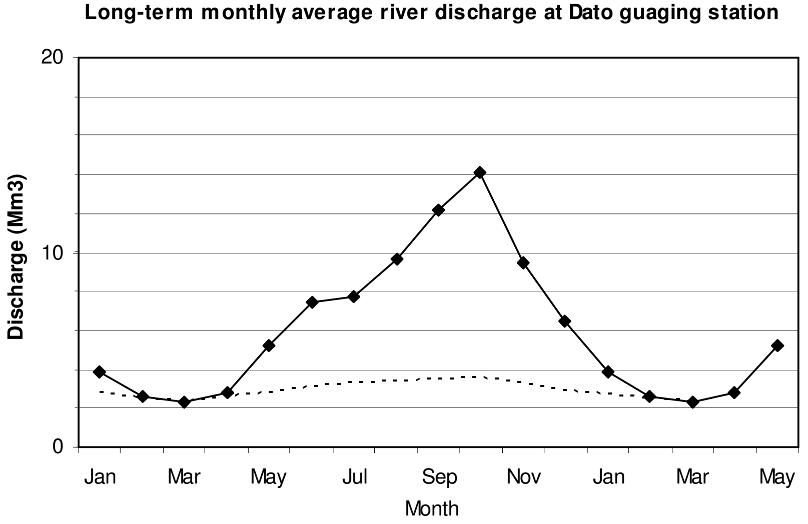


Figure 21 Long-term monthly average river discharge hydrograph (Dato station)

As estimated from the long-term monthly average discharge direct runoff and base flow constitutes 60% and 40% respectively of the total mean annual flow from the Tikurwuha sub-catchment.

4.2. Rainfall data

Rainfall data sets of seven rain gage stations namely Awassa, Yirbadubancho, Shashemene, Haisawita, Shone, Coffele and Wondogenet are obtained from National Meteorological Services. As coffele and Shone lay far outside of the catchment of interest the remaining rainfall data sets are considered in the computation of areal depth of precipitation.

A single rain gauge station should represent an area that complies with the world Meteorological organization. Thus the rainfall gauge density for tropical mountainous regions as indicated by Dingman [2002] is 300-1000 Km^2/gauge. The study area gauge density ranging from 139 Km^2 /gauge to 519 Km^2/gauge is found to be adequate.

To prepare the rainfall data for further application in the lake and catchment water balance estimates, the consistency of point rainfall measurements on the stations is checked using double mass curve analysis by taking nearby stations and no significant shift of slope on the plot is found.

There are different approaches for estimating missing rainfall data varying with and based on the effect of orography on rainfall, distance between the rainfall stations and the variation of rainfall amount recorded on the stations as discussed by Dingman, [2002]. Normal-ratio method is one of them 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 stations in the study area since the difference in annual rainfall between most of the stations exceeds 10%. This approach enables to estimate missing data by weighting the observation at G gages by their respective annual average rainfall values as expressed by the equation;

$$p_0 = \frac{1}{G} \times \sum \frac{P_0}{Pg} \times pg$$

Where p_0= the missing data,

P_0= the annual average precipitation at the gage with missing data.

P_g= annual average of neighbouring station, g

$p_{g=}$ monthly rainfall data in station for the same month of the missing station

G= the total number of gages under consideration

If the rain gage network is Uniformly distributed over an area , then a simple arithmetic average of the point-rainfall data for each station could be sufficient to determine the effective uniform depth of precipitation over the drainage catchment (Fetter 1994). However except Yirbadubancho station which is located south west of the catchment the rest four stations are situated on the eastern half of the catchment. The fact that rainfall records at Wondogenet station are high while it is located at the lowland area appears to be affected by the eastern escarpment since it is located close to the foot of the mountain. The rest of the stations have little indication of rainfall variability due to their respective locations. Despite Haisawita and Yirbadubancho stations are situated in relatively elevated areas there is no relation between altitude and the amount of rainfall table(2). It has been observed from the digital elevation model that there is no abrupt topographic difference around the stations that would enhance rainfall. Therefore long term spatial average precipitation has been estimated using Theissen polygon method that is considered adequate for a catchment where topography do not have clear effect on precipitation as indicated on Dingman[2002]. Catchment mean annual rainfall computations have been made from individual contributing stations by averaging annual precipitation values for years when records of respective gauge site is complete, which varies from 12 to 31 years record, and multiplying with the weighted area of each Theissen polygon represented by each rainfall station Table (2). Monthly and annual rainfall areal distributions are also computed both for the lake and for the total catchment.

Station name	Mean Annual rainfall (mm)	Area represented by the station(Km^2)	Elevation m.a.m.s.l
Wondogenet	1136	300.93	1770
Awassa	956	519.87	1701
Shashemene	947	139.53	1943
Haisawita	992	221.78	2249
Yirbadubancho	1117	273.20	2034
Catchment mean annual precipitation (mm)	**1028mm**		

Table 2 Mean annual rainfall over the Lake Awassa catchment

During the lake water balance estimation precipitation over 6% and 94% of the lake area is taken from Yirbadubancho and Awassa's rainfall station records respectively.

Interannual variability of rainfall on the catchment is apparent as indicated on fig (22), that annual rainfall ranges from 810mm on the driest year (1999) to 1204mm on the wettest year (1996).

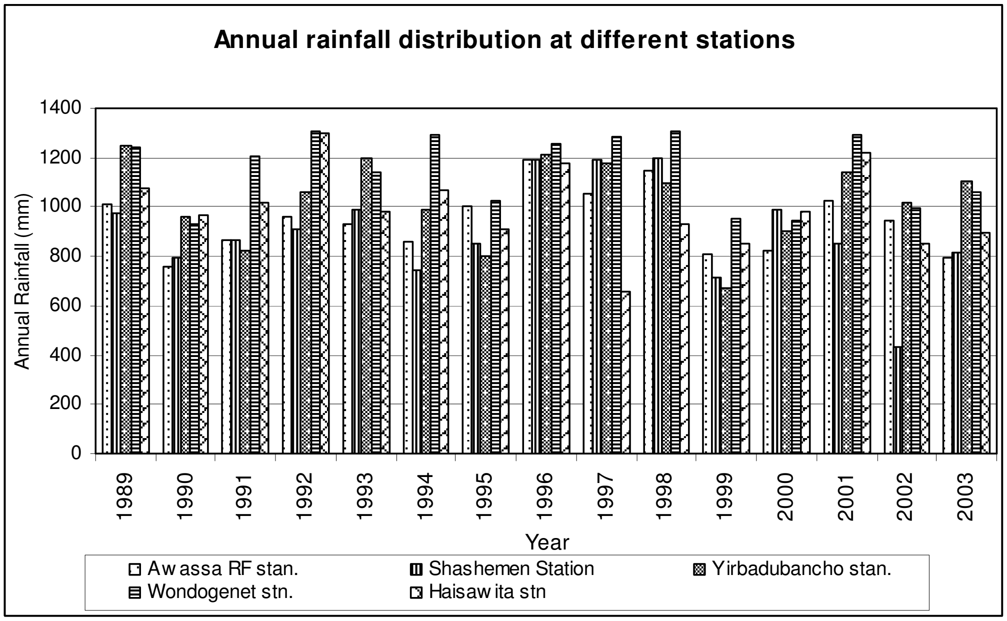


Figure 22 Annual rainfall distributions at different stations

4.3. Evaporation data

There are many ways of calculating Evaporation from large water bodies. Water balance approach, Mass transfer approach, Energy balance approach, or Penman combination approach and pan evaporation approach are some to mention. Dingman 2002, indicates that due to its demand of usually an available data from most of meteorological stations like surface water temperature, most of the approaches are less applicable to data scarce areas.

Penman (combination approach) is an approach which does not require surface water temperature and is recommended for estimating free water evaporation Maidment, [1993]. The Penman equation reads;

$$E_p = \frac{\Delta}{\Delta + \gamma} \times (R_n + A_h) + \frac{\gamma}{\Delta + \gamma} \times \frac{6.43 \times (1 + 0.536 U_2) \times (e_s - e_a)}{0.1555 \lambda}$$

Where,

E_p= potential evaporation that occurs from free water evaporation…….. [mm day^{-1}]
R_n= net radiation exchange for the free water surface,………………… [mm day^{-1}]
A_h= energy advected to the water body, ……………………………….. [mm day^{-1}]
U_2= windspeed measured at 2m, ……………………………………………… [ms^{-1}]
e_s-e_a= vapour pressure deficit ………………………………………………… [kPa]
λ= latent heat of vaporization……………………………………………… [MJ kg^{-1}]
γ= psychrometric constant ……….. [kPa $^0c^{-1}$]
Δ=slope of saturation vapour pressure curve at air temperature………..... [kPa $^0C^{-1}$]

Monthly evaporation data estimated using Penman (combination) equation is presented in appendex (2.1).The mean monthly evaporation values are presented on table (4).

Class A pan Evaporation data have been collected from National Meteorological Services. The Pan is placed 500m to 1 km east of the lake. In contrast to a lake, the Class A pan receives large quantities of energy from radiation and conduction through its base and sides because it is exposed to air and sun. Evaporation from the pan, therefore, will be larger than a lake under the same meteorological conditions. Moreover, the difference between pan and lake will vary through the year because of seasonal differences in radiation, air temperature, wind and heat storage with in the larger body of water. A coefficient that varies through the year must, therefore, be applied to measurements of pan evaporation in order to estimate water loss from the lake, Dunne and Leopold [1978].

Pan coefficients (Kp) for Class A pan for different pan siting, environment and different levels of mean relative humidity and wind speed have been presented in FAO drainage and Irrigation Paper 56 as in Table(3).To account for the differences in meteorological conditions of each month, different coefficients have been used. The pan evaporation estimates as is shown on fig (24) have been dropped dramatically since 1995. Although the general trend of evaporation on the study area, even for Penman method is slightly decreasing such a sudden drop has no explanation if not an error associated to the recorded data.

Class A pan	Case A: Pan placed in short green cropped				Case B: Pan placed in dry fallow area			
RH(%) →		Low <40	Medium 40-70	High >70		Low <40	Medium 40-70	High >70
Wind speed (ms^{-1})	Windward side distance of green crop (m)				Windward side distance of dry fallow (m)			
Light <2	1	0.55	0.65	0.75	1	0.7	0.8	0.85
	10	0.65	0.75	0.85	10	0.6	0.7	0.8
	100	0.7	0.8	0.85	100	0.55	0.65	0.75
	1000	0.75	0.85	0.85	1000	0.5	0.6	0.7
Moderate 2-5	1	0.5	0.6	0.65	1	0.65	0.75	0.8
	10	0.6	0.7	0.75	10	0.55	0.65	0.7
	100	0.65	0.75	0.8	100	0.5	0.6	0.65
	1000	0.7	0.8	0.8	1000	0.45	0.55	0.6
Strong 5-8	1	0.45	0.5	0.6	1	0.6	0.65	0.7
	10	0.55	0.6	0.65	10	0.5	0.55	0.65
	100	0.6	0.65	0.7	100	0.45	0.5	0.6
	1000	0.65	0.7	0.75	1000	0.4	0.45	0.55
Very strong>8	1	0.4	0.45	0.60	1	0.5	0.6	0.65
	10	0.45	0.55	0.6	10	0.45	0.5	0.55
	100	0.5	0.6	0.65	100	0.4	0.45	0.5
	1000	0.55	0.6	0.65	1000	0.35	0.4	0.45

Table 3 Pan Coefficients for Class A pan for different pan siting and environment and different levels of mean relative humidity and wind speed (FAO Irrigation and Drainage paper No. 24)**.**

Month	Mean monthly evaporation values	
	Pan evaporation method	Penman evaporation method
January	147.8	146.3
February	137.9	133.4
March	149.1	146.2
April	130.2	108.1
May	138.3	115.2
June	127.7	100.7
July	111.1	64.9
August	115.1	79.2
September	113.4	86.5
October	121.5	114.1
November	135.5	136.7
December	140.2	142.5

Table 4 Mean monthly evaporation estimates of Pan and Penman (combination) methods

Note that the pan in case of Awassa station is placed in a compound surrounded by short grass that is assumed to be a green crop. Mean annual estimate of the pan evaporation is 1567 mm year^{-1} and from Penman (combination) method is 1375 mm year^{-1}.

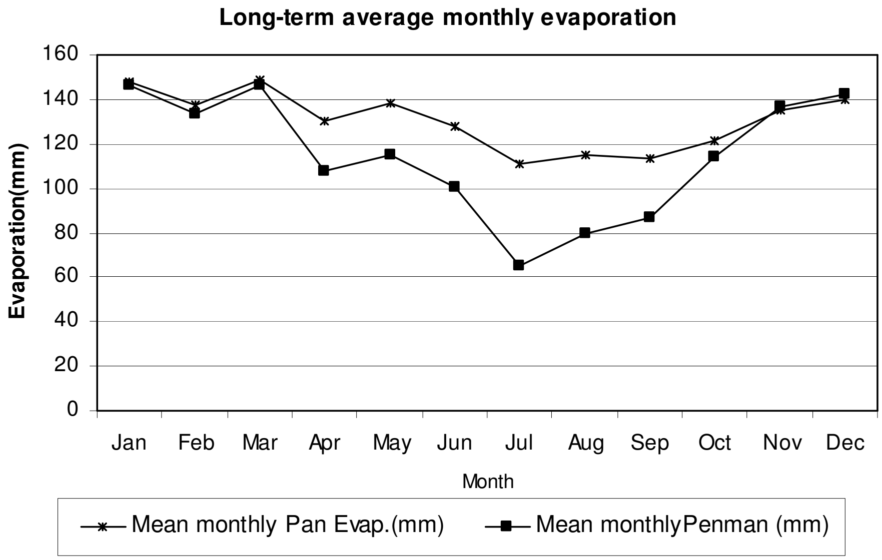


Figure 23 Evaporation distribution of Lake Awassa (1986-2002)

Figure 23 shows a plot of long-term mean monthly evaporation data after converting the pan evaporation with the pan coefficients of table 6. Pan evaporation data and Penman (combination) evaporation values follows similar pattern during the dry season Penman values being at the lower level, but during the wet months of April to September the magnitude and trend of evaporation values lose its previous pattern. This could possibly be attributed to human and instrument errors exacerbated due to intensive rainfalls when records of Pan Evaporation or variables used in the Penman (combination) method are measured.

The process of vapour removal depends to a large extent on wind and air turbulence which transfers large quantities of air over the evaporating surface. When water vaporizes, the air above the evaporating surface becomes gradually saturated with water vapour. If this air is not continuously replaced with drier air, the driving force for water vapour removal and the evapotranspiration rate decreases Allen et al, [1998]. It is reasonable from the plot of wind speed fig (26) and evaporation fig (24) both in a decreasing trend that indicates the decreasing ability of the wind speed to remove the water vapour has contribution in the slight reduction of the evaporation.

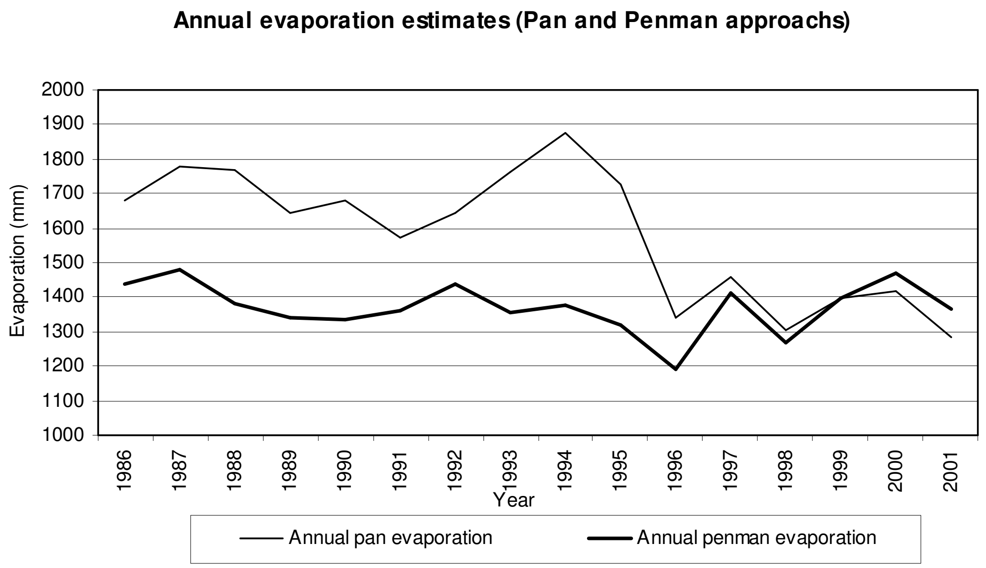


Figure 24 Annual evaporation estimates of Pan Evaporation and Penman (combination) approach

4.3.1. Sensitivity analysis of Penman (combination) evaporation method

Penman Combination approach of evaporation estimation as can be seen in the fig (25) is more sensitive to shortwave radiation followed by relative humidity. An increase or decrease of estimated shortwave radiation by 10% could result in an increase or decrease of estimated evaporation up to 20%. This method is least sensitive to wind speed but it could bring a significant effect on the lake level fluctuation since 10% increase of wind speed increases the estimated evaporation by 1%. Thus evaporation is one of the most sensitive variables in the lake water balance model that 1% increase or decrease in evaporation could lead to 0.003% (5cm) increase or decrease in lake level.

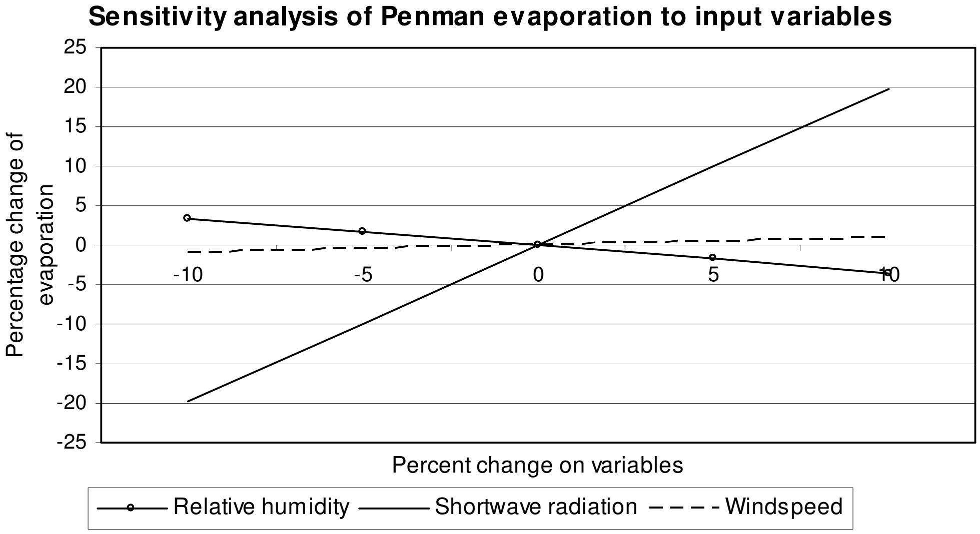


Figure 25 Sensitivity analysis of evaporation to different variables

	Change in evaporation in percent upon change of variables		
Change of variables in percent	Relative humidity	Shortwave radiation	Wind speed
-10	3.3	-19.7	-0.9
-5	1.7	-9.9	-0.5
5	-1.7	9.9	0.4
10	-3.5	19.8	0.9

Table 5 Sensitivity analysis of Penman (combination) method

4.4. Wind speed

Wind speed time series data covering the period from 1981 through 2003 had a missing records ranging from one month to 2 years in some cases. An average value of the preceding years of the same month to the missing data has been filled. No explanation could also be given for the lowest records in Oct., 1988-Dec. 1989. Since it is an outlier it has been replaced with an average value of the same month of the preceding years for the purpose of evaporation and reference potential evapotranspiration computations. The trend of wind speed over the past decades as shown in fig (26) has decreased from 1.47 ms^{-1} in 1973 to 0.79 ms^{-1} in 2003 with some variations in-between. The fact that the meteorological station at Awassa is located at the centre of the town construction of buildings and overall expansion of the town might have an effect on the continuous decrease of the wind speed.

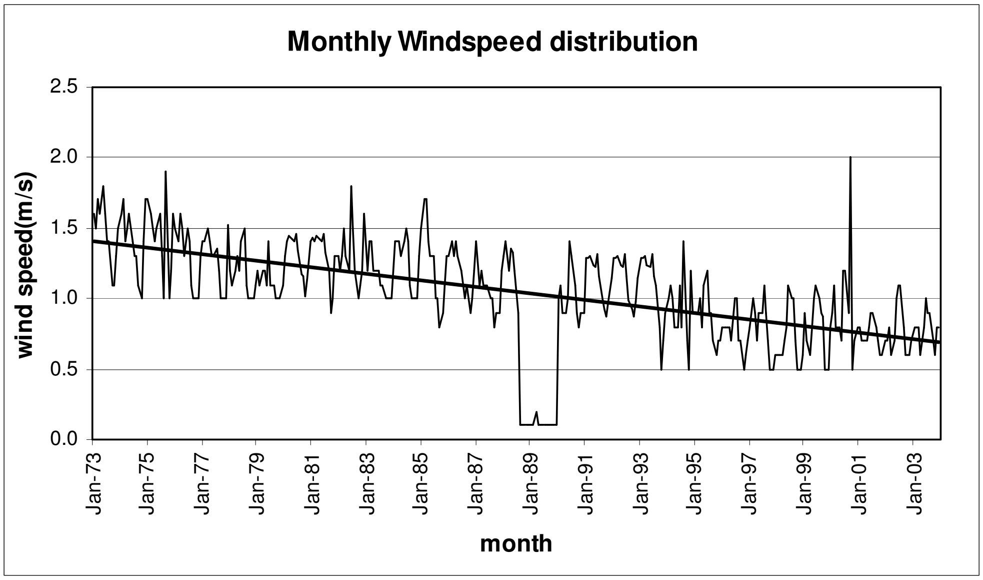


Figure 26 Wind speed trend of the study area over time (1973-2003)

4.5. Evapotranspiration

In calculating evapotranspiration, which is an input to the soil water balance model, applying Penman method or other methods which take into account a more complete range of meteorologic observations are recommended by (Donker 1987).

Major study has also been undertaken by American society of civil engineers and a consortium of European research institutes to evaluate the performance of different evapotranspiration estimation procedures under different climatoligical conditions. Both have indicated the FAO Penman-Monteith approach of reference crop evapotranspiration as relatively accurate and has consistent performance in both arid and humid climates. Thus it is recommended as the sole standard method in the evapotranspiration estimation (Allen.et.al 1998). Evapotranspiration of any crop could be estimated by multiplying the reference crop evapotranspiration with crop coefficient of the crop of interest. Estimated monthly average Reference crop evapotranspiration using FAO Penman-Monteith approach has been used to estimate the crop potential evapotranspiration and actual evapotranspiration in the Thornthwaite and Mather soil water balance procedure Table(6).

The equation is expressed as:

$$ETo = \frac{0.408\Delta(Rn - G) + \gamma \frac{900}{T+273} U2(es - ea)}{\Delta + \gamma(1 + 0.34U2)}$$

Where,

ETo= reference evapotranspiration ……………………………………………[mm day $^{-1}$]
Rn= net radiation at the crop surface ………………………………………..[MJ m^{-2}day^{-1}]
G= soil heat flux density ……………………………………………………[MJ m^{-2}day^{-1}]
T= mean daily air temperature at 2 m height …………………………………………..[^{0}c]
U_2= wind speed at 2 m height ………………………………………………………..[ms^{-1}]
e $_{s=}$ saturation vapor pressure ………………………………………………………...[kPa]
e_a= actual vapor pressure ………………………………………………………………..[kPa]
e_s-e_a= saturation vapor pressure deficit ………………………………………………[kPa]
Δ= slope vapor pressure curve …………………………………………………[kPa ^{0}c^{-1}]
γ= psychrometric constant ……………………………………………………..[kPa ^{0}c^{-1}]

Month	Mean monthly ETo Estimated with FAO Penman-Monteith method (mm)
January	100
February	91
March	99
April	73
May	75
June	65
July	39
August	47
September	52
October	76
November	91
December	96

Table 6 Mean monthly Reference crop evapotranspiration estimated using FAO Penman -Monteith method

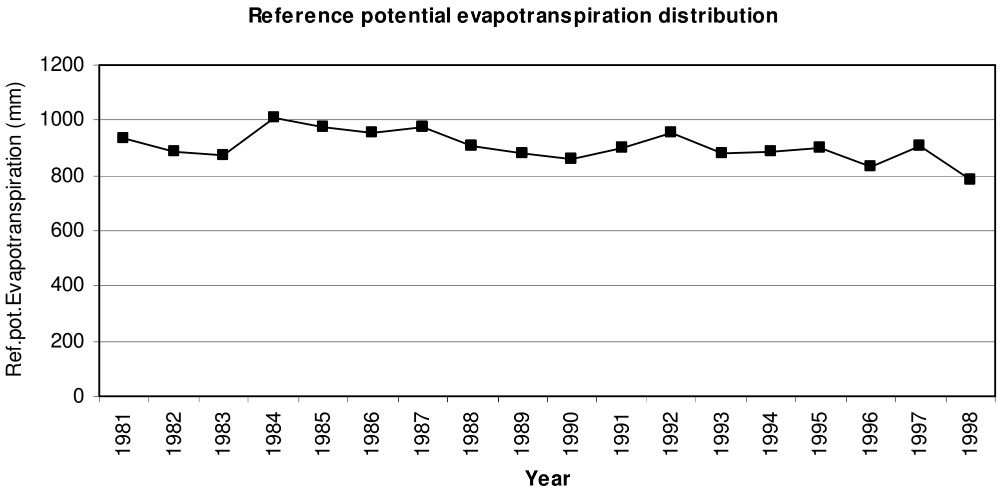


Figure 27 Reference potential evapotranspiration distribution

Figure 27 shows a slight decline of reference potential evapotranspiration which in turn could have a contribution on an increase of catchment runoff.

4.6. Relative humidity

Relative humidity is a measure of the water vapour content of the air at a given temperature. The variation in relative humidity is the result of the fact that the saturation vapour pressure is determined by the change of air temperature. It can be seen from fig (28) that relative humidity has decreased during the past 30 years as temperature increases. As indicated in appendix (1) forests generally cool and humidify the atmosphere. The decrease in relative humidity and increase in temperature over the catchment could possibly signify the effect of deforestation at regional level. Relative humidity record covering 1981-2003 and averaged in to monthly time scale is used in the calculation of evaporation and reference crop evapotranspiration of the catchment. The mean monthly relative humidity value is given in table (7).

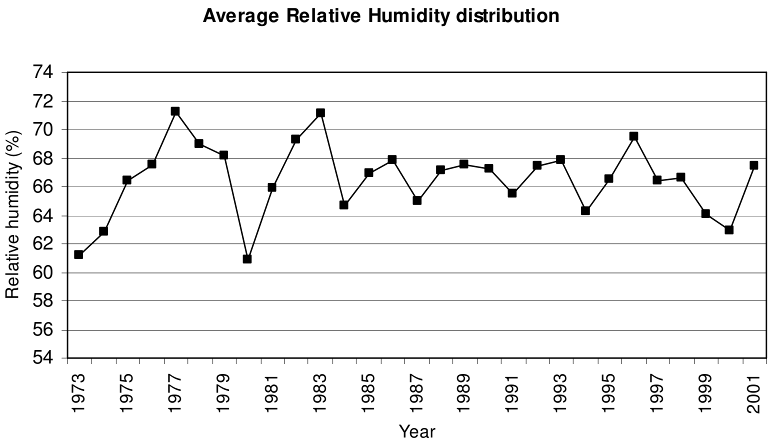


Figure 28 Average Relative humidity distribution

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean monthly RH (%)	54.6	53.9	60.7	67.8	73.1	70.3	74.3	75.3	77.3	70.3	59.7	56.2

Table 7 Mean monthly relative humidity at Lake Awassa area (1973-2002)

4.7. Temperature

Awassa meteorological station is the only station in the catchment from which temperature records since 1981 till 2003 was obtained. A mean, minimum and maximum temperature value from this station is used in the computation of reference potential evapotranspiration and evaporation. The increasing trend of temperature fig (29) could be an indication of climatic changes over the region. It is difficult however to explain the cause of the possible climatic change in terms of regional or local land use changes at this level.

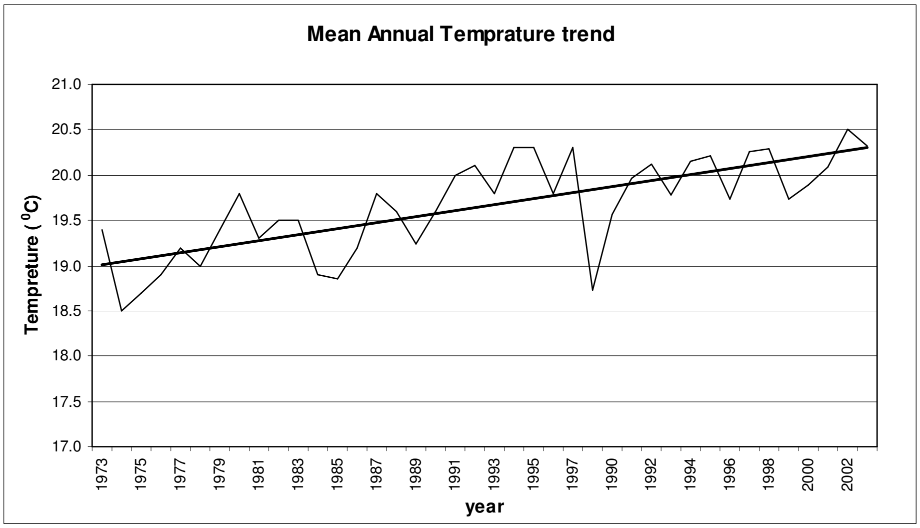


Figure 29 Mean annual temperature trend on Lake Awassa area (1973-2002)

4.8. Abstraction data

Lake water abstraction for human consumption is assumed to be minimal as in most cases the rural people are using groundwater source from hand dug wells, boreholes and springs. However livestock water consumption, diversion of streams and high yielding springs for small scale irrigation and towns water supply have decreased the a amount of water that has been entered in to the lake. An abstraction of $7.56*10^5$ m^3/year from Kedo river Nidaw, (1995); NAPI, [1994]; an approximated $9*10^5$ m^3/year for Shashemene town water supply from Wosha river, (Nidaw, 1995), has been estimated. Loke cold spring (yielding 20 l/sec), which was entering the lake until it has been diverted to Awassa town water supply in 2001 could be considered as additional abstraction of $6.3*10^5$ m^3/year. That means a total of close to $2.286*10^6$ m^3/year of water which ultimately would have been reached on the lake could be assumed abstracted. This abstraction accounts for 1% of the estimated total mean annual inflow of approximately 222 Mm^3 to the lake in terms of surface runoff from Tikurwuha sub-catchment, direct precipitation over the lake and through groundwater inflow from the surrounding aquifer. So it is considered to be negligible in the lake water balance computation and lumped to the groundwater outflow.

5. The Water balance

5.1. The hydrologic cycle

As indicated in most of hydrology literatures the continuous movement of all forms of water on the earth is called hydrologic cycle. This includes condensation of vapour in the atmosphere that gives rise to precipitation. Precipitation partly intercepts by vegetation and partly reaches the surface. Evaporation takes place from the intercepted water by vegetation and from the surface storage. Water also flows through streams and reach lakes and oceans from where evaporation and seepage to groundwater occurs. Precipitation that infiltrates in to the soil could also leave by evapotranspiration or reach streams by through flow and partly percolates to groundwater. The depletion of water in the surface and subsurface due to evaporation and evapotranspiration causes groundwater to move upward direction through the process called capillary rise. Some of it evaporates or moves to streams as base flow or to the oceans and lakes through deeper routes.

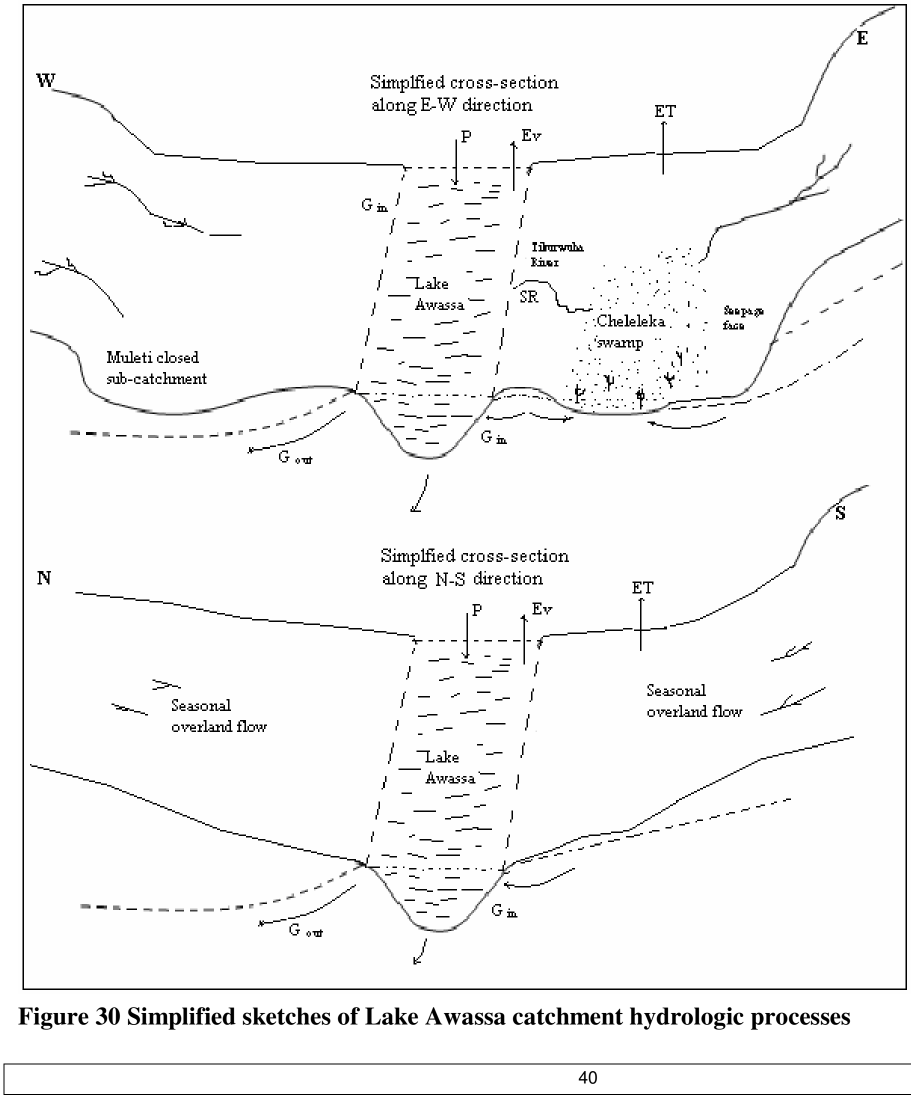


Figure 30 Simplified sketches of Lake Awassa catchment hydrologic processes

5.2. Catchment water balance model

Generally in a rift valley system tectonic activities are intensive and geological processes are more dynamic. The nature and behaviour of Lake Awassa catchment is more complex. Multidirectional faulting systems, caldera collapse, recent ground cracks and other possible hidden structures are some of the manifestations of the complexities. However, to understand how the land use and climatic changes could have contributed to the lake level rise, simplified hydrologic relations of surface and sub-surface of the catchment has been assumed. Variables like crop coefficient and water capacity in the root zone for different land use types are assigned by an average value weighted by the area covered with particular land use. Additionally assumptions are introduced where there are no published values for variables of a certain land cover type in a specific environment similar to the study area.

The Thornthwaite and Mather procedure has been used in the catchment water balance estimation. This procedure is based on lumped conceptual soil water balance model where catchment characterstics like soil, land use, rainfall and evapotranspiration are aggregated to represent catchment or sub-catchment of interest.

In the simplified hydrologic process as explained by (Meijerink 1994) fig (31) a certain percent of total rainfall leaves the area as surface runoff (direct storm runoff). The remaining part, which is effective rain, goes to the soil as infiltration and when water holding capacity of the soil fills surplus water percolates to groundwater. When the atmospheric demand is not met by the effective rain water is withdrawn from the soil moisture by evapotranspiration. Evapotranspiration from the soil depends on the capacity of the soil to retain moisture and it is expressed by the soil moisture depletion curve; the drier the soil is, the more difficult it becomes to extract water. Groundwater store acts as a buffer and causes a delay in the groundwater runoff. Therefore only fixed fractions of the surplus of the current month and water detained in the previous month become part of the groundwater flow. The direct storm runoff and groundwater runoff together form total predicted catchment outflow. The equations involved in the soil water balance accounting procedure are expressed as;

$$SR= C1*P$$
$$SRECH=(P-SR)-ET$$
$$GRECH=(SRECH-(WHC-SM)$$
$$SM=WHC*Exp(-APWL/WHC)$$
$$GRO=(DET+GRECH)*C2$$
$$Tout=SR+GRO$$

Where;

SR= direct storm runoff	C1= runoff coefficient
SRECH= surface recharge	P= precipitation
ET=actual evapotranspiration	GRECH= groundwater recharge
Sm= soil moisture	GRO= groundwater runoff
Tout= predicted catchment outflow	APWL= accumulated potential water loss.

Where unit of all variables is in mm

A computer program called WTRBLN developed and discussed below by (Donker 1987)on bases of the Thornthwaite and Mather [1957] water balance calculation method is used. This technique uses long-term average monthly rainfall, long-term average potential evapotranspiration, and soil and vegetation characteristics. The last two factors are combined in the water capacity of the root zone. Three additions to the original methods are implemented in the program, WTRBLN. Direct runoff can be entered as average monthly figures which will be subtracted from the monthly rainfall figures. Direct runoff bypasses the calculations for the water balance and is treated immediately as runoff.

Instead of using the Thornthwaite method to calculate potential evapotranspiration, which is based on air temperature only, more realistic results can be obtained by applying a reference potential evapotranspiration calculated by the Penman or other methods which take in to account a more complete range of meteorologic observations applied to a reference (grass). Crop coefficient is also another variable introduced in to the model.

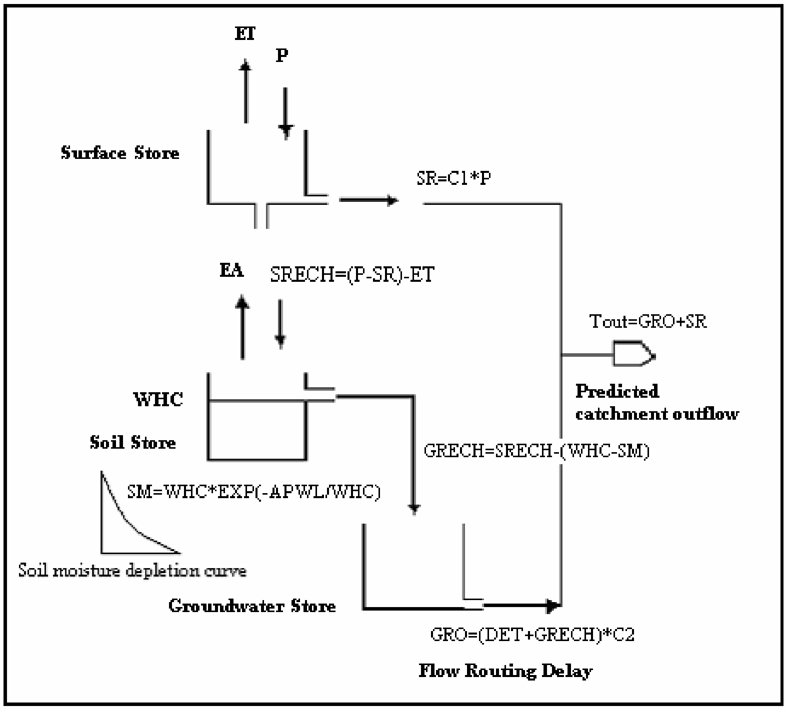


Figure 31 Graphical representation of a simple water balance model (adopted from Meijerinck, et al 1994)

Total available water refers to the capacity of a soil to retain water available to plants. Water holding capacity of different soils and rooting depths of different land cover types is obtained from the table (8).

Soil and land cover maps of 1998 at a scale of 1:50,000 obtained in a hardcopy form from Water Works Construction and Supervision Enterprise (W.W.C.S.E) is modified and crossed to obtain the spatial distribution of water capacity of the root zone fig (32). In soil moisture condition assessment in relation to land use, detail knowledge of the vegetation species including rooting depth is vital. However with respect to the diversity of vegetation found in the lakes region the rooting depth of most of the vegetation is not available. Therefore this emphasizes the need to use such values by inferring studies conducted in different parts of the world preferably in a similar climate. The rooting depths and crop coefficients of different land cover units are obtained from different sources as indicated on the table (8) and table (9) respectively and some assumptions are made when there are no published values. For the cultivated land an average of 150 to 180 days of growing period is assumed as obtained from the local people (mid-April to Mid-Oct) and the remaining period assumed to be barren soil wetted and dried with the seasonal rainfall. To account a loss in the form of evaporation of the soil an initial crop coefficient value determined as a function of the frequency of wetting and evaporating power of the atmosphere indicated in FAO Irrigation and Drainage Paper 56 of Kc of 0.2-0.4 is assumed. Thus with the moderate evaporating power (3-5mm/ day) of the study area and a wetting interval of longer than once per week, the minimum value of kc 0.2 is considered for the area.

Vegetation	Soil texture	Available water capacity (% volume)	Rooting depth(m)	Available water capacity of root zone(mm)
Shallow rooted crops(spinach, peas, beans beets, carrots, etc)	Fine sand	10	0.5	50
	Fine sandy loam	15	0.5	75
	Silt loam	20	0.62	125
	Clay loam	25	0.40	100
	Clay	30	0.25	75
Moderately deep rooted crops(corn, cereals, cotton, tobacco)	Fine sand	10	0.75	75
	Fine sandy loam	15	1.00	150
	Silt loam	20	1.00	200
	Clay loam	25	0.80	200
	Clay	30	0.50	150
Deep rooted crops (alfalfa, pasture grass, shrubs)	Fine sand	10	1.00	100
	Fine sandy loam	15	1.00	150
	Silt loam	20	1.25	250
	Clay loam	25	1.00	250
	Clay	30	0.67	200
Orchards	Fine sand	10	1.50	150
	Fine sandy loam	15	1.67	250
	Silt loam	20	1.50	300
	Clay loam	25	1.00	250
	Clay	30	0.67	200
Mature forest	Fine sand	10	2.50	250
	Fine sandy loam	15	2.00	300
	Silt loam	20	2.00	400
	Clay loam	25	1.60	400
	Clay	30	1.17	350

Table 8 Suggested available water capacities for combinations of soil texture and vegetation. (from Thornthwaite and Mather, 1957)

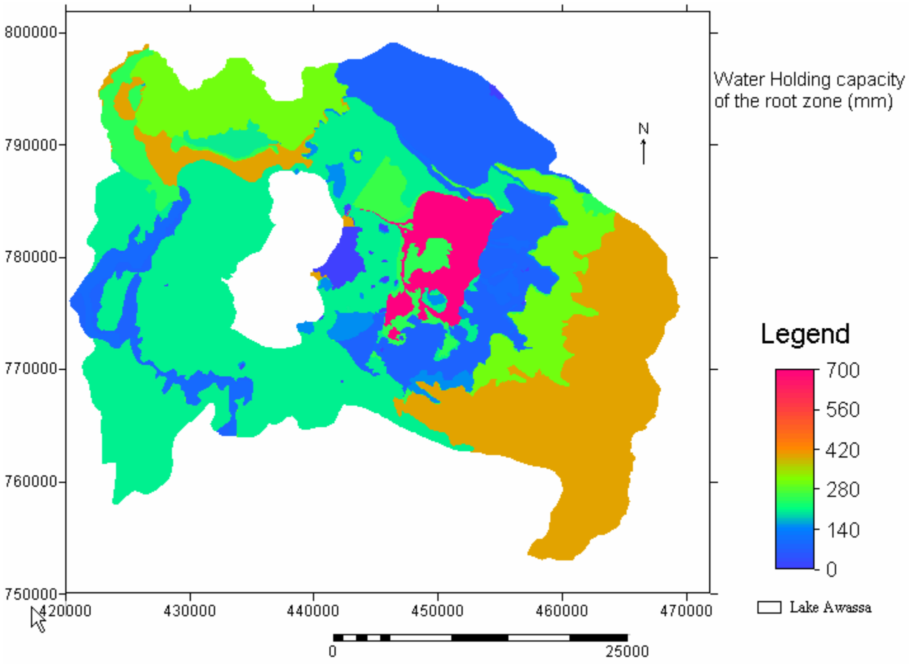


Figure 32 Map of Water Holding Capacity of the root zone

Land cover	Crop coefficient (Kc)	Remark
Open grass land (grass cover for grazing)	0.8	An average Kc for grazing pasture is assumed. Source (FAO, I&D paper 56)
Open bush land with cultivated land(scattered bushy area with some crop fields in-between)	1*	
Cultivated land (All seasonal crops)	0.8	An average Kc for major crops on the area (Maize and wheat) Source FAO I&D paper 56.Average value for the variable Kc of different growth stage.
Dense bushy woodland (Mainly covered with bush, natural evergreen vegetation and some grass in a closed area)	1	Assumed the value given for fully covered forest in FAO I&D paper 56
Swampy grass land (Water logged grass land covered fully or partially with long grass and papyrus)	1.1	An average for reed swamp, standing water given in FAO I& D paper 56.
Built up (Towns)	0.2	Assume 20% of the town is covered with grass and trees
Bare land (rock exposures)	0	Assumed
Shrubby grass land(grass land with scattered shrubs)	0.8	Similar to value given for grass above
Open shrub land (mainly composed of shrub with little grass)	1*	Assumed

Table 9 Kc values assumed for different land cover types in the estimation of evapotranspiration.

NB:1* value given as recommended by Donker, 1987 when the Kc value is not known.

5.2.1. Run the soil water balance model

The water balance of Lake Awassa catchment is estimated based on long-term average climatic variables and 1998 land use map and soil maps obtained from W.W.C.S.E [2001]. However the marshy area which covers large part south of cheleleka swamp as observed on the 1994 and 2004 images and verified during the field work is represented by open grassland in the 1998 land use map. For water balance computation purpose this map is modified so that the grassland will be replaced with swampy grassland covering similar area interpreted as a swamp in the satellite images. Water balance for the gauged Tikurwuha sub-catchment has been treated separately in order to see whether or not possible to estimate the water balance components of the catchment using Thornthwaite and Mather soil water balance procedure fairly. As it has been discussed earlier WTRBLN program has an advantage for the user to enter direct runoff so that by deducting this value from precipitation it improves the estimates of the remaining water balance terms and it is also possible to validate the predicted total runoff estimates with the measured stream flow data, Tikurwuha river gauging station in case of Tikurwuha sub-catchment. Therefore direct runoff is simply estimated using hydrograph separation technique from monthly river gauged data as discussed in section 4.1. All the discussed catchment parameters earlier are used in the water balance model.

5.2.2. Model output and analysis

Results from the Thornthwaite and Mather water balance procedure with many of the catchment soil type, land cover and crop coefficient values assumed and spatially lumped gives values with significant seasonal and annual discrepancy with the measured discharge values, table (10). On annual basis predicted total runoff for example from the gauged Tikurwuha sub-catchment based on land use map of 1998 is 200Mm^3 which is more than 100% higher than what is measured in the sub-catchment outlet 83Mm^3, not to mention the inaccuracy of the river discharge measurement itself. Since abstraction of water for irrigation and water supply from rivers and boreholes upstream is not quantified it might have contributed to the water balance estimation discrepancy. On top of that the possible existence of subsurface structures which might divert water in to different direction or in to deep aquifer, could also be another reason for lower measured discharge values at the outlet.

The model as indicated in fig (33) underestimates the predicted runoff component from the gauged Tikurwuha sub-catchment during the dry months and overestimates it during the wet season. This is due to the fact that soil water balance modelling using long-term average input data as explained in (Dune and Leopold 1978), tend to underestimate extreme deficits and extreme surpluses. Individual storms that could contribute to the river discharge during dry season is undermined because the model assumes rainfall is utilized to fill the moisture demand of the catchment as far as a deficit exists. It is also possible that the high predicted discharge values during the wet season include water which might have been detained in the swamp. Although in a different catchment North of Lake Awassa, Tenalem [1998] stated that field base flow measurements revealed channel losses from the large rivers in the permeable lacustrine sediments. Some rivers in the eastern part of the basin also lose water in large marginal faults. As Awassa catchment is located in the same valley floor and the lowland which perennial rivers from the eastern escarpment pass through is formed of lacustrine sediments it may be assumed channel losses have reduced the water which would have reach in the discharge measurement station.

Month	Long-term measured river discharge (mm/month)	Long-term estimated discharge (mm/month)
January	6	10
February	4.1	4
March	3.6	3
April	4.4	2
May	8.2	5
June	11.6	18
July	12.2	47
August	15.1	59
September	19.1	74
October	22.2	53
November	14.9	31
December	10.2	19

Table 10 Comparison of discharge estimated using the soil water balance model with measured discharge from Tikurwuha sub-catchment

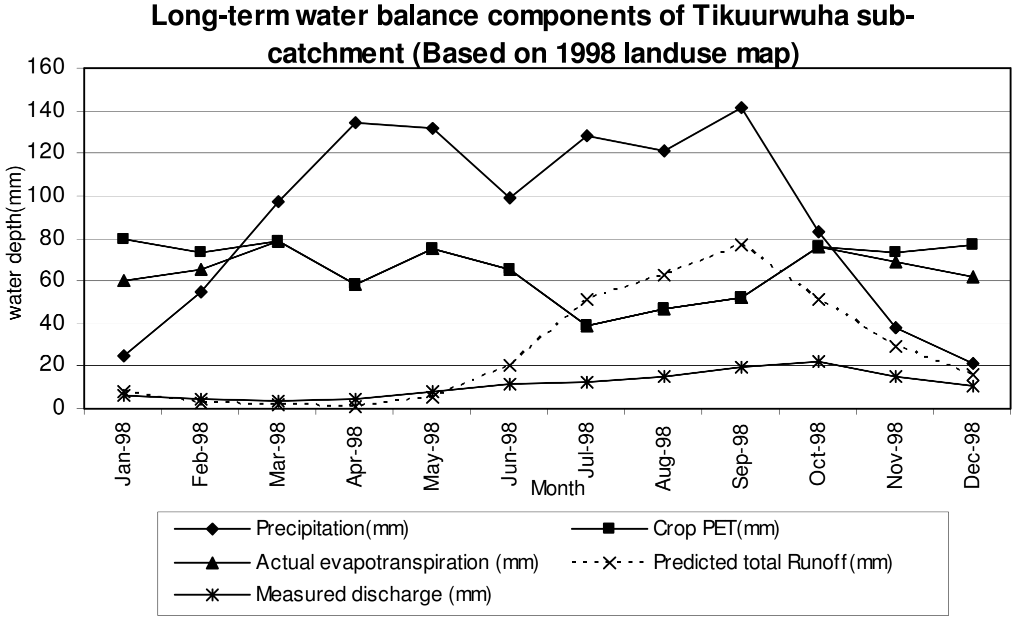


Figure 33 Long-term soil water balance of Tikurwuha sub-catchment

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	
P	27	50	92	127	126	98	116	114	133	86	33	25	**1027**
DRO	1	0	0	0	2	3	3	5	6	8	5	3	**36**
P-DRO	26	50	92	127	124	95	113	109	127	78	28	22	
RefPotEvp	100	91	99	73	75	65	39	47	52	76	91	96	**904**
Kc	0.6	0.6	0.6	0.6	1	1	1	1	1	1	0.6	0.6	
CropPotEvp	60	55	59	44	75	65	39	49	52	76	55	58	**687**
P-PET	-33	-5	33	83	51	33	77	65	81	10	-22	-33	**340**
AcPotWls	-88	-94									-22	-55	
Sm	185	181	214	260	260	260	260	260	260	260	239	210	
dSm	-25	-4	33	46	0	0	0	0	0	0	-21	-29	
AET	52	54	59	44	75	65	39	49	52	76	54	54	**673**
D	8	1	0	0	0	0	0	0	0	0	1	4	**14**
S	0	0	0	37	51	33	77	65	81	10	0	0	**354**
TLAVAIL	10	5	2	37	70	68	111	121	141	80	40	20	
Ro	5	3	1	19	35	34	55	61	71	40	20	10	**354**
DET	5	2	1	18	35	34	56	60	70	40	20	10	

Table 11 Long-term Awassa catchment soil water balance

Units of all the components are in mm.

Where; P=precipitation, DRO= direct runoff, P-DRO=precipitation minus direct runoff, RefPotEvp= reference evapotranspiration, Kc=crop coefficient, CropPotEvp=crop potential evapotranspiration, P-PET= precipitation minus runoff minus crop evapotranspiration, AcPotWls=accumulated water loss, Sm= soil moisture, dSM=change in soil moisture, AET= actual evapotranspiration, D=soil moisture deficit, S=moisture surplus, TL AVAIL= total water available for runoff, Ro= runoff without direct runoff, DET= detention

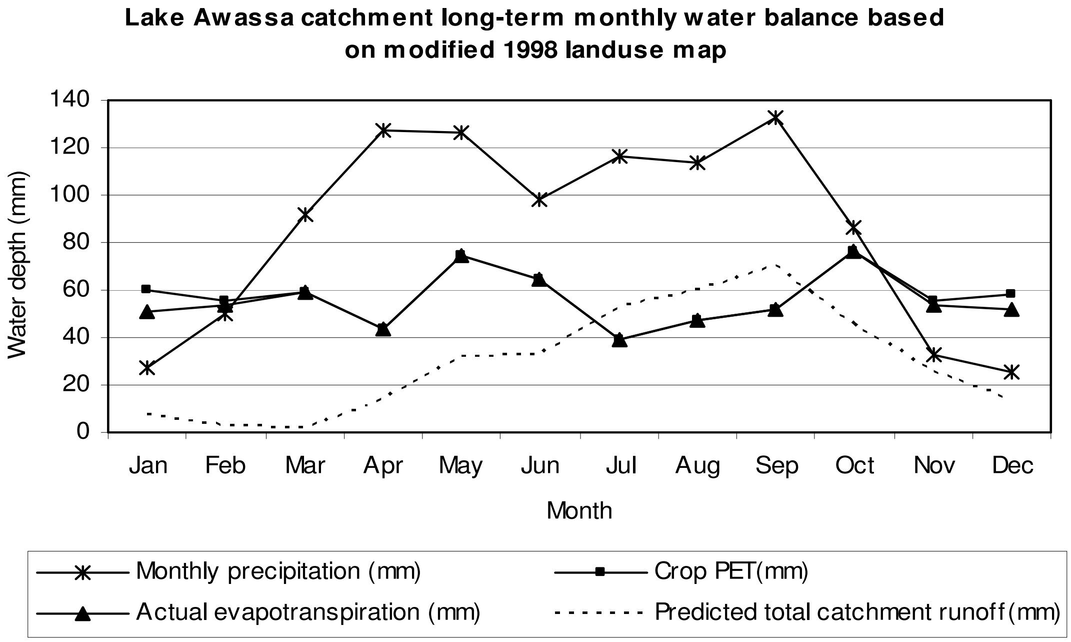


Figure 34 Lake Awassa catchment long-term monthly water balance

Despite all the uncertainties discussed above the soil water balance model can give indicative estimates of the long-term average water balance components from the land surface of the catchment. Accordingly annual long-term average precipitation, actual evapotranspiration and surplus water is estimated as 1398Mm^3, 916Mm^3 and 482Mm^3 respectively. The surplus water comprises the surface runoff from the gauged catchment reaching the Lake Awassa which is 83Mm^3 and some surface runoff from the un-gauged sub-catchments and groundwater inflow in to the lake. The remaining is part of groundwater outflow from the catchment to neighbouring catchments through deeper routes or fault zones.

5.2.3. Catchment response for different climatic and land use scenarios

To analyse the catchment response to different land use and climatic changes and the effect of the response on the Lake level rise different scenarios were considered.

Modelling Land use change scenario

The most rational way to model the impact of land use changes on the runoff dynamics of a river catchment would be through the implementation of spatially distributed physically based hydrological models in which the land surface characteristics of the catchment are represented and all the processes influenced by them are modeled using parameters that can physically be estimated a priori. However such models are highly demanding in terms of their data requirement and computational effort, which increases further as the size of the catchment increases. This limits their applicability to small or meso-scale catchments. Even under such a restriction, results obtained from previous studies done on the applicability of such an approach were not promising, (Parkin et al., 1996) cited by (Hundecha and Bardossy 2004)

Therefore to estimate the impact of a certain land use change on a catchment response with the lumped soil water balance model used in the present study could be less accurate. Thus the assessment of the impact of land use and climatic changes on the catchment response of this particular study area is meant only to give an insight to what extent land use of the area has changed during the past 30 years and its implications on runoff generation broadly.

Major land use changes in the catchment

Land use changes like urbanization, change of dense shrub land and dense wood land in to cultivated land and change of shallow Lake Cheleleka in to a swamp are found to be the major changes in the catchment. From the generalized map of the 1965, 1998 and 2004, it has been observed that aggregated area of dense bushy wood land, dense woodland and dense shrub land has decreased from 289km^2 in 1965 to 86km^2 in 1998. This area is transformed partly in to open bushy woodland and partly to open grassland and agricultural land. Similarly 4 km^2 built up area of 1965 has grown to 13 and 18 km^2 in 1998 and 2004 respectively.

The magnitude of decline or increment of catchment runoff varies with a land use type introduced to the model. Land use/ land cover change scenario is assessed by changing certain land use of 1998 arbitrarily assuming other mean monthly climatic variables and land use types remain constant. Although not significant land use change is observed between 1998 and 2004 an attempt has been made to see what the smallest urban area expansion has to make a difference on catchment runoff.

Model out put

Taking the year 1998 as a base, catchment runoff changes in percent are estimated for different land use scenarios. If the area covered with dense bushy woodland is doubled, this is less than the area covered with similar land cover in 1965, the estimated catchment runoff decreases by 11%. This means the transformation of the evergreen vegetation (dense wood land and dens shrub land) of 1965 in to cultivated land might gave rise to an increment of annual runoff (surface and subsurface runoff) by as high as 52Mm^3. Similarly when the model runs by replacing the urban areas to where it was in 1965, reducing the same area from cultivated land on a similar soil type, a decrease of 3Mm^3 runoff has been estimated. Therefore the urbanization has resulted additional water to the mean annual runoff although it is in small extent. Change of catchment runoff for different scenarios compared with respect to 1998 is presented as follows.

Scenario	Dense woodland doubled	Urban area doubled	Land use 1965 scenario	Land use 2004 scenario
Change in % of catchment runoff with respect to 1998 runoff condition	-11	0.4	-22	4

Table 12 Change of catchment runoff for different land use change scenario

To understand the effect of the cheleleka swamp on the river discharge the amount of water that would have been evaporated if it were a lake is estimated. Assuming the swamp is fully covered with tall grass to evapo-transpire at a potential rate it tends to increase the total input in to the system by around 5 Mm^3 (Dune and Leopold 1978) on annual bases than when it was a lake.

Climatic scenario

Maintaining the trend of mean monthly rainfall and reference potential evapotranspiration seasonal distributions the impact of climatic change on catchment runoff generation has been assessed by changing the rainfall and potential reference evapotranspiration values arbitrarily by 5 and 10% higher or lower than the actual value. Consequently the model output revealed that upon increase and decrease of current mean monthly rainfall by 10% the mean annual catchment runoff has increased or decreased by up to 139 Mm^3 or (28%). Where as by increasing reference potential evapotranspiration by 10% for example the runoff has decreased by 62 Mm^3 or 18% below the actual value. An increase of similar magnitude of catchment runoff is obtained by decreasing reference potential evapotranspiration by 10%. Therefore the changes in rainfall and potential evapotranspiration have considerable impact on increase or decrease of catchment runoff.

Conclusion

Evapotranspiration and runoff could vary depending on seasonal variations of rainfall and other climatic factors. For example there are times when high storms generate higher runoff while soil water balance estimates based on long-term climatic variables overestimate evapotranspiration and underestimate catchment runoff. But generally from the discussed results it can be concluded that the catchment has gone through great land use changes which can result in different rainfall-run of relation than when it was 20 to 30 years ago. Note that other land use changes that might have an impact on an increase of runoff are not assessed.

Therefore comparing the climatic change the chatchment has experienced the last three decades with the land use change occurred and its implications on high runoff generation land use change seems to have greater role on the lake level rise. But as the land use change usually is gradual and takes long time before it is noticed, detail and continuous assessment helps improve the uncertainties of water balance estimates and succeeding conclusions. Time series remote sensing images interpretation could help considerably in this aspect.

5.2.4. Sensitivity analysis of the Soil water balance model

Most of the variables used in the soil water balance calculation procedure are derived from large-scale maps and others are obtained from literature. Further more only land cover types which are dominant for the area are considered. Therefore the cachment factors and behaviours are oversimplified as the study area is too large to undertake detail survey and characterization of different land use types. Thus errors on assumed and classified cachment properties are expected. To understand the effect of errors on estimated and assumed parameters used in the model on the predicted total catchment runoff, sensitivity analyses have been executed by changing one variable at a time.

The total runoff predicted by the model when all variables are either measured or assumed to represent the reality on the catchment approximately are taken as the base value to compare with the model output upon change of different variables by a certain percentage. Accordingly water holding capacity in the root zone, crop-coefficient, precipitation and reference crop evapotranspiration, which are the main inputs to the model, are involved in the analysis.

As discussed in the climatic scenario analysis the impact of change in reference potential evapotranspiration and rainfall on the catchment runoff is high. Upon increase or decrease of 10% on crop coefficient the catchment runoff decreases or increases by 18%. Similar value is obtained when reference evapotranspiration is changed by 10%. As some crop-coefficients were determined from literature written on similar environment and others assumed there could be an error in this variable and yet at the same time it is very sensitive to the model. Available water capacity in the root zone appears to be less sensitive.

The reliability of the model out put highly depends on the quality of the input data used. It is possible for as high as 10% error to occur in any of the parameters for which the model is highly sensitive like crop coefficient, rainfall and reference crop evapotranspiration values. Therefore the catchment water balance estimates are only indicatives of the wider range of values of the main water balance components.

	Change in percent of predicted total catchment runoff upon change in the variables			
Change in %	Available water in the root zone	Crop Coefficient (Kc)	Rainfall	Reference potential evapotranspiration
-10	0.6	18.6	-28.8	18.6
-5	0.3	9	-14.9	9.6
5	-0.3	-8.1	13.0	-7.6
10	-0.6	-16.6	26.5	-16.6

Table 13 Sensitivity analysis of the Soil Water Balance model

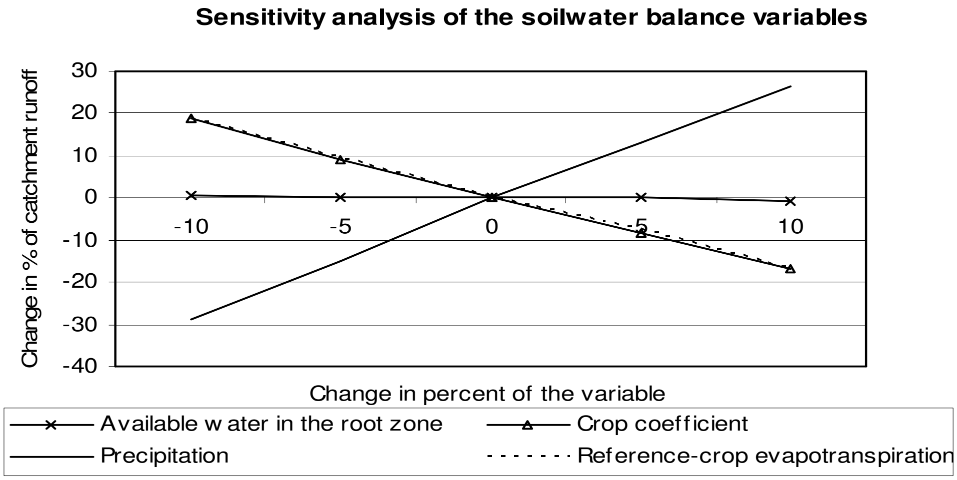


Figure 35 Sensitivity analysis on soil water balance model input variables

5.3. Lake water balance model

5.3.1. Introduction

In order to understand the basic hydrological processes, water balance computation of the lake is made using excel spreadsheet model. This model approach stems on solving the lake water balance equation read as;

$$\frac{\Delta S}{\Delta t} = P - E_v + G_{in} - G_{out} - Abs + Q_{in}$$

As quantification of Gin and Gout is difficult with the available data, the net groundwater flux (Gin-Gout) is estimated as residual to the model out put. It is indicated in chapter 4 that the abstraction from the lake for drinking and irrigation is considered negligible. Therefore the above equation is rewritten as:

$$\frac{\Delta S}{\Delta t} = P - E_v + \Delta G + Q_{in}$$

Where, P= Direct precipitation over the lake
E=Evaporation from the lake surface
R=Surface runoff in to the lake.
Gi= Groundwater inflow in to the lake
Go= groundwater outflow from the lake
Qin= Surface water inflow in to the lake
Abs= Abstraction from the lake
ΔG= net groundwater flow
ΔS= Change in lake storage

When the net groundwater flow is negative it could be considered as minimum groundwater out flow and if positive it could be considered as minimum groundwater inflow in to the lake. All hydrometeorological elements which are input for the model are processed and analysed in chapter 4.

5.3.2. Groundwater inflow and outflow estimation

Groundwater flow pattern around Lake Awassa is determined from peizometric map prepared from the groundwater depth point data sets and surface elevation from SRTM. A total of 43 hand dug wells and 41 borehole water points, which were collected during the previous studies, W.W.C.S.E, [2001], Taddese and Zenaw, [2003], are used. The water points used in the pieziometric map preparation are not uniformly distributed around the lake. In addition to that the digital elevation model from which ground surface elevation of the water points has been obtained is less accurate. Therefore groundwater flow directions determined under such condition might not be conclusive. However an attempt is made to present simplified and generalized sketches fig (35) that shows the groundwater flow conditions along different directions over the catchment. This serves in the attempt to understand the subsurface flow system and to estimate the groundwater components and its interaction with surface water bodies.

There is little indication from this map that water from the shallow aquifers of the catchment is leaving to Abaya and Chamo lakes on the south. As the elevation difference between Lake Awassa and Abaya and Chamo lakes is close to 500 meter, any possibility of regional groundwater flow from the former to the later needs to be investigated using different techniques including isotopic analysis. It seems more apparent however groundwater flows northward to Lake Shalla and westward, north of Muleti village.

It is shown in fig (35) that the existences of localized recharge areas like the area between Lake Awassa and cheleleka swamp. Ground water level decreases on both directions and the water table appears to follow the surface topography which is relatively elevated on the area east of Awassa town. It is also indicated that Lake Awassa and Cheleleka swamp are fed from surface runoff and groundwater seepages from different directions.

Though data on depth of the aquifer and hydraulic properties of the lacustrine sediments around the lake is not adequate an attempt has been made to quantify the groundwater inflow and outflow to/from the lake using Darcy's equation. Thus with the possible aquifer heterogeneity, existence of fractures and unknown aquifer geometry groundwater flow estimation using Darcy's approach could only give a broader range of values of subsurface flow components. Average transmissivity values of the lacustrine sediments from previous reports which were obtained from the pump test results and hydraulic gradients from piezometric map and boreholes around the lake have been used.

Darcy's equation can be expressed as:

$$Q = -K.A.\frac{\Delta h}{\Delta L},$$

Where,

Q= is volumetric discharge ……………………………………………………[L^3/T]
K=Aquifer hydraulic conductivity……………………………….………… [L/T]
I=Hydraulic gradient…………………………….…………..………[no unit]
A=Aquifer cross sectional area…………………………………….……………[L^2]

Where as the range of Transmissivity value of the aquifer around the lake is given the equation is rewritten as:

$$Q=TLI$$

Where,

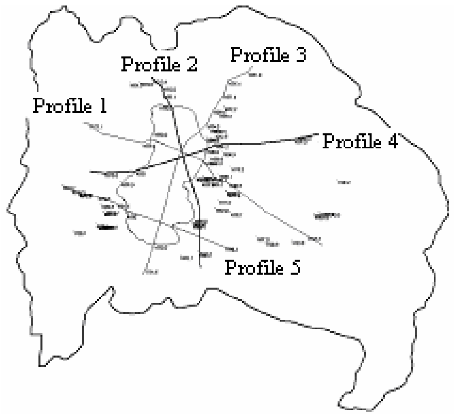
T = Aquifer transmissivity……………………………………………………..…[L^2/T]

L=lake perimeter through which groundwater exchanges with the lake…………….[L]

Out of the total perimeter of the lake which is estimated to be 48 km 16% represents the section of groundwater out flow mainly in the Northern direction toward Lake Shalla and small part to the western direction and 84% is the perimeter through which groundwater flows in to the lake fig(17).

The groundwater coming from the southern part of the lake is through the low permeability ignimbrites and tuff. In addition to that the distance and hydraulic head difference between the eastern groundwater divide and Lake Awassa is short so the contribution from that direction is assumed to be small. Therefore transmissivity value 750m^2/day is assumed for the groundwater inflow which is an average between the range 100-1400 m^2/day given for the lacustrine sediments and 1400m^2 is assumed for the highly permeable lacustrine sediments covering most of the groundwater outflow direction. Hydraulic gradients are assumed to be 0.004 and 0.003 for the groundwater outflow and groundwater inflow respectively assuming 3km distance of cone of influence away from the lake. The distance of cone of influence and the head difference between the contributing aquifer and the lake is estimated based on the average distance and head of the existing boreholes and based on the groundwater flow directions.

Thus 12Mm^3 and 36Mm^3 annual groundwater outflow and inflow of water from/to the lake is estimated respectively. In section 5.2.2 a total catchment runoff is estimated to be 482Mm^3. Assuming the groundwater inflow in to the lake estimated using Darcy's equation to be reasonable the total input in terms of groundwater and surface water that is measured at Tikurwuha amounts to 119 Mm^3. Subtracting this value from the total catchment runoff 363Mm^3 might be considered as groundwater outflow to the near by catchments. On top of that 43Mm^3 of constant groundwater outflow from the lake is estimated in the lake water balance model. Therefore more than 400Mm^3 of water can be assumed leaving the catchment to neighbouring catchments.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Profile 2
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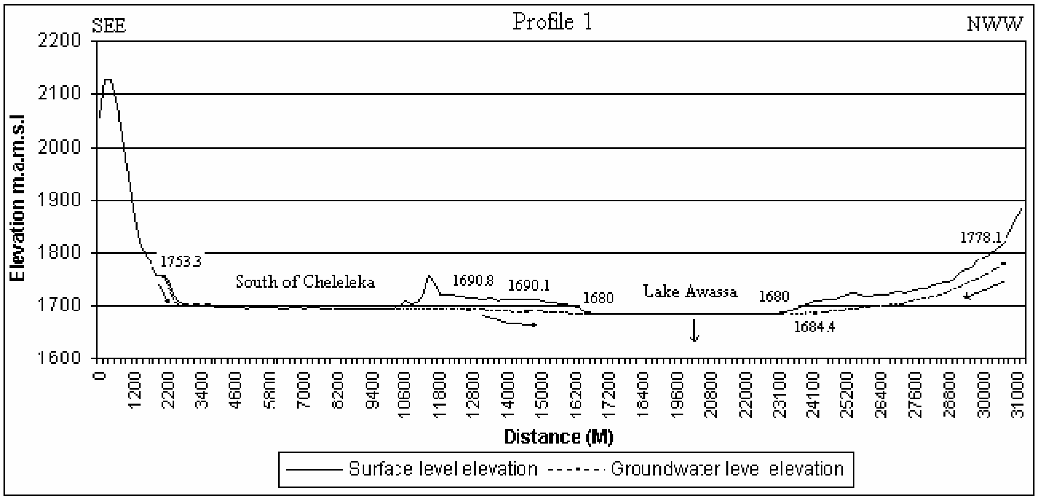
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1600
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1690.1
1680
Lake Awassa
1680
1684.4
1778.1
0
1200
2200
3400
4600
5800
7000
8200
9400
10600
11800
12800
14000
15000
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17200
18400
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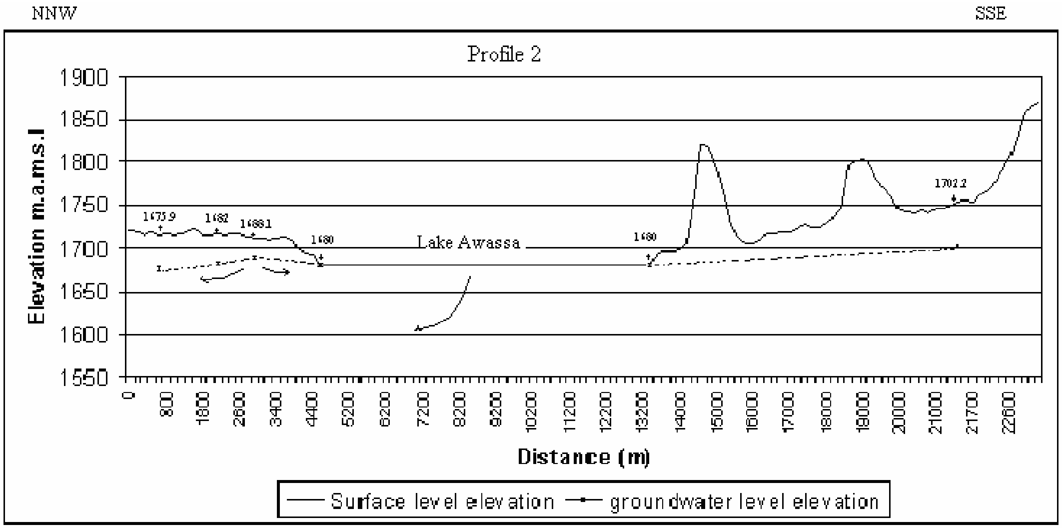
28800
30000
31000
Distance (M)
Surface level elevation
Groundwater leve elevation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SSE
Profile 2
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1702.2
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800
1800
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3400
4400
5200
6200
7200
8200
9200
10200
11200
12200
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16000
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Distance (m)
Surface level elevation
groundwater level elevation

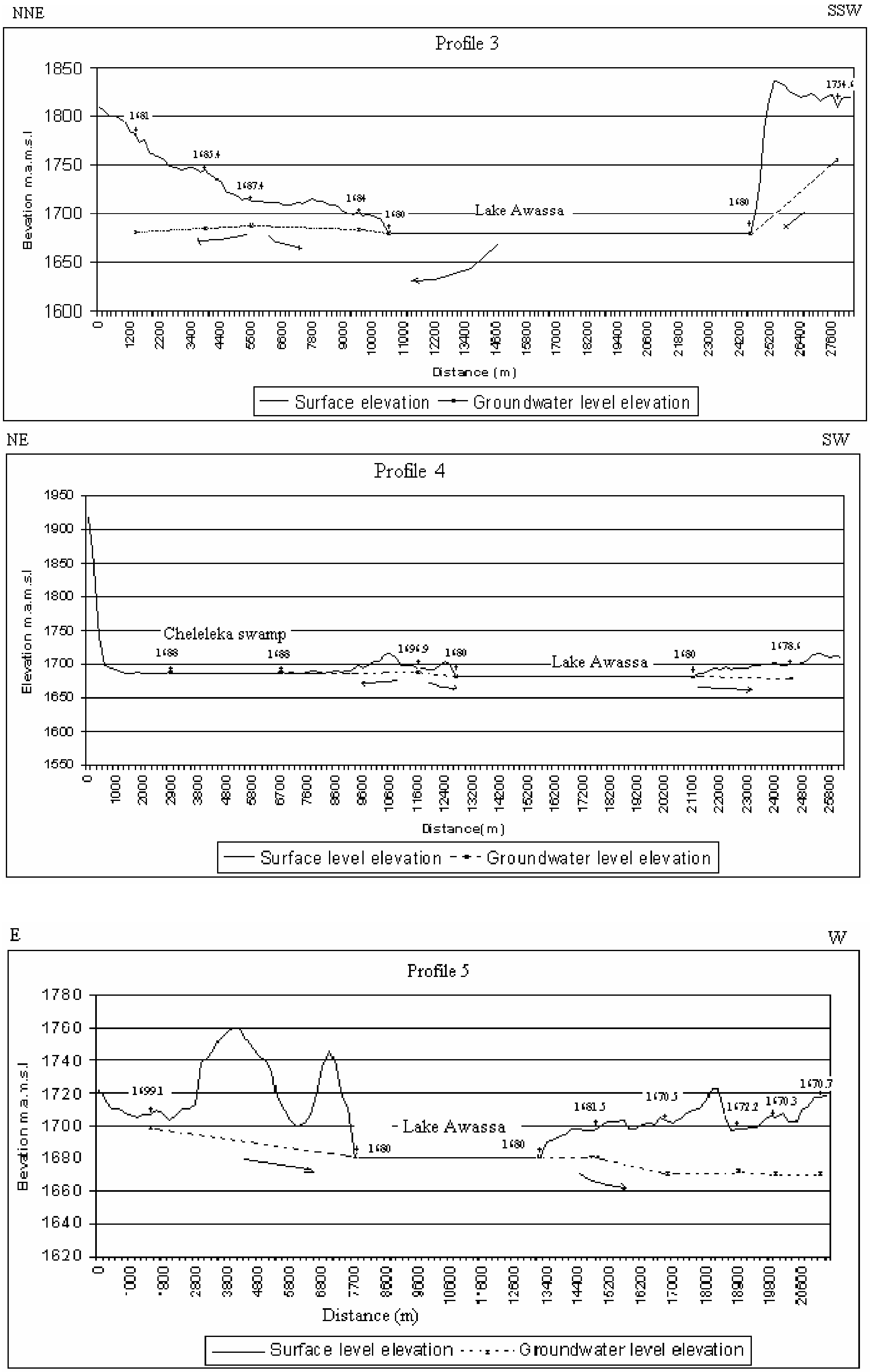


Figure 36 Groundwater flow directions on the lake Awassa catchment

5.3.3. Lake level Volume/ Surface area relationship

The bathymetric map digitized from the hardcopy data obtained from W.W.C.S.E, [2001] is used to calculate the corresponding lake level area and volume parameters in the Ilwis, Arcview/GIS environment. Linear trend line fit the lake level area relationship and polynomial trend line for the lake level/ volume relationship. Mathematical expressions for both relations were obtained by which lake level Area/volume parameters were calculated in the lake water balance spreadsheet model.

The equations are;
$A = 4E{+}06*h + 9E{+}06$ with regression coefficient $R^2=0.99$ and
$V=2E{+}06*h^2 + 1E{+}07*h - 5.95E{+}07$ with regression coefficient $R^2=0.99$
Where,

h= relative height of the lake level ……………………………………………[m]
A=Lake area………………………………………………………………[m^2]
V=lake volume……………………………………………………………[m^3]

As one of the objectives of the study is to understand the lake level fluctuations of Lake Awassa during recent years only the lake levels above which the level has never been low is considered in the lake level Area/volume capacity curves fig(37).

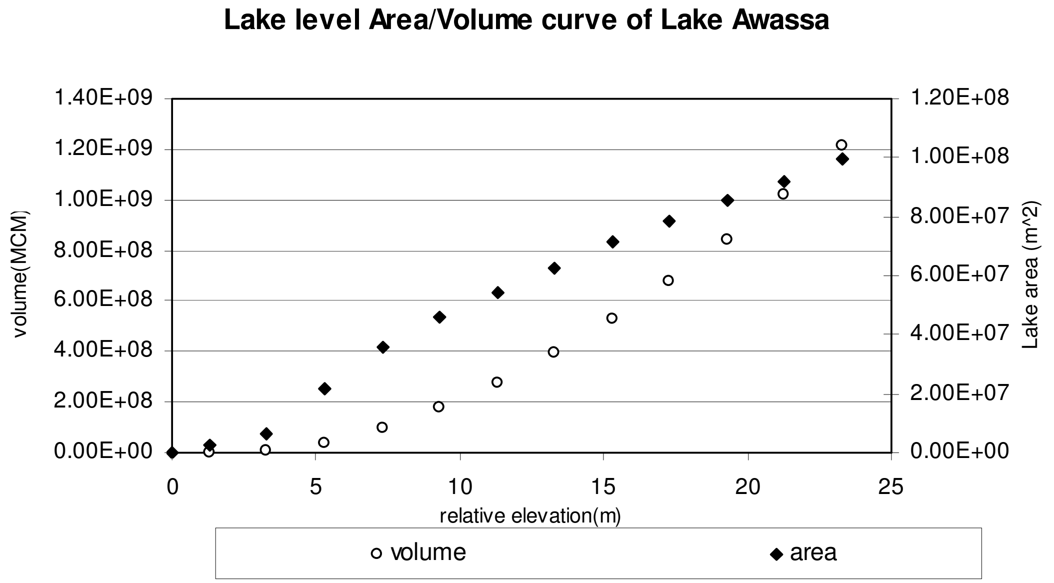


Figure 37 Lake level Area/Volume curves of Lake Awassa

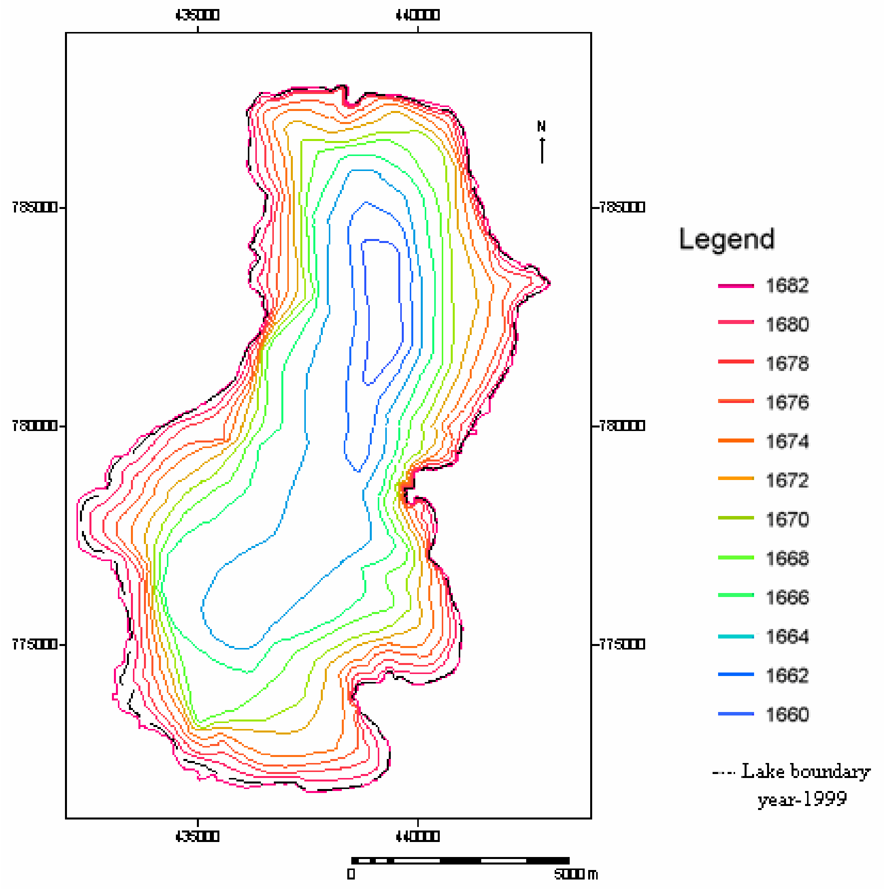


Figure 38 Lake Awassa Bathymetry

5.3.4. Water balance model design

A simplistic bucket model is assumed to represent the Lake. Monthly lake storage changes which are added or subtracted from/to the previous month’s lake volume and lake level are calculated from the lake level/ volume equations. As storage of the lake changes the head difference between the hypothetical aquifer attached to the lake also changes. Thus the net groundwater flow is calculated using the groundwater discharge equation;

$$Q=C(\Delta h)$$

Where,

Q=net groundwater flow…………………………..…………$[L^3/T]$

C=lake aquifer conductance……………………………………$[L^2]$

Δh=head difference between the aquifer and the lake level……[L]

Using this Spreadsheet model calibration of lake level fluctuations is possible given the measured bathymetric level and estimated input and output hydrologic variables to the lake. The certainty of such calibration technique is assessed by setting minimum summation of squared difference (objective function) between the measured and estimated lake levels.

5.3.5. Model execution

5.3.5.1. Model calibration and optimization

Model calibration has been done by adjusting model input parameters to fit the simulated lake levels with the observed lake levels. The first adjustment of the parameters of the theoretical aquifer attached to the bucket (the lake) the model out put shows simulated lake levels laying at higher levels than the observed lake levels. This signifies the need for the water in the lake to flow out some how to achieve the best fit. Parameters have been further adjusted by visually inspecting the fitness of observed and simulated levels. Finally a "solver" optimization function in excel has been run to optimize the groundwater outflow to bring the simulated level down to the observed lake level. The best possible fit has attained at 2.55 Mm^3 monthly constant groundwater outflow fig (39).

5.3.6. Simulation results and analysis

5.3.6.1. Lake levels

A reasonable agreement between the measured and simulated lake level is achieved for the simulation period. The period from 1989 to 1993 have shown poor fit between the simulated and observed lake levels. An error in the measurement of lake level data or in any of the variables (rainfall, runoff and meteorological variables from which evaporation has been calculated) and most importantly under/overestimation of net shortwave radiation for which evaporation is more sensitive could be one of the reasons. As the model is also more sensitive to evaporation and rainfall errors in any of this variables will have large effect on the simulation output. Similarly the misfit between the observed and simulated lake levels observed after 1996 may also be due to uncertainties on the hydrometeorological records or due to abstraction of water from springs and rivers for irrigation and water supply. Diversion of Wosha River partly to Shashemene water supply and Loke spring to Awassa water supply are some of the known abstractions. But generally the model is able to calculate lake levels with reasonable accuracy over the modelled period.

The sharp rise of the lake level from 1996 onwards seems to be due to high rainfall intensity during the years 1996, 1997and 1998, which is 16%, 7% and 12% above catchment average respectively. The resulting river discharge at the available gauge during these years is also 13 to 70 % higher than long term average.

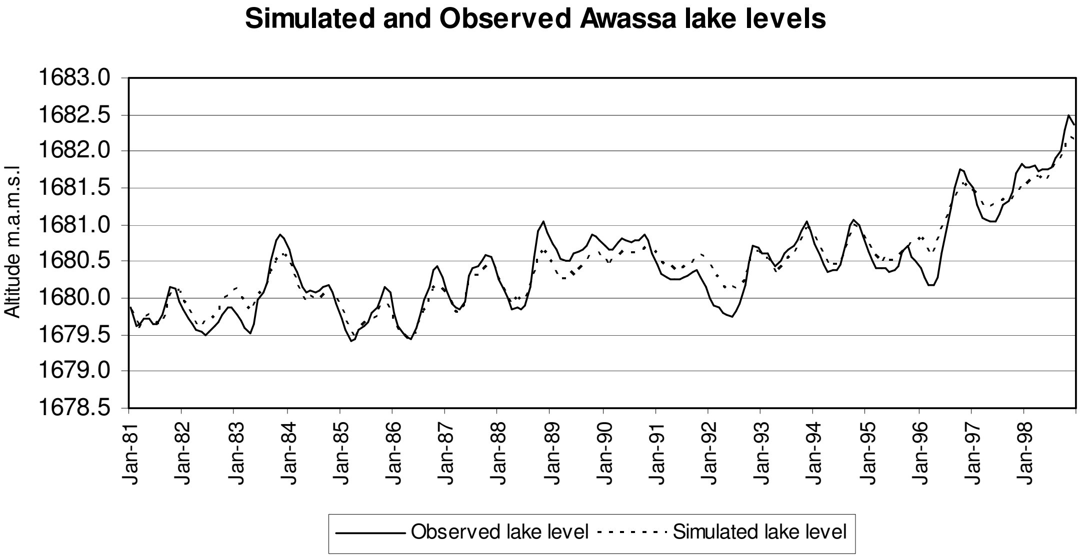


Figure 39 Observed and Simulated Awassa lake levels

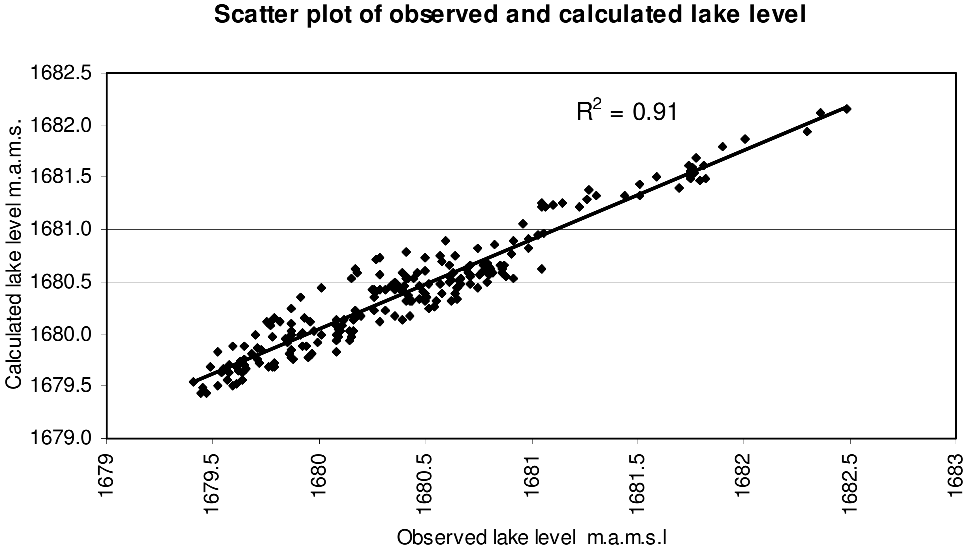


Figure 40 Scatter plot of Observed and Simulated lake levels

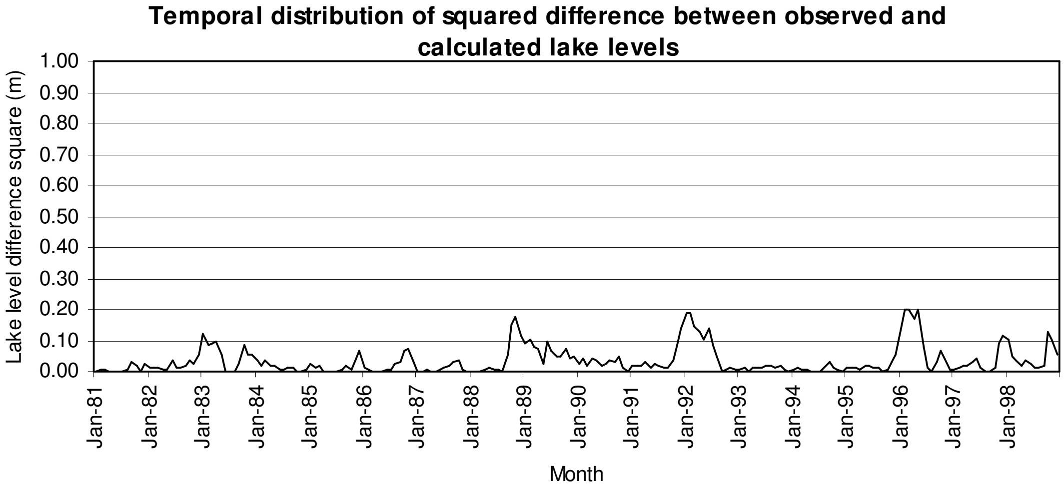


Figure 41 Temporal distribution of square difference between observed and calculated lake levels

5.3.6.2. Lake storage

Observed lake storage values are obtained from observed lake levels using the lake level-volume relationship. The closeness between observed and calculated lake volume as can be seen in figure (42) is also as good as the observed and calculated lake levels with similar regression coefficient except some wider divergence during years 1989 to 1991 and 1997 onwards.

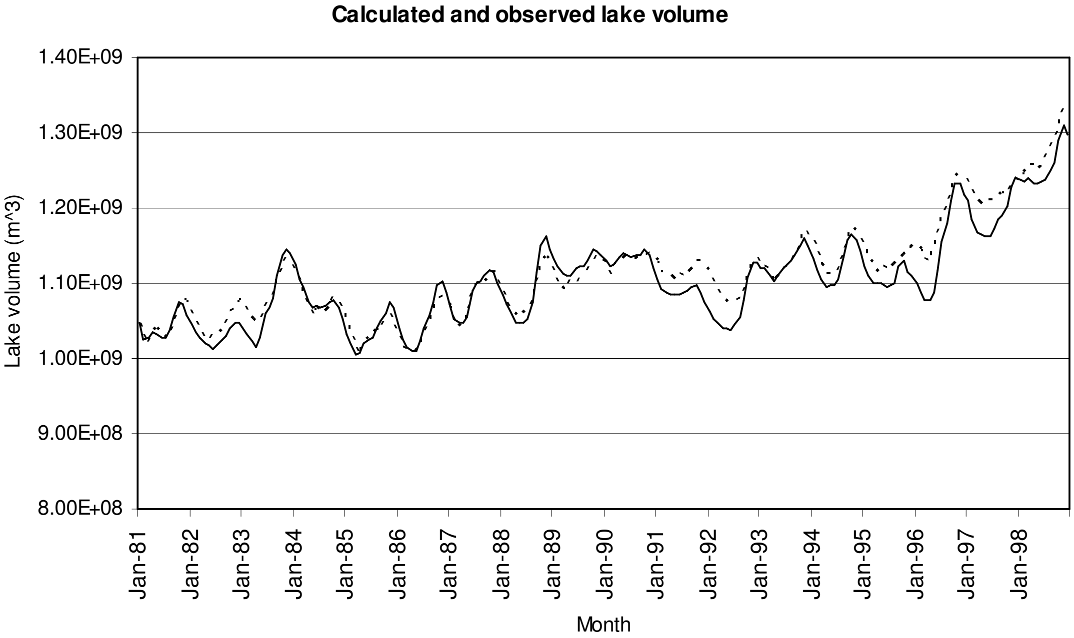


Figure 42 Calculated and Observed lake volume

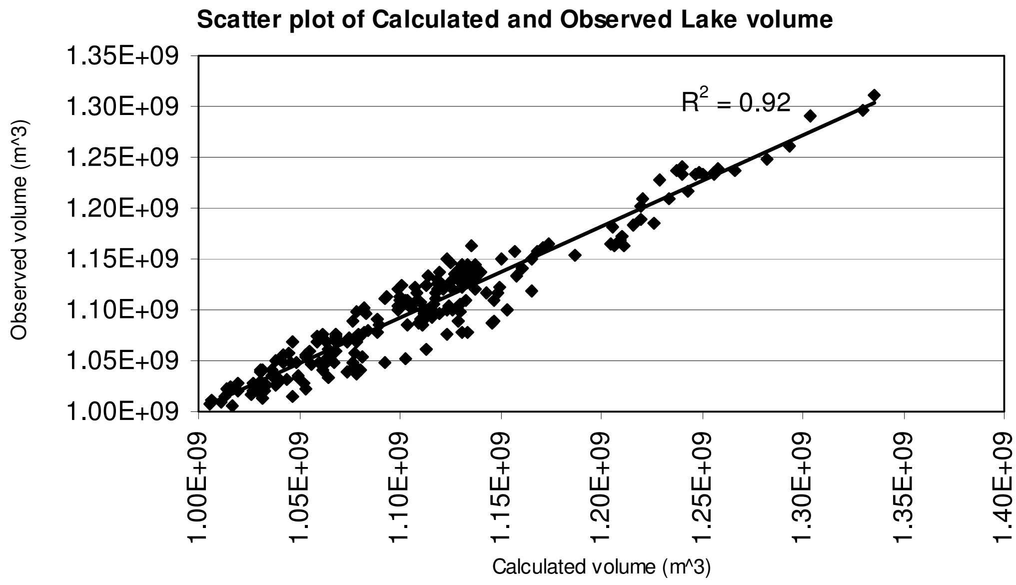


Figure 43 Scatter plot of observed and calculated lake volume

	Long-term mean monthly volumetric components of Lake Awassa (m^3)					
	Precipitation	Evaporation	Surface runoff	Net groundwater flow	Storage change	Constant groundwater out flow
Jan	2.42E+06	1.40E+07	3.84E+06	-1.44E+06	-1.18E+07	2.55E+06
Feb	5.29E+06	1.28E+07	2.58E+06	-1.20E+06	-8.65E+06	2.55E+06
Mar	9.96E+06	1.39E+07	2.28E+06	-8.69E+05	-5.12E+06	2.55E+06
Apr	1.44E+07	1.03E+07	2.77E+06	-6.21E+05	3.67E+06	2.55E+06
May	1.49E+07	1.10E+07	5.22E+06	-4.75E+05	6.09E+06	2.55E+06
Jun	9.35E+06	9.60E+06	7.39E+06	-5.72E+05	4.02E+06	2.55E+06
Jul	9.32E+06	6.20E+06	7.76E+06	-7.31E+05	7.60E+06	2.55E+06
Aug	1.08E+07	7.59E+06	9.65E+06	-8.28E+05	9.47E+06	2.55E+06
Sep	1.39E+07	8.33E+06	1.22E+07	-1.02E+06	1.42E+07	2.55E+06
Oct	9.26E+06	1.10E+07	1.41E+07	-1.26E+06	8.55E+06	2.55E+06
Nov	3.93E+06	1.33E+07	9.48E+06	-1.62E+06	-4.01E+06	2.55E+06
Dec	2.77E+06	1.38E+07	6.49E+06	-1.81E+06	-8.90E+06	2.55E+06
	1.06E+08	**1.32E+08**	**8.37E+07**	**-1.24E+07**	**1.51E+07**	**3.06E+07**

Table 14 Long-term mean monthly volumetric components of Lake Awassa

Net groundwater flow component has negatively increased over the simulation period as shown in fig (44). This is reasonable because when the lake area increases the land surface through which the lake seeps to the aquifer will increase. Surface runoff progressively increases over time while rainfall and evaporation remains swinging around the average value. This signifies that lake level rise primarily is influenced by an increase in surface runoff. Thus continuous increase in surface runoff could indicate continuous land use change on the catchment. Some of the clear land use changes occurred during the last two to three decades and their implications on surface runoff are discussed in the previous sections.

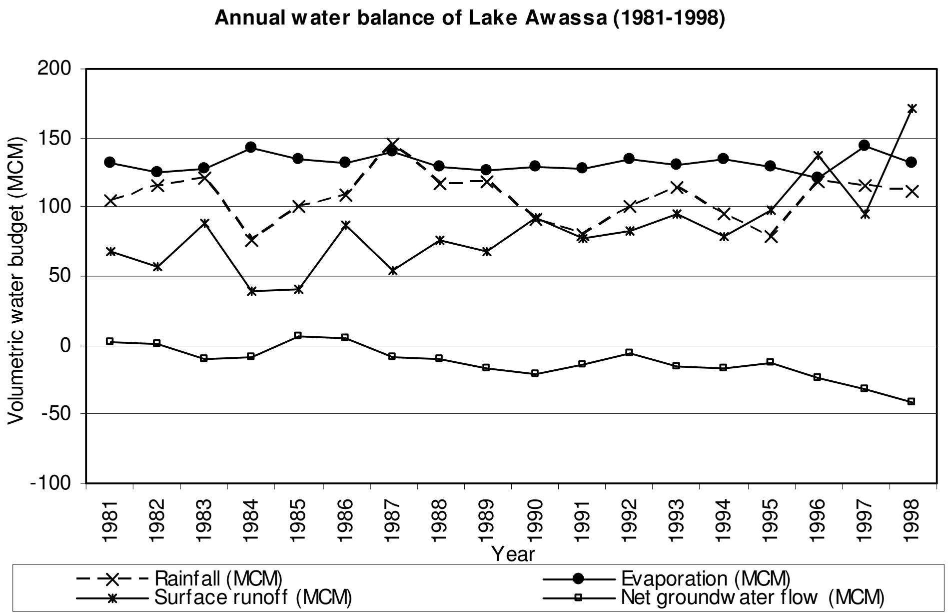


Figure 44 Annual water balance of Lake Awassa (1981-1998)

Taking the dry season 1990 and wet season 1996 an attempt has been made to see which water balance term is contributing to the lake during extreme climatic conditions. Assuming Dec., 1989 and Dec., 1995 lake levels as a base the water budget in terms of water depth is estimated for 1990 and 1996 respectively. The storage change in volumes of water is converted in to water depth by dividing it to the lake area of the same month. Lake area is estimated from observed lake levels using the area-lake level relationship.

Results for the wet year, 1996, shows that lake level usually declines starting the month of November and continue decreasing until it transfers in to the positive territory in response to the April rainfall. The largest amount of input water from the surrounding groundwater and surface runoff from the un-gauged catchment is required in the month of July to achieve the observed lake level. The highest groundwater outflow has occurred in the month of April as the lake water flows towards the depleted aquifer due to the dry months of 1995 (below average rainfall) and early 1996. The lake level fluctuation follows more the pattern of the surface runoff than precipitation. This is because even when the rainfall over the lake surface becomes low the river discharges the base flow and the quick flow from the highlands where rainfall might be high at that time. It should be noted that the rainfall input indicated on the figure is rain that falls over the lake area. Even though months of May and September seems to have the same amount of input from surface runoff and precipitation and comparable out put in terms of evaporation the change in lake level is higher in September than in May. Because September was gaining from the groundwater and ephemeral streams from the un-gauged catchment, since it is the end of the wet season, where as in May the lake was rather loosing water in the form of groundwater outflow. Because May is the end of the dry and the beginning of the wet period that rainfall which is high in May is taken to compensate the slightly higher evaporation and large amount of shortage of surface runoff. Surface runoff in March, April and May is low even if it appears rainfall to be high in the lake area and Tikurwuha sub-catchment, 10, 17 and 10 cm respectively, since the soil moisture deficit utilises most of the rainfall on the catchment.

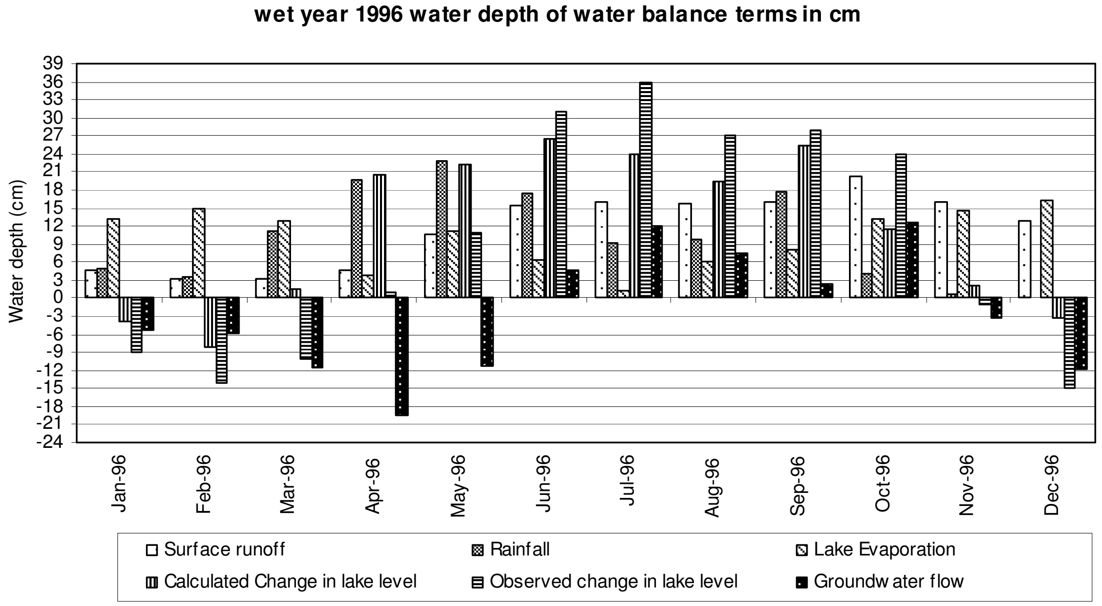


Figure 45 Wet year 1996 water depth of the lake water balance components

The difference between observed lake level and calculated level is designated by groundwater flow. Surface runoff from the ungaged sub-catchment is also included to the groundwater component.
When the groundwater flow component is negative the same depth of water must have been withdrawn from the lake water in terms of groundwater outflow plus abstraction to achieve the observed lake level. If it is positive the same depth of water has been added from groundwater and surface runoff from un-gauged catchment to achieve the observed lake level.

High evaporation and low rainfall distributions is the characteristic feature of the dry year 1990. Similar to the wet year the discharge and precipitation values do not coincide in most cases. One of the reasons as explained above is due to the fact that the rainfall value is from the record of the station on the lake area where as the discharge is coming from the eastern highlands where rainfall intensities could be different. Almost throughout the dry year the lake was seeping water to the aquifer.

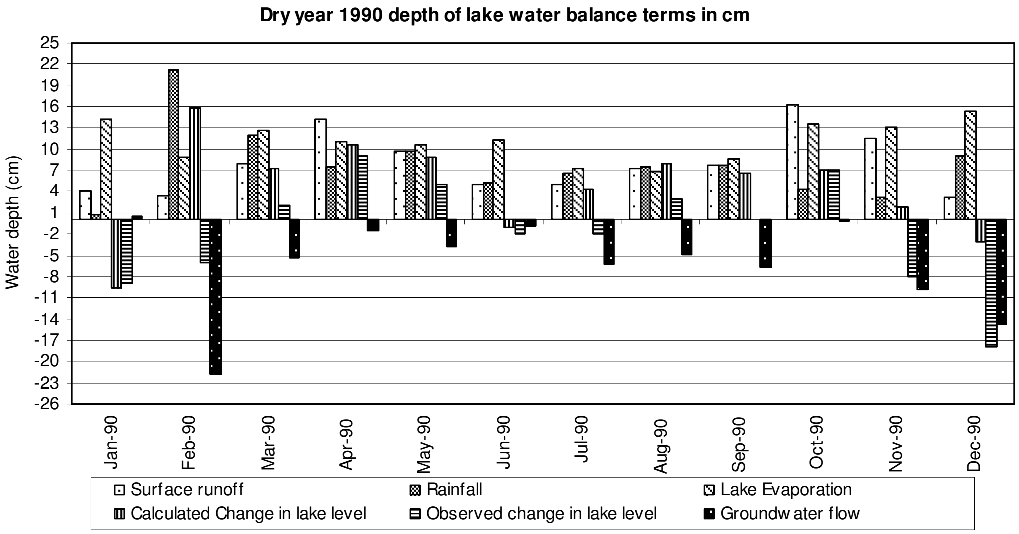


Figure 46 Dry year 1990 water depth of the lake water balance components

5.3.7. Validation of the lake water balance model

Lake area obtained by digitizing the lake perimeter from landsat image of January 1994 and the lake area calculated during the simulation process for the same month and year have been compared to see how close the simulation has reflected the reality on ground. An area of 93 km^2 and 97 km^2 has been found from the satellite images and from the simulation respectively. Thus during the period when simulated and observed lake levels differ by 10 cm the model has been able to reproduce the lake area with close to 5% error. This difference could be attributed among other things to the resolution of the DEM used to extract the lake area and uncertainties on the lake bottom morphology from which the lake level area/capacity expressions derived. The lake area perimeter of satellite image Jan., 1994 and the sliced DEM based on simulated lake level 1680.9 m.a.m.s.l of the same month is shown in fig (47).

Similarly on January, 1994 the model simulates the lake volume to be 1157 Mm^3 where as the observed lake volume obtained from the observed lake level-volume equation was 1133 Mm^3, which means the model overestimates the volume 2% higher than observed.

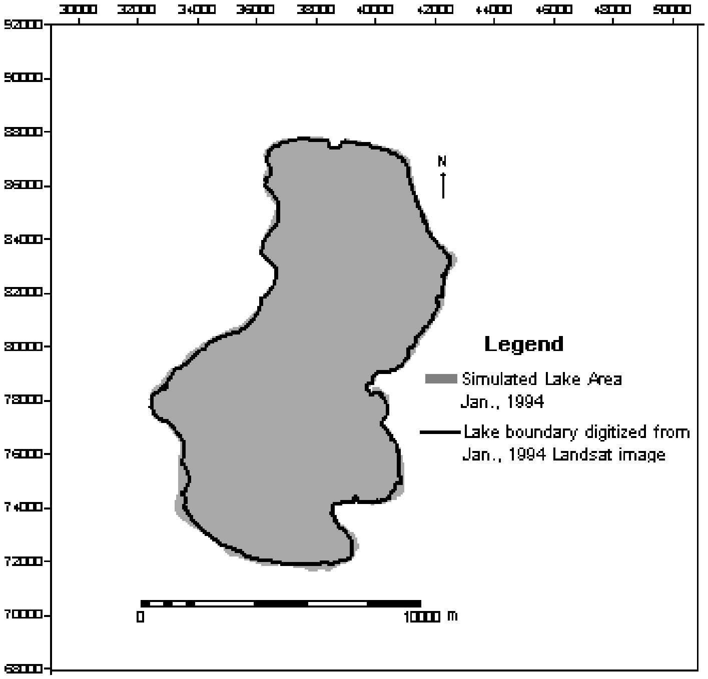


Figure 47 Lake area perimeter digitized from Jan., 1994 Landsat TM image Overlaid on Sliced DEM based on Jan., 1994 simulated lake level.

5.3.8. Sensitivity analysis of the lake water balance

There are uncertainties at the time of measurement and computation due to human, instrument and shortage of data. During calibration of the lake water balance model sensitivity analysis has to be made to understand to which variable the model is more sensitive and estimate the variation on the out put parameter that could arise due to uncertainties in the sensitive variable.

Sensitivity analysis has been made to all variables considered in the lake water balance. As it is indicated in fig (48), the model is more sensitive to evaporation and precipitation. 10 % change in the evaporation can cause up to 43 cm rise or fall on average in the simulated lake level. Similarly by changing rainfall over the lake by 10% from what has been measured a change up to 34cm on the simulated lake level is obtained. The variable to which the model is least sensitive is aquifer area and lake aquifer conductance.

As it is discussed by Winter, [1981], Evaporation calculated by the energy budget method is generally considered to be the most accurate; with proper care, the error in annual estimates can be 10 % or less, and seasonal estimates are considered to be within about 13%.

It is clear from the above conclusion that any other method of estimation of evaporation will have more than 13% error in its seasonal estimates and so (combination) method does.

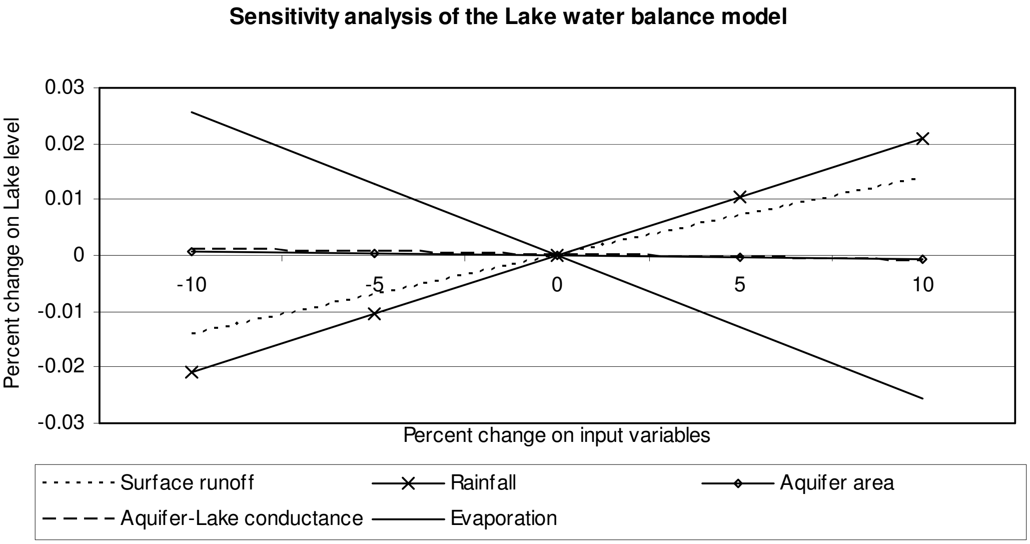


Figure 48 Sensitivity analysis of the lake water balance spreadsheet model

	Surface runoff		Rainfall		Evaporation		Aquifer area		Aquifer Lake conductance	
Change in % on Variable	Change in lake level %	Change in lake level (cm)	Change in lake level %	Change in lake level (cm)	Change in lake level %	Change in lake level (cm)	Change in lake level %	Change in lake level (cm)	Change in lake level %	Change in lake level (cm)
-10	-0.014	23.8	-0.021	34.9	0.026	43.1	0.001	1	0.001	1.8
-5	-0.007	11.8	-0.01	17.5	0.013	21.6	0	0.5	0.001	0.9
5	0.007	11.7	0.01	17.5	-0.013	21.6	0	0.4	-0.001	0.8
10	0.014	23.2	0.021	34.9	-0.026	43.2	-0.001	0.9	-0.001	1.6

Table 15 Sensitivity analysis on the Lake water balance spreadsheet model

6. Conclusion and Recommendation

6.1. Conclusion

According to the water balance estimated using the spreadsheet model, hydrological components that plays an important role in the lake level fluctuations are known to be evaporation, rainfall, and surface runoff with 131, 106, and 83 Mm^3 long-term mean annual values respectively.

The discharge measured at Tikurwuha gauging station is in an increasing trend. The correspondence of runoff values to the fluctuations of the lake level shows the close relationship of lake level rise to catchment runoff. The lake level is also sensitive to extreme wet and dry conditions. The highest peaks observed in the lake level records correspond to the highest rainfall events in the catchment. The decrease of wind speed seems to have resulted in slight decline of evaporation and evapotranspiration, which also have a role in the lake level rise. From the land use maps of 1965, 1998 and 2004 it is possible to understand that the catchment land use has changed during the past 30 years. This is evidenced by the transformation of Lake Cheleleka to a grass covered swamp and extensive deforestation which transforms evergreen vegetation in to cultivated land. Sensitivity analysis on the input variables to the soil water balance model shows highest sensitivity to rainfall, evapotranspiration and crop coefficient. The water balance of 1998 compared to the 1965 scenario yields an increment of catchment runoff by as high as 22%. Therefore the higher runoff generation in recent years even for small rainfall inputs as compared to 20 years ago could be the result of both climatic and land use changes.

Another important component is groundwater. The attempt made to quantify groundwater component based on piezometric map using Darcy's equation indicates the importance of groundwater inflow in the lake water balance. Nevertheless, constant groundwater outflow from the lake estimated to be 43 Mm^3 per year is an important groundwater component which plays a role in the water balance and the freshness of the Lake Awassa.

Although the lake level fluctuations mimic most to the fluctuation of surface runoff it is not possible to conclude whether land use or climatic change alone is the cause for the increase of the runoff. Therefore the lake level rise is attributed to combined effect of land use and climatic changes.

The contribution of the recently developed ground cracks or any other concealed geological structures to the lake level rise is difficult to confirm with the simplified models applied in the study.

Groundwater outflow towards Lake Shalla (North) and to Muleti area (west) of Lake Awassa is interpreted from the piezometric map. The topographic set up of Lake Awassa and other neighbouring catchments of Lake Shalla and Abaya and Chamo to the south favours groundwater outflow from the former to the rest of near by catchments provided hydrogeological conditions permit.

With detail study of the catchment factors like soil texture, vegetation type and rooting depth, Thornthwaite and mather soil water balance procedure could give reasonable estimates of the catchment water balance. Due to input data and time constraints many assumptions towards the real world hydrologic behaviour have been imposed on the water balance simulation. These assumptions and aggregation of catchment characteristics could be some of the reasons for the discrepancies between the measured river discharge and the estimated runoff from Tikurwuha sub-catchment. It is still believed however that the model gives reasonable results and that the overall magnitude of water balance terms is approximated. The large amount of annual surplus water obtained in the land surface of the catchment has indicated the presence of groundwater outflow from the catchment to neighbouring catchments; otherwise Lake Awassa would have flooded all the lowland areas.

6.2. Recommendation

Implementation of distributed rainfall-runoff models which takes into account the detail representation of the physiographic and climatic characteristics of the catchment are crucial to get more reliable water balance estimates of the catchment.

It is known that the rift floor is disturbed with multi-directional fault systems, thus their relationship with the surface and groundwater flow systems need to be studied in detail.

The reliability of the lake water balance estimates depends on the accuracy of the input variables. Filling in missing rainfall data on basis of neighbouring stations and use of climatic variables obtained from Awassa meteorological station being in the center of the town possibly have introduced uncertainties in quantifying some of the variables which can not be found in other stations otherwise. This climatological data needs to be evaluated by comparing with measurements outside of the town. Furthermore accurate quantification of groundwater inflow and outflow from/to the lake improves the water balance estimates. Therefore levelling the existing water points to know the exact elevations of the surface and the groundwater level and knowledge of detail hydrogeological conditions of the lake catchment is required.

To understand the impact of land use and climatic change on the catchment runoff better, water balance studies specific to Tikurwuha sub-catchment is vital by assessing the land use changes in detail using remote sensing data. Estimated runoff values could be calibrated to the measured discharge values of the sub-catchment.

The quantity and direction of groundwater outflow from Lake Awassa catchemnt to Lake Shalla to the north and Lake Abaya and Chamo to the south needs further investigation.

The amount of water entering directly to the lake from Awassa town in the form of sewerage and abstractions from the lake, from springs, boreholes and rivers upstream for irrigation and domestic water supply have not been accounted in the water balance due to shortage of data, so it needs consideration in the future studies.

Allen.et.al. 1998. FAO Irrigation and drainage paper 56. FAO, Rome.

Armstrong. F. M. 2002. Water balance of the southern Kenya rift valley lakes. Msc. International Institute for Geo-Information Science and Earth observation (ITC), Enschede

Ayalew, L. e. a., H. Yamagishi, and G. Reik. 2004. Ground cracks in Ethiopian Rift Valley: facts and uncertainties. Engineering Geology **75**:309-324.

Dessie, N. 1995. Hydrogeological Investigation of lake Awassa Catchment. Msc. Addis Ababa University, Addis Ababa.

Dingman, S. L. 2002a. Physical hydrology, second edition. printice Hall, New Jersey.

Donker, N. H. W. 1987. WTRBLN: a computer program to calculate water balance. reprinted from Computer and Geoscinces, 13<1987>2,:pp.95-122.

Dune, T., and L. Leopold. 1978. Water in Environmental Planning. H. H. Freeman and Company, New York.

Fetter, C. W. 1994. Applied Hydrogeology. Printice Hall, New Jersy.

Hughes, D. A., P. Hannart, and D. Watkins. 2003. Continuous baseflow separation from time series of daily and monthly streamflow data. Water SA **29**:43-48.

Hundecha, Y., and A. Bardossy. 2004. Modelling of the effect of landuse changes on the runoff generation of a river basin through parameter regionalization of watershed model. Journal of Hydrology **292**:281-295.

Lamb, A. L., M. J. Leng, H. F. Lamb, R. J. Telford, and M. U. Mohammed. 2002. Climatic and non-climatic effects on the [delta]18O and [delta]13C compositions of Lake Awassa, Ethiopia, during the last 6.5 ka. Quaternary Science Reviews **21**:2199-2211.

Legesse, D., C. Vallet-Coulomb, and F. Gasse. 2003. Hydrological response of a catchment to climate and land use changes in Tropical Africa: case study South Central Ethiopia. Journal of Hydrology **275**:67-85.

Maidment, D. R. 1993. Handbook of Hydrology. McGraw-Hill, New York.

Meijerink, A. M. J., C.M.M. Mannaerts, J.A.M de Brouwe and C.R. Valenzuela. 1994. Introduction to the use of geographic information systems for practical hydrology. International Institue for Aerospace survey and Earth Observation(ITC), Enschede, the Netherlands.

Nyssen, J., J. Poesen, J. Moeyersons, J. Deckers, M. Haile, and A. Lang. 2004. Human impact on the environment in the Ethiopian and Eritrean highlands--a state of the art. Earth-Science Reviews **64**:273-320.

Tadesse, and Zenaw. 2003. Hydrogeology and Engineering Geology of Awassa Lake Catchment. Geological survey of Ethiopia, Addis Ababa.

Tenalem. 1998. The hydrological system of the lake district basin, Central Main Ethiopian Rift. Ph.D thesis. International Institue for Geographic Information Science and Earth Obseration(ITC), Enschede.

Thornthwaite, C. W., and J. R. Mather. 1957. Instructions and tables for computing potential evapotranspiration and the water balance. 3, New Jersey.

W.W.D.S.E. 2001. The study of Lake Awassa level, lake Awassa study and design project. Water Works Design and Supervision Enterprise, Addis Ababa.

Winter, T. C. 1981. Uncertainties in Estimating the Water Balance of Lakes. Water resources Bulletin **17,No.1**:82-115.

Appendix-1 Effect of land use change on different hydrological variables

Land-use change	**Component affected**	**Principal hydrologic process involved**	**Geographic scale and likely magnitude of effect**
Afforestation (Deforestation has converse effect)	Annual flow	-Increased interception in wet periods - Increased transpiration in dry periods through increased water availability to deep root systems	Basin scale; magnitude proportional to forest cover, world average is 34 mm/year reduction for 10% increase in forest cover.
	Seasonal flow	-Increased interception and increased dry period transpiration will increase soil moisture deficit and reduce dry season flow.	Basin scale; can be of sufficient magnitude to stop dry season flows
		Drainage activities associated with planting may increase dry season flows through initial dewatering and also through long term effects of the drainage system	Basin scale; drainage activities will increase dry season flows
	Floods	Interception reduces floods by removing a proportion of the storm rainfall and by allowing build-up of soil moisture storage.	Basin scale; effect is generally small but greatest for small storm events
		Management activities: cultivation, drainage, road construction, all increase floods	Basin scale; increased floods for all sizes of storm events
	Climate	Increased evaporation and reduced sensible heat fluxes from forests affect climate	Micro, meso and global scale; forests generally cool and humidify the atmosphere; a 2 ^{0}C increase in regional temperature is predicted for Amazonia if deforestation continues.

Continued….

Agricultural intensification	Water quantity	Alteration of transpiration rates affects runoff	Basin scale: effect is marginal
		Timing of storm runoff altered through land drainage	Basin scale: the effect is significant
	Water quality: fertilizers	Application of inorganic fertilizers	Basin scale; increased nutrient concentrations in surface and groundwaters
Draining wetlands	Seasonal flow	Upland peat bogs, groundwater fens, and African dambos have little effect in maintaining dry season flows	Basin scale: drainage or removal of wetland will not reduce, and may increase dry season flows
		Lowering of the water table may induce soil moisture stress, reduce transpiration, and increase dry season flows	Basin scale; a reduction of water table depth to minimum of 30cm below surface is required
		Initial dewatering following drainage will increase dry season flows	Basin scale; effect may last from 1-2 years to decades
		The deeper flow outlet of drainage system will lead to increased dry season flows	Basin scale; effects will be long-term
	Annual flow	Initial dewatering following drainage will increase annual flow	Basin scale; effect may last from 1-2 years to decades
		Afforestation following drainage will reduce annual flow.	Basin scale effects as for afforestation.

Appendix-2 Long-term mean monthly values of climatic variables on Lake Awassa catchment

Month	**Climatic variables**					
	Rainfall (mm)	Reference crop evapotranspiration (mm)	Relative humidity (%)	Wind speed (ms^{-1})	Temperature (^0C)	Sun-shine hours
January	26.7	99.9	54.6	1.14	19.6	8.8
February	49.7	90.8	53.9	1.16	20.5	8.4
March	92.4	99.3	60.7	1.15	21.0	7.7
April	127.1	72.9	67.8	1.09	20.9	6.6
May	126.4	75.3	73.1	1.12	20.3	7.3
June	98.1	65	70.3	1.24	19.6	6.6
July	115.9	38.7	74.3	1.12	19.0	4.8
August	114.3	47.4	75.3	0.99	19.1	5.3
September	133.1	52.4	77.3	0.9	19.2	5.6
October	86.1	76.4	70.3	0.76	19.1	6.9
November	33.1	91.5	59.7	0.87	18.7	8.9
December	24.9	95.9	56.2	1.02	18.9	9.1

Appendix-2.1 Monthly free water evaporation the Lake (Penman-combination approach) (mm)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1981	159.3	153.7	102.9	91.0	126.2	123.3	64.3	82.6	63.6	128.0	153.5	158.7
1982	138.4	117.1	164.9	108.2	108.1	108.6	72.6	74.5	92.2	116.9	107.7	134.2
1983	150.8	133.8	157.1	102.6	101.3	107.1	69.8	49.9	76.9	125.9	131.7	132.3
1984	161.7	165.3	161.9	126.8	103.0	92.1	89.6	96.6	81.8	149.6	138.3	146.4
1985	162.6	153.8	166.0	120.6	107.9	114.7	64.4	79.8	83.3	113.7	135.3	154.4
1986	164.0	126.5	148.5	94.9	123.3	72.8	76.7	109.3	102.0	126.6	143.4	149.0
1987	151.1	131.2	140.5	94.4	99.0	109.6	112.9	107.7	99.6	113.1	153.7	166.2
1988	148.3	127.0	158.6	130.6	142.1	97.0	32.1	67.0	77.7	112.5	158.6	129.9
1989	143.1	137.9	135.4	97.1	134.8	104.0	52.2	93.1	76.4	113.5	134.9	115.5
1990	140.9	88.2	125.1	109.1	104.7	115.4	74.8	68.3	86.2	136.2	130.8	153.0
1991	148.9	119.0	129.1	134.2	125.3	104.5	49.0	61.4	89.9	129.9	135.9	133.2
1992	134.3	119.4	166.2	150.9	136.7	113.0	82.7	72.8	81.4	107.6	134.7	139.0
1993	123.1	109.9	181.5	108.5	111.4	88.8	63.1	85.9	85.7	107.4	142.2	147.9
1994	166.3	155.2	140.4	108.0	104.3	83.1	51.0	79.2	78.4	141.5	135.0	134.2
1995	165.8	124.4	135.1	94.8	132.3	120.1	55.5	71.9	98.4	39.8	150.2	130.9
1996	129.4	145.5	125.1	36.2	110.3	63.1	53.0	59.9	79.9	128.8	142.8	159.3
1997	142.6	175.3	159.3	102.1	95.5	98.9	81.2	106.8	114.3	111.8	95.6	130.2
1998	107.0	120.4	137.9	137.9	110.8	96.6	63.1	66.2	80.5	50.7	142.7	155.6
Mean	146.6	133.5	146.4	108.2	115.4	100.7	67.0	79.6	86.0	114.1	137.1	142.8

Appendix-2.2 Reference potential evapotranspiration (mm)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1981	110.7	107.2	66.4	57.6	84.2	83.1	36.8	50.4	35.6	84.2	105.4	109.3
1982	93.4	78.6	114.6	70.5	69.8	72.5	44	44.2	57.3	76.4	70.5	92.2
1983	102.6	91.8	108.5	66	64.8	69.8	40.4	24.9	46.1	83.4	87.8	87.3
1984	112.4	115.7	112	85	66.6	59.3	56.5	60.8	49.8	100.4	92.6	100.1
1985	114.1	109.9	117.4	79.8	69.9	75.6	36.1	47.5	50.6	72.9	91.2	106.8
1986	113.9	86.8	101.3	60.8	81.9	43.5	45.7	70.6	65.7	83.6	97.1	102.1
1987	105	88.1	94.6	58.8	62.7	71.1	72.6	68.6	61.9	72.4	105.1	115.3
1988	102.2	87.2	108.6	88.7	96.1	61.9	10	38	46.9	73.1	108.8	87.9
1989	98.8	95.3	91.9	62.7	90.5	67.7	27.9	57.9	46.1	73.8	90.6	76.8
1990	94.8	55.7	82.1	69.5	66.5	76.9	45	39	52.1	89.8	85.9	101.7
1991	104.5	81.1	87	90.6	83.6	68.9	24.5	33.4	55.7	85.7	91.1	90.7
1992	92.6	81.3	116	103.6	92.2	75	50.3	41.8	49.1	69.3	90.9	95.4
1993	83.4	73.6	127.4	70.6	72.9	56.4	35.2	52.3	51.7	67.2	93.7	98.3
1994	112.8	106.5	93.3	67.3	65.4	50.7	24.3	48.5	45.4	91.9	91.5	87.9
1995	111.4	81.2	89.3	58.2	88.4	79.8	27.8	40.5	61.8	76.8	100.1	85.1
1996	85	96.6	81.2	68.3	70.9	35.1	36.3	30.5	47.1	83.1	94	105.7
1997	94.1	120.1	106.4	63.8	58.8	62.5	49	67.5	73.6	70.2	57.6	83.5
1998	66	77.7	89.7	89.7	70.1	61	34.1	36.4	46.7	20.6	92.5	100.4
Mean	99.9	90.8	99.3	72.9	75.3	65.0	38.7	47.4	52.4	76.4	91.5	95.9

Appendix-2.3 Class-A Pan Evaporation (Adjusted) (mm)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1986	172.9	158.8	180.7	150.1	96.2	119.3	105.7	124.8	138.2	146.5	144.4	141.1
1987	179.9	150.1	134.9	134.8	162.1	147.7	130.1	146.4	131.3	131.3	156	172.9
1988	159.7	152.5	182.4	144.1	154.7	145.7	93.6	124.6	119.2	139.8	205.1	144.8
1989	147.3	94.7	170.7	132.1	164.7	156	110	130.6	141.6	134.8	141.8	119
1990	135.4	122.1	142.1	130.4	159	140.8	127.2	121.7	134.6	149	148.9	168.2
1991	166.7	143.3	133.6	116	130.1	119.3	102.5	120.8	127	137.7	133.9	141.1
1992	114.4	90.7	190.8	162.2	155	139.2	151.6	120.5	115	132.2	133.2	138.3
1993	137	122.7	177.8	144.5	170.1	137.3	130.2	137.4	126	144.2	159.2	176.1
1994	187.6	182.2	176.5	146.3	152.7	152.7	103.4	120.3	138	154.6	173.5	186.7
1995	200.5	181.9	180	154.7	172.5	168.6	104	91.4	100.7	104.4	118.9	152
1996	111.1	137.3	119.3	119.3	110	93	92.1	100.3	87.7	112.4	123.6	132.4
1997	127.2	158.9	152.3	107.6	143.7	122.3	124.4	130.8	97.2	108.9	82.7	104.5
1998	155.7	97.4	112	114.4	122	105.9	96.7	88.2	94.1	79.4	108.7	127.7
Mean	153.5	137.9	157.9	135.1	145.6	134.4	113.2	119.8	119.3	128.9	140.8	146.5

Appendix-2.4 Relative Humidity (%)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1972	0.0	0.0	0.0	0.0	0.0	0.0	57.7	77.0	76.7	65.0	62.7	60.0
1973	59.7	45.0	43.0	57.7	74.0	72.0	56.7	79.7	76.3	69.3	52.0	48.7
1974	51.3	48.3	68.7	58.0	69.7	75.0	58.7	77.0	80.7	67.3	50.0	49.0
1975	45.0	51.0	52.3	70.0	72.3	77.3	84.3	82.7	81.3	75.0	56.0	49.0
1976	48.7	53.0	57.3	65.7	73.7	73.3	80.3	78.3	79.7	73.3	70.3	57.3
1977	65.3	59.7	57.7	68.0	74.7	76.3	79.3	78.0	80.3	80.7	70.0	65.0
1978	55.0	61.0	70.7	66.7	77.7	71.3	76.3	68.9	78.7	75.7	66.3	59.0
1979	67.3	64.7	61.3	63.7	74.3	73.0	76.7	75.0	78.0	73.0	55.0	55.7
1980	49.7	49.7	54.3	62.3	71.0	69.7	72.3	70.0	72.3	65.0	52.7	41.7
1981	40.7	48.3	70.3	75.0	73.0	71.3	78.3	78.7	81.7	68.0	58.3	47.3
1982	60.0	56.7	58.7	73.0	71.3	73.7	77.7	78.3	74.7	72.0	70.0	65.3
1983	56.0	61.0	63.0	76.0	80.0	76.3	78.3	80.7	81.7	76.3	65.7	59.0
1984	51.0	44.3	56.0	56.7	74.7	75.7	76.0	77.7	78.0	64.7	62.7	58.7
1985	51.3	47.0	55.7	78.7	77.0	73.7	79.7	75.7	80.3	69.3	60.7	54.7
1986	46.3	58.0	57.7	73.3	75.0	77.3	78.0	76.7	80.0	71.7	61.7	58.7
1987	52.3	54.3	65.3	65.7	76.3	70.3	67.7	70.3	71.0	69.0	65.0	52.3
1988	58.7	59.3	59.7	66.7	67.3	71.3	80.0	78.7	79.3	75.3	55.3	53.3
1989	54.0	56.0	58.0	74.0	68.3	76.0	76.0	73.7	80.3	68.3	57.7	68.7
1990	62.3	71.3	73.0	69.3	73.0	67.7	76.3	74.0	73.0	62.3	56.0	48.3
1991	51.0	61.7	68.0	67.3	72.3	65.5	78.0	75.0	77.7	62.3	52.0	55.3
1992	55.7	66.3	59.3	64.0	72.7	70.0	74.0	67.5	78.3	74.3	64.7	62.7
1993	66.0	69.0	54.3	71.7	74.3	74.3	73.0	72.0	75.7	74.3	57.7	51.3
1994	45.3	45.0	60.3	65.3	73.7	71.7	78.7	77.7	76.0	63.7	60.3	53.7
1995	46.7	55.7	64.3	73.7	72.0	71.0	75.7	75.3	77.7	66.7	58.3	61.7
1996	65.7	53.0	70.0	74.7	78.3	78.0	77.0	78.0	78.3	68.3	59.7	53.0
1997	58.3	41.7	54.7	74.3	72.3	74.7	74.3	71.3	73.0	71.7	69.7	61.0
1998	67.0	65.0	67.0	61.7	70.7	68.3	73.0	73.7	74.3	73.3	57.3	47.7
1999	50.7	40.7	66.0	63.3	70.0	69.7	75.3	73.0	75.0	74.7	57.0	53.7
2000	44.7	39.3	43.0	64.3	74.3	69.0	73.3	72.0	77.3	74.7	65.0	58.7
2001	53.0	53.3	68.7	69.7	73.0	73.7	74.7	75.3	76.3	71.3	52.7	67.4
2002	56.7	43.3	65.0	63.0	71.3	70.7	66.3	72.7	72.7	63.7	47.7	63.0
2003	57.0	49.7	59.0	68.7	68.3							

Appendix-2.5 Wind speed (m/s)

Year	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
1973	1.6	1.5	1.7	1.6	1.8	1.6	1.4	1.4	1.1	1.1	1.3	1.5
1974	1.6	1.7	1.4	1.5	1.6	1.4	1.3	1.3	1.1	1	1.4	1.7
1975	1.7	1.6	1.5	1.4	1.5	1.6	1.3	1	1.9	1	1.2	1.6
1976	1.5	1.4	1.6	1.5	1.3	1.5	1.4	1.1	1	1	1	1.3
1977	1.4	1.4	1.5	1.4	1.3	1.3	1.4	1.2	1	1	1	1.5
1978	1.2	1.1	1.2	1.3	1.2	1.4	1.5	1.1	1	1	1	1.1
1979	1.2	1.1	1.2	1.2	1.1	1.4	1.1	1.1	1	1	1	1.1
1980	1.3	1.4	1.4	1.4	1.4	1.5	1.3	1.2	1.2	1.0	1.1	1.4
1981	1.4	1.4	1.4	1.4	1.4	1.5	1.3	1.2	0.9	1	1.3	1.3
1982	1.2	1.3	1.5	1.3	1.2	1.8	1.5	1.2	1	1.1	1.2	1.6
1983	1.2	1.4	1.4	1.2	1.2	1.2	1.1	1.1	1	1	1	1
1984	1.4	1.4	1.4	1.3	1.4	1.5	1.4	1.1	1	1	1	1.3
1985	1.5	1.7	1.7	1.4	1.3	1.3	1	1	0.8	0.9	1.1	1.3
1986	1.3	1.4	1.3	1.4	1.3	1.2	1.1	1	1.1	0.9	1	1.2
1987	1.4	1.1	1.2	1.1	1.1	1.1	1	1	0.8	0.9	0.9	1.2
1988	1.3	1.4	1.2	1.4	1.3	1.2	0.9	1.1	1.1	1.0	1.1	1.3
1989	1.4	1.4	1.4	1.4	1.3	1.4	1.3	1.1	1.1	1.0	1.1	1.3
1990	1	1.1	0.9	0.9	1	1.4	1.3	1.1	0.9	0.8	0.9	0.9
1991	1.4	1.4	1.4	1.3	1.3	1.4	1.2	1.1	1.0	1.0	1.1	1.3
1992	1.4	1.4	1.4	1.3	1.3	1.4	1.2	1.1	1.0	1.0	1.1	1.3
1993	1.4	1.4	1.4	1.3	1.3	1.4	1.2	1.1	0.8	0.5	0.7	0.9
1994	1	1.1	1	0.8	0.8	1.1	0.8	1.4	0.7	0.5	1.2	0.9
1995	0.9	0.9	1	0.8	1.1	1.2	0.9	0.9	0.7	0.6	0.7	0.7
1996	0.8	0.8	0.8	0.8	0.7	1	1	0.7	0.7	0.5	0.6	0.7
1997	0.8	1	0.9	0.7	0.9	0.9	1.1	0.9	0.7	0.5	0.5	0.6
1998	0.6	1	0.6	0.7	0.8	1.1	1.0	1.0	0.7	0.5	0.5	0.6
1999	0.9	1	0.6	0.8	1.0	1.1	1.0	0.9	0.9	0.5	0.5	0.8
2000	0.9	1	0.8	0.8	0.7	1.2	1.2	0.9	2.0	0.5	0.7	0.8
2001	0.8	1	0.7	0.7	0.8	0.9	0.9	0.8	0.7	0.6	0.6	0.7
2002	0.7	1	0.6	0.7	1.0	1.1	1.1	0.8	0.6	0.6	0.6	0.7
2003	0.8	0.8	0.8	0.6	0.8	1	0.9	0.9	0.7	0.6	0.8	0.8
Mean	1.19	1.21	1.19	1.14	1.17	1.29	1.17	1.06	0.97	0.82	0.94	1.11
St.Dev	0.30	0.30	0.34	0.31	0.27	0.21	0.19	0.16	0.30	0.23	0.26	0.33

Appendix-2.6 Maximum air Temperature (^{0}C)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1972							24.0	23.9	24.9	26.1	27.5	28.0
1973	28.9	30.6	32.0	30.7	26.3	24.9	23.6	22.8	24.5	25.6	27.6	26.7
1974	28.1	29.1	26.7	28.5	25.5	24.3	22.9	23.3	23.4	26.4	26.2	27.1
1975	28.0	29.2	30.0	26.8	26.2	23.9	21.9	21.8	23.6	24.7	26.1	27.3
1976	28.0	29.3	28.7	27.7	25.2	24.7	23.1	23.0	24.7	26.1	25.7	27.0
1977	26.5	26.6	29.0	27.6	25.6	24.3	23.1	23.5	24.7	24.6	25.1	26.2
1978	27.6	27.4	27.4	28.7	25.5	24.9	23.3	24.1	23.9	24.9	25.8	26.5
1979	25.7	27.3	28.6	28.1	26.4	25.0	23.5	24.5	24.9	26.2	26.7	27.6
1980	28.8	29.9	30.2	28.6	26.8	23.1	23.9	24.6	25.6	26.9	27.7	28.5
1981	29.4	29.3	26.6	25.4	26.5	25.9	23.1	23.5	23.4	26.4	27.3	27.8
1982	27.5	28.0	29.1	26.2	26.5	25.3	23.3	23.6	25.3	25.5	25.8	26.4
1983	27.4	28.3	30.3	26.9	25.7	25.8	23.8	23.7	24.5	25.6	27.1	27.4
1984	28.5	29.5	30.5	30.5	25.9	25.8	23.4	24.1	24.3	27.7	28.1	27.8
1985	28.9	29.3	30.1	25.7	25.2	24.8	23.1	23.5	24.6	26.2	27.6	28.1
1986	28.8	29.4	28.9	26.3	26.5	23.9	23.5	24.5	25.1	26.7	28.3	28.2
1987	28.5	29.2	27.6	27.4	26.3	25.5	25.2	25.4	26.6	27.0	29.3	29.3
1988	29.2	29.6	30.0	28.4	27.5	24.7	22.8	23.8	24.0	25.9	27.9	27.8
1989	27.7	28.0	28.7	26.2	27.1	23.9	23.3	24.3	24.4	26.4	27.3	27.1
1990	28.6	27.7	27.5	27.8	27.2	26.1	24.4	24.4	25.8	28.0	29.5	29.2
1991	30.4	29.0	27.7	29.3	28.0	26.1	23.3	25.1	26.0	27.8	29.2	28.1
1992	29.4	28.5	30.5	29.8	27.5	26.3	24.3	23.8	24.9	25.8	27.1	28.5
1993	27.6	26.9	30.8	27.0	26.9	25.2	24.4	24.8	25.7	26.9	30.1	29.7
1994	30.5	32.0	30.9	29.0	26.7	24.7	23.5	25.0	26.2	28.3	28.3	29.3
1995	30.4	30.7	30.0	27.3	27.9	27.0	24.3	24.7	25.9	27.5	29.3	29.3
1996	28.3	30.8	29.4	27.7	26.8	23.8	23.8	24.3	25.2	27.0	28.1	28.6
1997	28.9	30.3	30.8	26.9	27.5	25.7	23.9	25.5	26.7	26.5	26.4	27.3
1998	27.7	28.7	29.0	29.7	27.3	26.3	24.3	23.6	25.4	25.3	27.5	28.1
1999	29.1	31.4	28.1	29.1	27.2	26.1	23.6	25.0	25.6	25.0	27.2	28.0
2000	29.5	30.7	31.8	28.8	26.1	25.7	24.7	24.8	25.1	25.6	27.2	28.3
2001	28.7	29.1	28.4	28.4	26.9	24.8	24.4	24.5	25.9	26.7	28.2	28.6
2002	28.2	30.9	28.8	28.6	27.1	25.7	25.6	25.4	26.1	28.3	29.8	28.9
2003	28.4	31.3	30.6	28.1	28.3	25.6	24.2	24.8	25.9	28.2	29.3	27.2
Max	**30.5**	**32.0**	**32.0**	**30.7**	**28.3**	**27.0**	**25.6**	**25.5**	**26.7**	**28.3**	**30.1**	**29.7**

Appendix-2.7 Minimum air Temperature (^{0}C)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1972							14.3	13.6	12.8	11.0	9.6	10.0
1973	11.0	11.1	10.9	13.7	14.2	14.5	13.7	14.3	13.6	11.0	8.3	4.4
1974	8.8	10.4	13.0	10.3	12.4	13.4	13.3	13.6	12.5	9.6	6.7	7.7
1975	6.8	10.5	11.9	13.8	13.8	13.8	13.1	14.4	13.1	11.5	8.1	8.3
1976	9.2	10.4	11.9	12.7	12.4	13.5	13.8	12.7	11.8	11.6	10.4	9.3
1977	13.2	11.8	12.4	13.9	14.1	14.4	14.3	13.3	13.4	14.0	10.2	8.6
1978	8.1	11.8	12.9	13.1	14.3	13.3	14.5	14.2	12.5	12.2	8.2	10.1
1979	13.0	12.5	12.1	13.0	14.9	14.4	13.9	13.0	13.2	12.2	8.4	10.0
1980	11.0	11.5	12.9	14.3	14.7	14.5	13.8	13.1	12.9	11.8	10.8	8.3
1981	10.4	11.5	14.9	14.5	13.6	13.8	14.4	13.7	13.3	10.9	8.7	8.9
1982	12.1	13.1	12.4	14.4	13.7	13.8	13.9	14.4	13.2	11.7	11.9	10.6
1983	10.0	13.1	14.8	14.3	13.8	15.1	13.1	14.5	13.4	11.8	9.4	8.7
1984	8.3	7.2	10.1	12.0	13.4	13.4	13.1	12.9	11.6	8.5	9.1	8.0
1985	8.5	10.0	11.2	12.5	12.5	12.3	12.7	13.3	12.7	10.5	8.9	7.8
1986	7.5	11.2	10.5	14.8	14.4	13.7	13.5	12.1	12.8	10.8	8.7	9.7
1987	9.9	11.5	14.0	13.0	14.3	14.5	13.9	13.4	12.7	12.7	9.2	9.5
1988	11.0	13.7	12.3	14.6	13.5	13.9	14.7	14.1	16.9	12.8	6.5	7.0
1989	9.5	10.7	12.7	13.5	12.4	13.1	14.1	13.4	12.9	11.7	9.7	13.0
1990	9.0	14.1	12.6	13.7	13.3	12.8	14.2	10.7	12.9	10.5	10.4	9.0
1991	11.9	12.5	13.4	12.8	14.0	15.3	14.3	13.7	12.9	9.5	9.4	9.6
1992	12.4	13.6	12.8	14.3	13.5	14.0	13.9	14.5	12.7	13.1	10.5	11.0
1993	12.1	12.3	9.7	14.1	14.0	14.2	13.9	13.7	12.9	13.2	9.3	9.2
1994	9.7	12.0	13.0	13.8	14.3	14.5	14.3	14.7	14.0	10.1	10.0	8.9
1995	9.8	12.7	13.6	14.9	13.1	13.6	14.2	14.5	13.0	12.3	8.4	10.6
1996	12.1	10.5	13.0	14.0	14.1	14.3	14.5	14.4	13.7	10.9	8.8	9.6
1997	12.4	10.0	13.3	13.9	13.2	13.6	14.2	14.2	13.2	13.6	13.8	14.4
1998	13.3	14.3	13.9	14.8	15.7	14.7	15.7	15.9	14.5	14.4	8.9	7.8
1999	10.2	9.9	13.8	12.5	13.6	14.0	14.2	13.7	13.8	14.0	9.3	9.3
2000	9.6	10.6	11.1	14.1	14.0	13.7	14.3	14.0	13.4	14.0	10.5	9.7
2001	11.5	11.1	13.7	14.4	14.1	15.0	14.7	15.0	13.1	13.8	10.3	10.9
2002	12.4	11.8	14.0	13.5	14.8	14.5	14.4	14.2	13.4	12.8	9.8	13.2
2003	11.8	11.6	13.2	14.3	14.2	14.3	14.5	14.5	14.0	11.9	11.2	10.4
Min	**6.8**	**7.2**	**9.7**	**10.3**	**12.4**	**12.3**	**12.7**	**10.7**	**11.6**	**8.5**	**6.5**	**4.4**

Appendix-2.8 Average air Temperature (^{0}C)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1972							19.2	18.8	18.9	18.6	18.6	19.0
1973	20.0	20.9	21.5	22.2	20.3	19.7	18.7	18.6	19.1	18.3	18.0	15.6
1974	18.5	19.8	19.9	19.4	19.0	18.9	18.1	18.5	18.0	18.0	16.5	17.4
1975	17.4	19.9	21.0	20.3	20.0	18.9	17.5	18.1	18.4	18.1	17.1	17.8
1976	18.6	19.9	20.3	20.2	18.8	19.1	18.5	17.9	18.3	18.9	18.1	18.2
1977	19.9	19.2	20.7	20.8	19.9	19.4	18.7	18.4	19.1	19.3	17.7	17.4
1978	17.9	19.6	20.2	20.9	19.9	19.1	18.9	19.2	18.2	18.6	17.0	18.3
1979	19.4	19.9	20.4	20.6	20.7	19.7	18.7	18.8	19.1	19.2	17.6	18.8
1980	19.9	20.7	21.6	21.5	20.8	18.8	18.9	18.9	19.3	19.4	19.3	18.4
1981	19.9	20.4	20.8	20.0	20.1	19.9	18.8	18.6	18.4	18.7	18.0	18.4
1982	19.8	20.6	20.8	20.3	20.1	19.6	18.6	19.0	19.3	18.6	18.9	18.5
1983	18.7	20.7	22.6	20.6	19.8	20.5	18.5	19.1	19.0	18.7	18.3	18.1
1984	18.4	18.4	20.3	21.3	19.7	19.6	18.3	18.5	18.0	18.1	18.6	17.9
1985	18.7	19.7	20.7	19.1	18.9	18.6	17.9	18.4	18.7	18.4	18.3	18.0
1986	18.2	20.3	19.7	20.6	20.5	18.8	18.5	18.3	19.0	18.8	18.5	19.0
1987	19.2	20.4	20.8	20.2	20.3	20.0	19.6	19.4	19.7	19.9	19.3	19.4
1988	20.1	21.7	21.2	21.5	20.5	19.3	18.8	19.0	20.5	19.4	17.2	17.4
1989	18.6	19.4	20.7	19.9	19.8	18.5	18.7	18.9	18.7	19.0	18.5	20.1
1990	18.6	19.4	20.7	19.9	19.8	18.5	18.7	18.9	18.7	19.0	18.5	20.1
1991	18.8	20.9	20.1	20.8	20.3	19.5	19.3	17.6	19.4	19.3	20.0	19.1
1992	21.2	20.8	20.6	21.1	21.0	20.7	18.8	19.4	19.5	18.7	19.3	18.9
1993	20.9	21.1	21.7	22.1	20.5	20.2	19.1	19.2	18.8	19.5	18.8	19.8
1994	19.9	19.6	20.3	20.6	20.5	19.7	19.2	19.3	19.3	20.1	19.7	19.5
1995	20.1	22.0	22.0	21.4	20.5	19.6	18.9	19.9	20.1	19.2	19.2	19.1
1996	20.1	21.7	21.8	21.1	20.5	20.3	19.3	19.6	19.5	19.9	18.9	20.0
1997	20.2	20.7	21.2	20.9	20.5	19.1	19.2	19.4	19.5	19.0	18.5	19.1
1998	20.7	20.2	22.1	20.4	20.4	19.7	19.1	19.9	20.0	20.1	20.1	20.9
1999	20.5	21.5	21.5	22.3	21.5	20.5	20.0	19.8	20.0	19.9	18.2	18.0
2000	19.7	20.7	21.0	20.8	20.4	20.1	18.9	19.4	19.7	19.5	18.3	18.7
2001	19.6	20.7	21.5	21.5	20.1	19.7	19.5	19.4	19.3	19.8	18.9	19.0
2002	20.1	20.1	21.1	21.4	20.5	19.9	19.6	19.8	19.5	20.3	19.3	19.8
2003	20.3	21.4	21.4	21.1	21.0	20.1	20.0	19.8	19.8	20.6	19.8	21.1
Mean	**19.5**	**20.4**	**20.9**	**20.8**	**20.2**	**19.5**	**18.9**	**19.0**	**19.1**	**19.1**	**18.5**	**18.7**

Appendix-2.9 Sun-shine hours (hrs)

Year	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
1974									5.6	8.1	9.9	9.6
1975	9.4	9.0	8.2	6.2	7.2	6.5	3.8	3.4	4.9	7.0	9.3	9.8
1976	9.6	8.9	7.9	7.2	6.8	7.3	4.7	5.1	5.8	7.3	8.3	9.5
1977	7.4	8.4	7.8	6.4	6.9	5.9	4.0	5.0	5.3	5.0	8.5	9.6
1978	9.6	6.6	7.0	7.7	7.5	6.8	4.0	5.4	5.1	6.2	8.8	8.6
1979	8.5	8.1	7.4	7.5	6.9	7.4	5.0	6.1	5.6	7.2	9.7	9.2
1980	8.9	9.3	7.8	6.7	7.2	6.1	5.1	6.3	4.9	7.5	8.7	10.0
1981	8.6	8.9	5.8	5.6	7.6	7.9	4.6	5.5	4.6	7.8	9.6	9.5
1982	8.5	7.1	8.5	6.5	6.6	7.0	5.0	5.0	5.9	7.3	7.3	8.6
1983	9.2	8.2	8.1	6.3	6.6	7.2	5.0	3.7	5.3	8.0	8.7	8.6
1984	9.4	9.6	8.2	6.6	6.4	6.2	6.0	6.3	5.5	8.9	8.9	9.2
1985	9.3	8.6	8.2	7.5	6.9	7.7	4.8	5.3	5.7	7.1	8.6	9.5
1986	9.5	7.6	7.8	5.7	7.5	5.3	5.4	7.0	6.6	7.8	9.1	9.3
1987	8.8	8.0	7.7	5.5	6.3	7.2	7.1	6.6	6.2	6.9	9.7	10.0
1988	8.8	7.6	8.3	7.3	8.2	6.5	2.9	4.6	5.2	7.1	9.9	8.0
1989	8.5	8.4	7.0	5.9	7.9	7.1	3.8	5.9	5.2	6.9	8.5	7.6
1990	8.8	6.0	7.3	6.5	6.5	7.3	5.1	4.5	5.5	8.0	8.1	9.4
1991	8.4	7.3	7.1	7.5	7.4	6.5	3.7	4.1	5.8	7.6	8.2	8.2
1992	7.8	7.5	8.5	8.2	8.1	7.2	5.5	4.5	5.4	6.8	8.7	8.7
1993	7.7	7.2	9.2	6.4	6.8	6.0	4.3	5.4	5.6	6.9	8.9	9.1
1994	9.6	8.9	7.4	6.3	6.6	5.7	4.0	5.1	5.2	8.5	8.4	8.4
1995	9.7	7.6	7.3	5.9	7.9	7.7	4.1	4.8	6.4	2.9	9.5	8.5
1996	8.3	8.9	7.1	2.7	7.1	4.8	1.6	4.3	5.4	8.0	9.3	10.1
1997	8.8	10.4	8.3	6.4	6.0	6.8	5.5	6.6	7.1	7.1	6.8	8.6
1998	7.2	7.9	7.8	7.8	6.8	6.3	4.4	4.4	5.3	3.8	9.4	10.0
1999	9.4	9.7	6.7	6.9	7.5	7.1	4.6	5.9	6.0	5.1	8.6	9.9
2000	9.8	9.8	8.9	7.0	11.3	6.6	5.6	5.3	5.4	6.2	9.1	9.4
2001	8.8	9.1	6.5	6.9	7.5	5.8	5.5	5.2	5.8	6.8	9.1	9.7
2002	9	9.6		7.6	7.1	6.4	7.1	6.3	7.1	6.9	9.7	8.1
2003	9	9.5	8.3	6.8	7.8	4.5	7.3	5.3				
Mean	8.8	8.4	7.7	6.6	7.3	6.6	4.8	5.3	5.6	6.9	8.9	9.1

Appendix-2.10 Rainfall at different stations (mm)

	Meteorological Stations				
Mon-Year	**Awassa**	**Shashemen**	**Yirbadubancho**	**Wondogenet**	**Haisawita**
Jan-81	0.0	1.5	5.1	0.1	1.5
Feb-81	25.0	18.9	30.9	7.3	20.1
Mar-81	198.7	205.7	306.4	197.9	218.4
Apr-81	135.9	124.0	112.6	173.4	131.7
May-81	48.3	48.3	40.8	76.4	51.3
Jun-81	127.2	69.1	52.2	45.4	73.4
Jul-81	132.9	106.2	96.5	128.6	112.8
Aug-81	155.9	117.0	107.3	129.3	124.3
Sep-81	157.3	156.1	196.1	179.7	165.8
Oct-81	52.4	88.5	105.0	152.5	94.0
Nov-81	7.0	28.4	68.0	25.9	30.2
Dec-81	0.0	12.7	3.4	42.9	13.5
Jan-82	49.6	58.0	50.2	100.4	61.6
Feb-82	46.6	33.6	33.9	31.7	35.7
Mar-82	99.9	72.3	56.7	85.6	76.8
Apr-82	92.1	81.8	108.2	77.0	86.9
May-82	70.8	113.9	177.3	149.1	121.0
Jun-82	121.1	93.7	81.9	112.2	99.5
Jul-82	166.3	109.8	99.2	99.0	116.7
Aug-82	117.1	91.8	75.2	116.8	97.5
Sep-82	72.7	110.2	193.1	117.1	117.0
Oct-82	95.9	80.7	63.4	114.1	85.7
Nov-82	84.4	114.4	177.1	134.8	121.5
Dec-82	12.4	61.8	137.6	69.9	65.6
Jan-83	60.5	30.2	22.1	14.8	32.1
Feb-83	47.9	47.9	39.4	76.7	50.9
Mar-83	56.3	75.6	117.6	87.7	80.3
Apr-83	186.2	180.7	182.1	248.8	191.9
May-83	239.4	194.2	191.1	224.9	206.3
Jun-83	76.2	80.0	106.4	91.4	85.0
Jul-83	102.8	104.2	92.6	161.7	110.7
Aug-83	125.9	139.5	188.0	165.3	148.2
Sep-83	153.9	124.2	150.7	113.7	131.9
Oct-83	90.6	108.7	151.6	132.5	115.4
Nov-83	14.2	76.6	39.0	222.4	81.4
Dec-83	6.4	3.9	5.3	1.2	4.2
Jan-84	0.0	0.0	0.0	0.0	0.0
Feb-84	0.0	0.0	0.0	0.0	0.0
Mar-84	36.5	41.4	36.8	69.5	44.0
Apr-84	17.4	27.9	48.3	31.5	29.6
May-84	170.2	159.7	213.5	159.6	169.7
Jun-84	70.7	66.7	55.0	102.0	70.9
Jul-84	96.1	77.1	65.5	98.6	81.9
Aug-84	92.7	90.4	118.6	96.8	96.0
Sep-84	165.7	147.0	180.3	152.6	156.2
Oct-84	27.4	27.0	21.0	44.1	28.7
Nov-84	34.5	42.5	65.9	46.3	45.2
Dec-84	13.3	12.1	8.1	19.9	12.9
Jan-85	9.2	5.0	6.0	0.9	5.3
Feb-85	0.0	1.3	0.6	4.2	1.4
Mar-85	75.7	60.4	65.9	61.7	64.1
Apr-85	201.9	219.9	294.6	258.1	233.6
May-85	93.3	155.7	196.8	254.6	165.4
Jun-85	106.9	88.7	108.5	83.8	94.2
Jul-85	146.1	120.1	121.3	138.1	127.5
Aug-85	80.7	81.9	77.6	122.3	87.0

Continued…

	Meteorological Stations				
Mon-Year	**Awassa**	**Shashemen**	**Yirbadubancho**	**Wondogenet**	**Haisawita**
Sep-85	116.4	129.9	160.7	169.5	138.0
Oct-85	50.2	39.7	51.8	31.3	42.1
Nov-85	12.8	8.8	8.3	8.3	9.4
Dec-85	8.3	11.0	3.9	26.3	11.7
Jan-86	0.0	0.2	0.8	0.0	0.2
Feb-86	34.7	45.9	112.6	10.8	48.8
Mar-86	69.6	69.0	90.9	75.1	73.3
Apr-86	109.8	115.5	148.6	137.2	122.7
May-86	167.2	129.7	138.1	130.7	137.8
Jun-86	193.0	163.3	128.8	231.6	173.5
Jul-86	153.3	98.5	83.4	89.3	104.6
Aug-86	194.2	153.8	165.8	157.8	163.4
Sep-86	171.8	159.9	198.7	173.5	169.9
Oct-86	57.3	52.6	53.4	68.1	55.8
Nov-86	22.8	14.7	20.3	5.4	15.6
Dec-86	18.4	17.3	32.6	7.7	18.4
Jan-87	0.1	1.4	4.0	0.9	1.5
Feb-87	11.8	27.3	42.7	41.9	29.0
Mar-87	151.4	155.8	199.2	182.6	165.5
Apr-87	127.8	124.4	174.4	121.6	132.1
May-87	230.8	276.4	415.8	305.6	293.6
Jun-87	58.0	83.1	129.0	101.6	88.3
Jul-87	97.3	70.3	100.2	37.0	74.7
Aug-87	108.1	113.6	119.3	162.1	120.6
Sep-87	68.8	102.3	159.2	127.6	108.6
Oct-87	100.1	122.9	183.6	140.3	130.6
Nov-87	0.4	9.8	34.1	0.6	10.4
Dec-87	4.1	9.9	23.6	7.0	10.5
Jan-88	25.8	24.5	9.6	48.5	26.0
Feb-88	68.5	55.5	40.7	78.4	59.0
Mar-88	17.5	47.8	99.0	52.1	50.7
Apr-88	80.9	128.0	235.2	129.2	135.9
May-88	100.1	76.8	111.4	45.8	81.6
Jun-88	110.9	105.5	136.9	111.3	112.0
Jul-88	117.7	144.0	157.1	223.1	153.0
Aug-88	138.8	125.0	156.8	128.6	132.8
Sep-88	205.0	175.0	185.6	201.8	185.9
Oct-88	83.9	97.4	115.3	136.5	103.5
Nov-88	1.3	0.4	0.0	0.0	0.5
Dec-88	6.6	8.9	10.9	13.5	9.5
Jan-89	38.8	24.1	9.2	38.3	13.9
Feb-89	49.9	56.8	67.7	71.3	31.3
Mar-89	62.8	82.3	139.2	111.7	83.2
Apr-89	191.8	151.5	226.7	208.2	169.6
May-89	95.2	67.3	77.6	54.9	127.2
Jun-89	123.8	117.9	154.1	160.5	189.1
Jul-89	78.1	78.9	82.6	108.7	84.2
Aug-89	86.4	80.5	130.7	77.6	50.3
Sep-89	166.3	135.2	145.3	197.3	155.7
Oct-89	44.7	68.5	100.3	111.8	49.1
Nov-89	22.3	25.3	19.0	29.9	26.9
Dec-89	50.2	84.0	92.6	71.0	91.4
Jan-90	10.5	15.1	6.3	17.8	35.0
Feb-90	93.7	99.2	220.0	112.2	116.7
Mar-90	121.1	109.5	119.3	137.6	161.8

Continued….

	Meteorological Stations				
Mon-Year	**Awassa**	**Shashemen**	**Yirbadubancho**	**Wondogenet**	**Haisawita**
Apr-90	89.9	109.3	74.1	160.2	161.6
May-90	85.3	80.4	97.4	72.6	86.5
Jun-90	44.4	55.1	51.8	50.4	59.0
Jul-90	139.5	99.6	60.5	137.0	110.4
Aug-90	39.5	58.5	76.9	63.2	52.0
Sep-90	94.1	87.9	75.5	105.2	115.2
Oct-90	27.3	29.3	45.1	52.0	2.4
Nov-90	7.6	23.6	34.9	13.3	52.2
Dec-90	3.8	26.0	97.0	6.9	14.0
Jan-91	12.3	17.2	20.5	25.9	18.2
Feb-91	90.6	83.3	99.3	138.9	88.5
Mar-91	87.4	132.0	153.2	182.4	153.6
Apr-91	48.0	78.9	64.7	181.8	153.7
May-91	129.5	116.1	138.3	93.1	108.9
Jun-91	116.7	68.6	81.7	101.1	50.6
Jul-91	109.2	89.3	21.2	159.0	114.4
Aug-91	90.6	90.1	59.4	95.2	104.6
Sep-91	104.0	113.6	134.6	141.7	119.5
Oct-91	21.6	23.2	16.0	39.0	43.0
Nov-91	12.2	17.2	20.1	6.1	32.7
Dec-91	44.8	33.3	15.9	40.5	32.8
Jan-92	23.4	55.1	36.3	46.6	31.3
Feb-92	83.2	44.3	34.3	93.7	96.6
Mar-92	73.0	29.3	71.3	54.5	107.8
Apr-92	109.0	114.3	100.8	134.8	113.0
May-92	60.5	117.6	183.9	114.0	118.6
Jun-92	83.0	125.6	80.1	67.7	133.6
Jul-92	92.8	96.4	87.7	146.1	131.4
Aug-92	123.6	99.9	93.8	164.3	141.0
Sep-92	74.5	124.6	165.0	136.2	184.9
Oct-92	142.3	27.4	115.1	213.0	137.7
Nov-92	80.1	36.6	59.6	99.6	77.5
Dec-92	16.6	41.5	36.4	36.9	27.3
Jan-93	101.6	61.2	87.3	77.8	24.8
Feb-93	109.1	43.7	87.8	96.4	89.8
Mar-93	22.3	0.0	20.5	35.1	43.0
Apr-93	104.9	137.0	223.2	207.3	174.5
May-93	165.3	75.8	216.9	157.3	174.6
Jun-93	46.7	23.0	55.4	99.4	16.3
Jul-93	54.7	162.8	47.2	71.2	78.4
Aug-93	130.8	112.8	115.5	96.9	66.3
Sep-93	47.8	243.8	111.9	144.4	123.4
Oct-93	130.8	131.5	206.1	137.0	156.2
Nov-93	10.5	0.0	9.1	13.4	10.4
Dec-93	3.9	0.0	13.8	1.9	25.9
Jan-94	0.0	0.0	0.2	0.7	6.6
Feb-94	4.7	0.0	7.3	0.8	23.8
Mar-94	56.8	59.5	42.9	130.2	137.2
Apr-94	108.7	112.6	128.6	126.4	113.8
May-94	80.8	65.8	119.6	116.7	109.4
Jun-94	146.2	40.5	115.6	141.6	56.2
Jul-94	195.7	192.0	235.0	408.6	236.9
Aug-94	118.9	64.2	157.7	171.5	190.4
Sep-94	68.9	185.5	135.4	147.9	120.8
Oct-94	58.8	1.3	17.7	16.4	7.3

Continued….

	Meteorological Stations				
Mon-Year	Awassa	Shashemen	Yirbadubancho	Wondogenet	Haisawita
Nov-94	19.1	20.9	26.8	28.5	63.2
Dec-94	2.9	0.0	4.1	2.2	1.1
Jan-95	0.8	0.0	0.0	0.0	0.0
Feb-95	21.4	23.0	32.8	21.7	16.4
Mar-95	61.8	135.8	91.0	104.0	99.7
Apr-95	156.1	184.8	214.5	212.1	202.8
May-95	43.6	76.2	52.8	97.1	99.2
Jun-95	118.7	68.5	72.3	68.1	35.6
Jul-95	175.7	65.1	74.4	134.7	113.1
Aug-95	134.7	102.9	59.9	187.6	133.2
Sep-95	166.8	130.4	80.8	134.1	144.8
Oct-95	22.3	35.8	64.7	19.2	25.7
Nov-95	18.3	5.2	14.3	1.0	0.0
Dec-95	84.2	24.9	43.0	45.3	37.4
Jan-96	78.4	16.0	46.3	38.9	53.7
Feb-96	36.9	0.0	35.4	19.4	56.4
Mar-96	89.6	108.5	113.1	102.8	179.6
Apr-96	113.8	135.9	201.8	179.2	135.2
May-96	161.5	187.2	234.2	105.4	146.5
Jun-96	243.3	107.6	170.8	155.9	126.2
Jul-96	121.2	209.2	88.6	183.1	116.8
Aug-96	108.7	128.8	96.6	246.4	122.2
Sep-96	145.0	170.5	178.1	153.3	134.6
Oct-96	69.6	82.0	40.1	41.3	69.3
Nov-96	19.7	33.7	6.0	19.2	24.1
Dec-96	1.4	7.9	2.4	8.2	12.2
Jan-97	23.4	52.5	46.2	39.5	39.6
Feb-97	1.7	0.0	2.9	6.5	0.0
Mar-97	75.1	96.1	119.0	54.1	56.8
Apr-97	125.0	169.8	131.4	252.6	136.7
May-97	73.0	120.4	133.0	76.2	102.6
Jun-97	111.2	106.2	86.8	192.0	88.5
Jul-97	98.6	91.0	128.0	92.4	23.5
Aug-97	113.9	184.0	144.3	158.7	38.8
Sep-97	118.9	58.3	94.5	109.9	62.2
Oct-97	157.1	167.2	159.5	153.5	59.5
Nov-97	132.2	140.7	125.3	141.4	46.9
Dec-97	24.0	2.2	2.9	4.7	0.0
Jan-98	92.0	48.6	93.7	91.3	16.6
Feb-98	140.0	96.1	114.5	157.0	75.6
Mar-98	90.8	113.2	76.7	175.1	163.9
Apr-98	86.4	76.6	99.9	75.5	122.5
May-98	88.4	126.0	129.2	155.1	119.7
Jun-98	56.0	73.5	82.8	108.1	82.5
Jul-98	172.9	162.4	80.3	131.9	110.6
Aug-98	108.3	149.9	81.5	99.8	11.0
Sep-98	109.6	156.1	94.1	120.9	192.4
Oct-98	193.3	186.0	224.2	181.1	12.5
Nov-98	10.6	12.9	20.6	9.1	25.2
Dec-98	0.0	0.0	1.7	0.0	0.0
Jan-99	19.8	14.5	4.1	7.7	7.1
Feb-99	0.4	0.0	2.7	0.0	7.9
Mar-99	105.5	50.3	95.7	127.6	128.1
Apr-99	27.1	37.5	57.6	53.3	90.6

Continued….

Meteorological Stations					
Mon-Year	**Awassa**	**Shashemen**	**Yirbadubancho**	**Wondogenet**	**Haisawita**
May-99	64.7	122.3	121.9	97.4	79.5
Jun-99	99.8	119.1	86.4	62.8	73.9
Jul-99	135.1	119.2	110.9	112.1	68.8
Aug-99	83.8	10.1	4.7	151.5	124.2
Sep-99	115.4	162.7	155.9	130.7	134.2
Oct-99	120.4	70.7	9.3	180.9	89.8
Nov-99	20.1	4.3	14.6	5.7	3.1
Dec-99	16.8	6.5	10.6	23.4	41.4
Jan-00	1.1	0.0	0.4	0.0	1.6
Feb-00	0.0	0.0	1.7	0.0	0.0
Mar-00	11.0	3.0	13.4	6.9	5.6
Apr-00	132.0	257.0	95.2	114.6	175.4
May-00	145.1	244.7	188.5	104.6	131.9
Jun-00	36.4	45.6	33.3	29.7	36.0
Jul-00	80.0	92.3	104.6	83.0	76.0
Aug-00	179.3	52.3	123.1	83.4	138.9
Sep-00	87.6	105.4	136.4	204.2	134.5
Oct-00	110.7	150.8	121.9	226.8	214.1
Nov-00	29.0	21.0	62.0	63.7	45.3
Dec-00	9.3	13.9	24.2	26.6	23.8
Jan-01	1.8	0.0	7.0	0.0	2.6
Feb-01	39.9	6.8	14.8	58.5	36.9
Mar-01	122.7	151.1	105.2	183.2	150.4
Apr-01	67.0	37.6	97.0	87.3	81.5
May-01	233.7	89.9	144.7	235.3	246.5
Jun-01	137.5	92.9	167.8	139.5	106.4
Jul-01	93.5	102.4	118.1	100.2	108.2
Aug-01	131.7	110.7	97.3	169.1	76.0
Sep-01	89.7	113.0	146.2	198.7	166.0
Oct-01	80.2	115.8	184.5	106.3	176.4
Nov-01	2.6	8.2	6.2	1.3	19.1
Dec-01	21.3	23.9	54.1	11.2	52.3
Jan-02	52.5	54.8	72.7	84.7	62.6
Feb-02	2.4	8.0	37.5	15.8	15.4
Mar-02	127.7	14.0	181.3	204.4	125.7
Apr-02	119.6	41.1	92.1	103.6	97.3
May-02	85.2	88.9	93.6	146.4	121.5
Jun-02	118.4	33.5	54.9	93.4	72.2
Jul-02	76.6	18.5	50.7	65.1	47.7
Aug-02	190.4	60.5	128.5	93.6	76.8
Sep-02	82.2	67.9	146.1	83.6	141.4
Oct-02	37.2	9.5	49.8	31.7	27.0
Nov-02	0.0	0.0	0.0	0.0	0.0
Dec-02	51.5	39.8	112.3	75.7	63.8
Jan-03	30.4	7.3	12.4	26.9	20.0
Feb-03	2.0	22.3	7.4	55.2	19.6
Mar-03	78.2	68.3	112.8	98.1	93.7
Apr-03	179.1	131.9	174.3	165.7	140.0
May-03	40.4	32.1	41.3	31.6	34.1
Jun-03	110.5	101.5	119.9	102.0	107.8
Jul-03	74.5	86.9	103.9	133.9	92.3
Aug-03	76.1	110.1	199.7	141.0	116.9
Sep-03	85.7	134.7	194.4	163.6	143.0
Oct-03	56.4	56.3	59.0	68.4	59.8
Nov-03	6.2	16.2	25.7	19.7	17.2
Dec-03	51.8	45.6	54.9	55.4	48.4

Appendix-3 Monthly flow of Tikurwuha River at Dato Village (Mm^3)

Drainage area =636 Km^2

YEAR	**MONTHS**											
	JAN	**FEB**	**MAR**	**APR**	**MAY**	**JUN**	**JUL**	**AUG**	**SEP**	**OCT**	**NOV**	**DEC**
1981	1.20	0.80	0.66	3.02	3.40	2.23	3.29	10.27	16.32	16.12	9.23	1.28
1982	0.57	0.51	0.48	0.91	2.32	2.30	7.62	7.44	10.91	13.24	6.02	4.55
1983	2.20	0.91	0.72	1.04	9.47	13.61	6.45	9.09	13.65	15.86	10.02	5.12
1984	3.22	1.93	1.34	1.02	1.23	2.80	4.12	6.07	8.07	6.57	1.60	0.90
1985	0.57	0.34	0.17	0.04	2.17	4.46	2.14	4.30	12.04	11.42	2.04	0.78
1986	2.00	0.39	0.53	0.83	2.66	14.01	13.00	13.92	10.04	13.53	9.23	6.31
1987	1.02	0.50	0.91	2.84	9.33	11.15	5.29	3.72	7.11	6.85	3.90	2.11
1988	1.37	0.99	1.14	1.13	1.59	2.96	7.18	14.32	16.65	15.03	9.34	4.87
1989	3.68	2.68	2.60	2.72	3.74	7.40	6.00	6.32	9.49	11.99	6.72	4.46
1990	3.90	3.28	7.77	13.74	9.39	4.97	4.96	7.05	7.44	15.84	11.25	3.03
1991	2.27	1.46	1.21	3.18	9.43	3.46	6.70	9.91	11.73	13.89	8.91	5.28
1992	2.08	0.76	0.62	0.83	3.05	4.26	5.80	7.95	16.85	21.57	14.55	4.99
1993	2.91	1.85	1.35	1.09	3.79	9.40	11.92	11.52	13.02	15.81	11.76	10.28
1994	5.83	1.60	0.90	1.62	2.69	4.35	7.54	14.82	15.84	10.82	7.34	5.92
1995	4.67	3.48	1.10	2.48	4.40	6.38	7.58	9.72	11.52	12.80	15.60	18.39
1996	4.50	3.20	3.00	4.42	10.00	14.82	15.81	15.73	16.10	20.54	16.29	12.85
1997	8.81	6.24	5.76	4.46	5.90	6.11	5.43	6.18	6.60	10.58	13.03	16.16
1998	18.40	16.00	10.70	4.50	9.40	18.40	18.80	15.30	15.50	21.50	13.90	9.60
mean	3.84	2.61	2.28	2.77	5.22	7.39	7.76	9.65	12.16	14.11	9.48	6.49
st.dev	3.67	2.89	3.07	3.29	4.98	4.38	3.87	3.53	4.29	4.36	5.08	5.08

Appendix-4 Boreholes and Hand dug wells

BH_ID	X(m)	Y(m)	Elev (masl)	BH_TD (m)	D_GWL (m)
BH_2	445176	780670	1720	-	30.80
BH_3	443273	779488	1711	-	21.92
BH_4	447100	791452	1780	157.00	100.00
BH_5	443150	787200	1718	72.00	25.40
BH_7	441515	771015	1748	-	51.78
BH_8	440951	774122	1690	-	6.27
BH_9	430171	763437	1963	150.00	82.50
BH_11	443521	779636	1711	46.30	20.70
BH_12	442779	781335	1700	50.00	14.24
BH_13	444761	777655	1735	61.70	51.00
BH_14	444725	777839	1735	60.00	51.41
BH_15	444253	782354	1705	52.00	17.05
BH_16	442856	781844	1695	36.10	13.40
BH_17	442024	779632	1695	34.40	9.10
BH_18	443347	775988	1750	89.25	63.95
BH_19	445052	775509	1736	82.00	54.30
BH_22	443859	779850	1715	40.00	21.85
BH_23	435563	769021	1810	128.00	54.40
BH_25	433850	790246	1711.2	83.00	48.68
BH_26	439497	770573	1740	119.00	55.94
BH_29	429345	785535	1820	275.00	35.93
BH_30	455189	775583	1705	40.00	11.00
BH_32	441456	770917	1750	119.00	55.94
BH_34	426350	778528	1718	66.00	46.25
BH_41	434384	759565	1840	197.40	43.40
BH_43	455851	775478	1720	75.00	12.00
BH_44	443521	779636	1711	46.30	20.70
BH_45	441772	779484	1695	34.40	12.20
BH_46	443764	776872	1735	66.00	28.25
BH_47	444932	778774	1720	56.00	26.20
BH_48	443836	786728	1706	30.00	22.16
BH_49	444389	787557	1705	32.50	24.80
BH_50	444329	788916	1715.2	28.90	26.60
BH_51	443190	785010	1696.7	18.00	15.50
BH_52	443342	784426	1685	20.00	4.20
BH_53	442423	785532	1700	57.50	17.00
TW_0	436488	790654	1710.8	72.00	40.05
TW_1	437578	788926	1700	41.80	22.90
TW_2	437542	789753	1709.8	54.00	33.00
TW_3	436484	790614	1711.1	64.77	40.05
TW_4	435064	790390	1709	81.00	46.00
DW_1	431007	774098	1709	-	28.20

Continued…

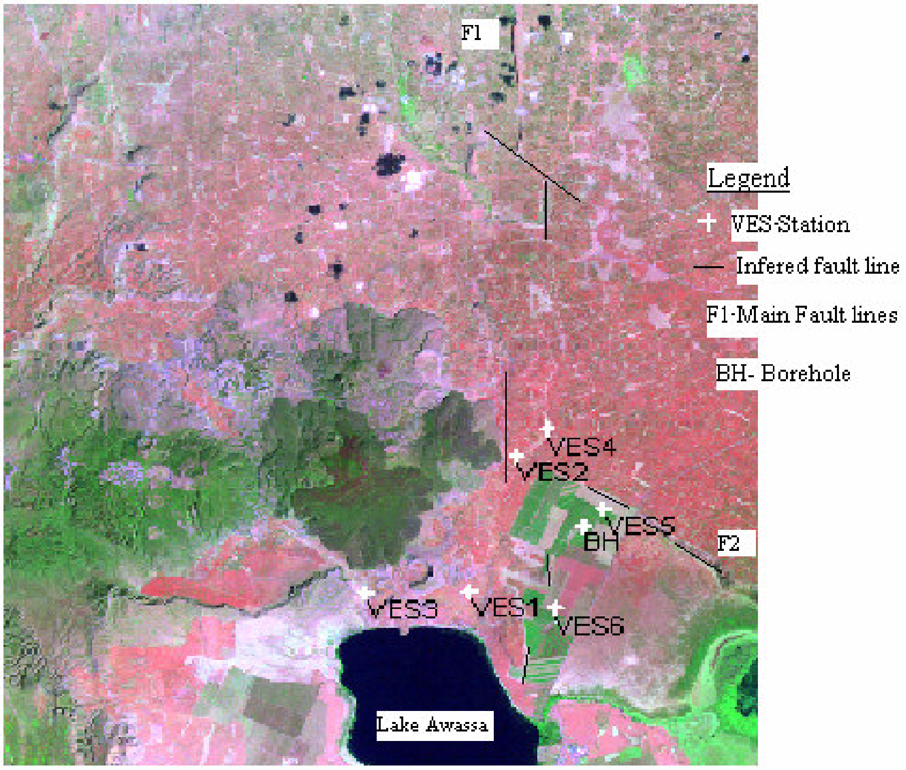
BH_ID	X (m)	Y (m)	Elev (masl)	BH_TD (m)	D_GWL (m)
DW_2	430697	774083	1705	-	32.00
DW_4	430372	774029	1705	-	29.79
DW_5	430394	774008	1705	-	36.80
DW_6	430075	774164	1705	-	38.05
DW_7	430704	776448	1698	-	27.72
DW_8	428250	777635	1695	-	24.19
DW_9	430939	775542	1709	-	35.27
DW_10	431205	775853	1706	-	30.87
DW_11	428233	777750	1695	-	24.20
DW_12	427361	778061	1705	-	36.70
DW_13	431045	779974	1696	-	20.35
DW_14	432842	778920	1682	-	7.07
DW_15	440878	774302	1690	-	4.50
DW_16	440887	774270	1690	-	4.30
DW_17	441854	778911	1700	-	13.10
DW_18	441212	779517	1681	-	0.20
DW_19	441281	779502	1685	-	4.25
DW_20	442803	785032	1697	-	10.40
DW_21	442924	778908	1720	-	28.30
DW_22	444519	771571	1700	8.20	7.85
DW_23	444656	777959	1700	11.00	10.29
DW_24	448033	772698	1693	17.25	17.00
DW_25	454439	775383	1699	19.25	19.87
DW_26	427574	773352	1730	39.40	38.90
DW_28	457036	779193	1712	-	23.35
DW_29	442418	784019	1683	-	1.50
DW_30	442518	783990	1696	-	6.87
DW_31	443408	783234	1696.7	-	6.80
DW_32	431664	754332	1770	-	7.00
DW_33	435474	761003	1844	-	8.20
DW_34	454997	775521	1702	6.00	1.00
DW_35	453680	772805	1750	-	3.70
DW_36	430262	777268	1699	-	32.50
DW_37	432383	776473	1690	-	15.50
DW_38	431003	775565	1723	-	35.80
DW_39	428194	777709	1736	-	25.75
DW_40	449015	772158	1729	-	6.15
DW_41	451914	772306	1735	-	7.20
DW_42	454542	775091	1753	-	15.50
BH_54	444813	790442	1734	-	59.65
DW_43	435288	783373	1682	-	24.57

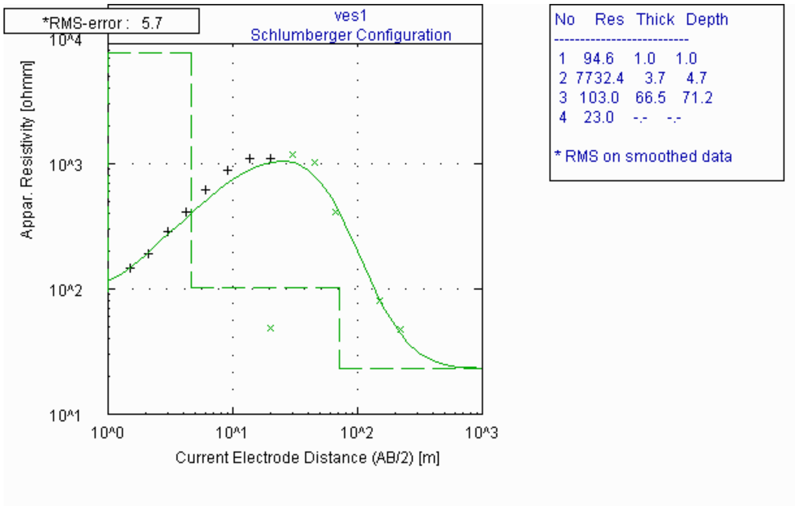
Where, DW= Hand dugwell, BH= Bore holes BH_TD= Borehole total depth
D_GWL= Depth to groundwater level Elev=surface elevation m.a.m.s.l

Appendix-5 Lake level (m.a.m.s.l)

year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1969	-	-	-	-	-	-	-	-	-	1679.66	1679.60	1679.45
1970	1679.34	1679.25	1679.26	1679.28	1679.30	1679.29	1679.28	1679.37	1679.64	1679.93	1679.97	1679.82
1971	1679.66	1679.52	1679.37	1679.33	1679.35	1679.45	1679.62	1679.75	1679.86	1680.01	1680.11	1680.04
1972	1679.93	1679.88	1679.82	1679.81	1679.92	1679.98	1680.04	1680.18	1680.39	1680.51	1680.42	1680.27
1973	1680.14	1679.96	1679.79	1679.62	1679.58	1679.57	1679.56	1679.73	1679.84	1679.90	1679.81	1679.62
1974	1679.49	1679.34	1679.24	1679.22	1679.15	1679.16	1679.20	1679.29	1679.36	1679.69	1679.60	1679.43
1975	1679.26	1679.13	1679.00	1678.94	1678.89	1678.87	1678.90	1679.18	1679.42	1679.68	1679.69	1679.52
1976	1679.36	1679.22	1679.12	1679.03	1679.00	1678.96	1678.97	1679.12	1679.29	1679.43	1679.48	1679.41
1977	1679.35	1679.32	1679.27	1679.16	1679.18	1679.25	1679.31	1679.47	1679.59	1679.81	1680.19	1680.27
1978	1680.15	1680.03	1680.00	1679.93	1679.94	1679.98	1680.01	1680.18	1680.44	1680.73	1680.78	1680.70
1979	1680.60	1680.57	1680.48	1680.46	1680.42	1680.43	1680.45	1680.55	1680.68	1680.82	1680.82	1680.70
1980	1680.56	1680.42	1680.32	1680.19	1680.16	1680.12	1680.09	1680.07	1680.07	1680.12	1680.05	1679.91
1981	1679.74	1679.48	1679.51	1679.59	1679.58	1679.52	1679.51	1679.63	1679.82	1680.03	1679.99	1679.83
1982	1679.71	1679.60	1679.52	1679.45	1679.41	1679.36	1679.42	1679.50	1679.55	1679.65	1679.74	1679.74
1983	1679.64	1679.57	1679.46	1679.39	1679.52	1679.85	1679.95	1680.07	1680.37	1680.66	1680.73	1680.69
1984	1680.54	1680.34	1680.23	1680.03	1679.95	1679.97	1679.95	1679.96	1680.01	1680.04	1679.95	1679.79
1985	1679.58	1679.45	1679.28	1679.31	1679.44	1679.49	1679.53	1679.66	1679.75	1679.86	1680.01	1679.95
1986	1679.66	1679.48	1679.39	1679.34	1679.32	1679.46	1679.65	1679.84	1680.02	1680.26	1680.30	1680.16
1987	1679.96	1679.79	1679.74	1679.73	1679.81	1680.18	1680.28	1680.31	1680.37	1680.45	1680.44	1680.29
1988	1680.13	1679.98	1679.88	1679.72	1679.74	1679.73	1679.78	1680.03	1680.42	1680.79	1680.92	1680.75
1989	1680.62	1680.52	1680.41	1680.39	1680.38	1680.49	1680.51	1680.52	1680.58	1680.73	1680.72	1680.67
1990	1680.58	1680.52	1680.54	1680.63	1680.68	1680.66	1680.64	1680.67	1680.67	1680.74	1680.66	1680.48
1991	1680.33	1680.21	1680.16	1680.12	1680.13	1680.13	1680.14	1680.18	1680.23	1680.26	1680.16	1680.02
1992	1679.88	1679.78	1679.74	1679.66	1679.64	1679.62	1679.69	1679.80	1680.04	1680.36	1680.57	1680.56
1993	1680.48	1680.49	1680.39	1680.30	1680.37	1680.48	1680.53	1680.58	1680.66	1680.78	1680.90	1680.79
1994	1680.62	1680.45	1680.32	1680.23	1680.26	1680.25	1680.34	1680.64	1680.86	1680.93	1680.86	1680.70
1995	1680.51	1680.37	1680.28	1680.27	1680.28	1680.23	1680.24	1680.29	1680.50	1680.58	1680.44	1680.37
1996	1680.28	1680.14	1680.04	1680.05	1680.16	1680.47	1680.83	1681.10	1681.38	1681.62	1681.61	1681.46
1997	1681.38	1681.14	1680.97	1680.94	1680.92	1680.92	1681.02	1681.13	1681.18	1681.31	1681.57	1681.69
1998	1681.66	1681.64	1681.68	1681.61	1681.62	1681.63	1681.65	1681.77	1681.88	1682.17	1682.36	1682.23
1999	1682.09	1681.92	1681.83	1681.73	1681.64	1681.57	1681.55	1681.61	1681.61	1681.78	1681.85	1681.73
2000	n.a	n.a	n.a	n.a	1681.14	1681.03	1680.96	1680.94	1681.00	1681.18	1681.27	n.a
2001	n.a	n.a	n.a	1680.78	1680.82	1680.96	1681.08	1681.21	1681.41	1681.58	1681.65	1681.57
2002	1681.44	1681.27	1681.20	1681.19	1681.16	1681.15	1681.11	1681.19	1681.30	1681.29	1681.17	1681.02
2003	1680.91	1680.77	1680.65	1680.60	1680.68	-	-	-	-	-	-	-

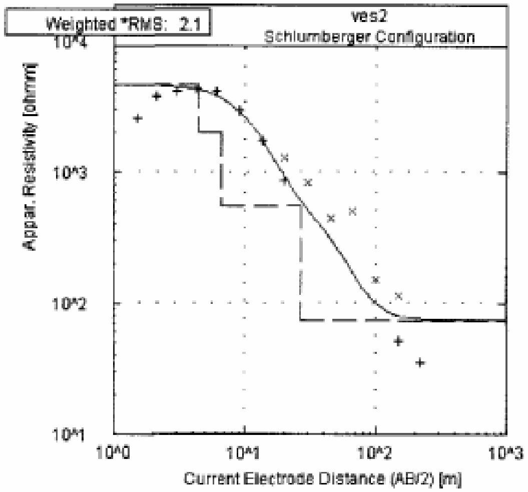
Appendix-6 Location map of the Vertical Electrical Sounding Stations and VES curves





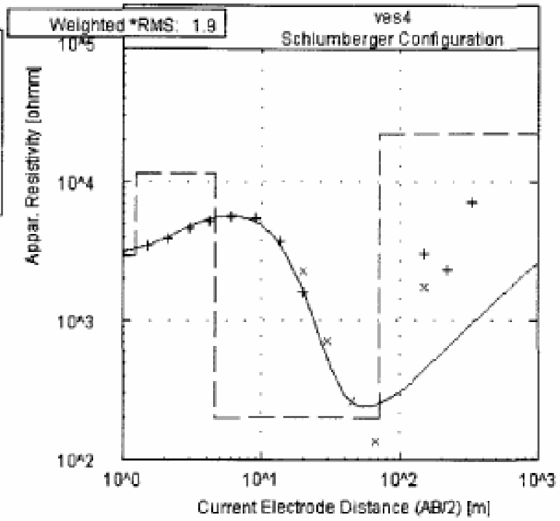
No	Res	Thick	Depth
1	94.6	1.0	1.0
2	7732.4	3.7	4.7
3	103.0	66.5	71.2
4	23.0	-.-	-.-

* RMS on smoothed data



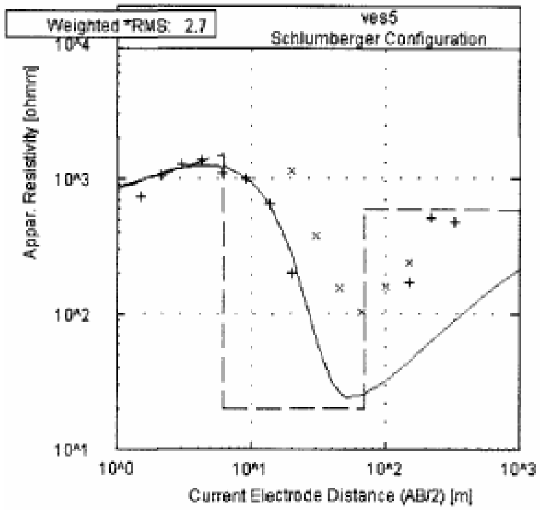
No	Res	Thick	Depth
1	4635.7	4.4	4.4
2	2008.2	2.3	6.7
3	542.8	19.8	26.5
4	74.1	-.-	-.-

* RMS on smoothed data



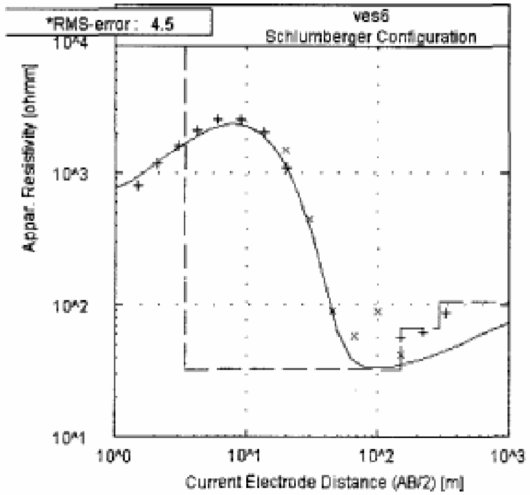
No	Res	Thick	Depth
1	2964.4	1.2	1.2
2	11580.7	3.4	4.7
3	198.4	66.9	71.6
4	22237.0	-.-	-.-

* RMS on smoothed data



No	Res	Thick	Depth
1	707.0	0.6	0.6
2	1493.7	5.7	6.2
3	20.1	64.0	70.3
4	596.1	-.-	-.-

* RMS on smoothed data



No	Res	Thick	Depth
1	652.5	1.0	1.0
2	9189.9	2.4	3.4
3	32.1	146.6	149.9
4	67.3	147.9	297.8
5	104.0	-.-	-.-

* RMS on smoothed data