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Hydrodynamics of topographically closed lakes in the Ethio-Kenyan Rift: The case of lakes Awassa and Naivasha

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Abstract
The hydrodynamics and the long-term water balance of two topographically closed crater lakes is presented in a comparative manner using a spread-sheet hydrological model. The main objective of the work is to study the role of groundwater and the effect of water abstraction from lakes Awassa and Naivasha. The rationale of selection of the two lakes separated by thousands of kilometers is the striking similarity of their hydrogeological and geomorphological setting and future intended water uses for large-scale abstraction from the lakes and feeder rivers. The net groundwater outflow from Lake Awassa and the effect of water abstraction from Lake Naivasha under different scenarios were calculated based upon the average monthly hydrometeorological data of rainfall, evaporation and river inflows. The net groundwater flux was obtained from the simulation as a residual of other water balance components and was found to be substantial in both lakes. The result revealed that the annual net groundwater outflow from Lake Awassa to adjacent basins is estimated at 58 $\times 10^6$ m^3. The predicted and recorded lake levels fit well for much of the simulation period. For Lake Naivasha groundwater flows into and out of the lake are successfully estimated based on the predicted water level fluctuations when water abstraction was at a minimal. The most accurate predictions of lake level were derived from the data sets of river discharges known to be from the most-reliable time period after the early 1970s. The model estimated an annual abstraction rate and groundwater outflow from Lake Naivasha of 60×10^6 m^3 and 56×10^6 m^3 respectively. The model demonstrated its validity as a good management tool to predict effects of large-scale pumping and extreme climatic events that may affect the lakes in space and time.

Key Words: Awassa, East African rift, hydrology, modeling, Naivasha, water balance

Introduction

Growing population density, excessive water abstraction and catchment land use changes are putting more and more pressure on the Ethio-Kenyan rift lakes and the rivers draining into them (Becht and Harper; 2002; Gebremariam, et al., 2002; Ayenew, 2004). For long time water abstraction from many rift lakes and tributary rivers preceded without the basic understanding of the complex hydrodynamics and fragile nature of the rift ecosystem. This is particularly the case in the Ethiopian rift where there is ever increasing pumping of water that may lead to negative environmental changes in the very near future (Makin et al., 1976; Halcrow, 1989; Ayenew, 1998, 2004). Little emphasis has been given to the effect of pumping, until recently when the Ethiopian government put forth new water sector development plan (MoWR, 1999, 20002).

In contrast the hydrology of most of the central Kenyan rift lakes has been studied over 100 years; initially because of scientific curiosity about the causes of its fluctuations but lately for its

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economic value for irrigation and potable water supply for the nearby towns. In the 1970s the first scientific evaluation of the Lake Naivasha's water balance was carried out to try to establish why it remained fresh (Gaudet and Melack, 1981). The low salinity was attributed to very fresh inflows combined with sediment uptake and loss of water with some solutes by seepage out (Mumbi, 1999).

The interest in the Naivasha's water balance has been driven by a desire to utilize the 'available' freshwater (Sikes, 1936; Tetley 1948; Brind and Robertson 1958; Oestergaard, 1974; Anon, 1984) although it was not until 1984 that any attention was given to how a yield of water from the lake would affect the ecology of the lake by trying to establish what a 'safe' level would be. This latter consideration suggested 16.5×10^6 m^3 annually as a 'safe yield' although it did not relate this to any inflow. These studies had assumed that catchment abstractions were minimal on an annual basis because the then existing licensed abstraction volume was very small. By the 1990s the nature of agriculture around the lake had changed substantially. Former stock rearing, ranching and sisal-cultivation had given way to approximately 100 km^2 of irrigated horticulture (Becht and Harper, 2002). This land use change, dramatic in itself, has brought even greater social changes (Anon, 1984)

The Lake Naivasha Riparian Association (LNRA) articulated the environmental concern about these changes. Consultants' report summarized all the scientific knowledge about Lake Naivasha and its conservation status (Goldson, 1993). The Association's subsequent lobbying led to the lake being declared Kenya's second Ramsar site in 1995 followed by the production of its management plan and strategy for implementation (Anon, 1997). Each of the Association's reports and its Management Plan focused upon the water balance and water yield as the most important issue. At the conclusion of the 20th Century the demands for freshwater were intense, not just for potable water as envisaged half a century earlier but also for intensive irrigation and for water in the Olkaria Geothermal Power Station, located 10 km south of the lake, which generates 15% of Kenya's power. The total calculated yield of freshwater from the lake plus catchment from these three uses in the late 1980s and early 1990s was estimated by Goldson (1993) at 37×10^6, 39×10^6 and 15×10^6 m^3 per year respectively. There is now an urgent need on the one hand to accurately measure what is actually happening to the water balance of the whole catchment and to support this with a hydrological model, which allows hypothetical scenarios to be evaluated. The model under consideration here is part of this effort.

The scope of the use of the model for Lake Awassa, however, is principally for estimating the net groundwater outflow, which is essential to use the model for scenario-analysis and water management in the future. Lake Awassa is not affected by direct water abstraction currently; there is a potential danger of using the lake and feeder rivers for irrigation in the near future (WWDSE, 2001). In some affected Ethiopian rift lakes, the increased abstraction of water led to conflicting opinions among the different riparian groups concerned with water resources development and conservation (Ayenew, 2004). There is mounting fear that increased abstraction will lead to drying up of the lakes and the surrounding shallow productive aquifers. On the other hand water users pumping the lakes and feeder-rivers believe what they abstract could not be the major factor in the lowering of the level of the lakes. Their argument is that what they abstract is negligible compared to climatic changes. Earlier works indicate that lakes were much smaller than today in the East African Rift system (Street-Perott and Harrison, 1985; Ase et al*.,* 1986).

There was hardly any irrigation at that time. Contrary to many lakes in the Ethiopian rift, the level of Lake Awassa is slightly rising in recent years. This change has been explained in terms of deforestation, which increases the runoff inputs and siltation of the lake (WWSDE, 2001). The fast decline of the size of Cheleleka swamp which feeds lake Awassa through Tikur Wuha river (Fig. 1) is explained in terms of the increasing siltation caused by alarming deforestation of the catchment (Gebreegziabher, 2005). Climate and neotectonism have also played important role (Geremew, 2000; Dessie and Tessema, 2003).

In all cases the justification is speculative rather than supporting by scientific evidences. These decripancies may be avoided if the water balance of the lakes and the role of the subdued groundwater in lake hydrodynamics are studied. This in turn requires careful evaluation of the components of the hydrologic cycle in relation to the probable natural and anthropogenic factors.
The water balance of Lake Awassa has been of wider interest for years; initially because of scientific curiosity about the causes of the lake level rise but lately for its influence on the infrastractural damage of the fastly growing Awassa town located right at the eastern shore as a result of flooding. During extreme wet seasons part of the town is flooded. There has always been urgency of protecting the town from flooding. In recent years the issue of the water balance is drawing more attention to utilize the water resources of the area in a sustainable manner.The surface water components may be quantified from limited hydrometeorological records. However; among the water balance components of lacustrine systems, groundwater is the most difficult to quantify. As a result, many hydrological studies of lake watershed systems have given little emphasis to groundwater (Crowe and Schwartz, 1981; Crowe, 1990; Almendinger, 1990). Limited groundwater modelling exercise in the Ethiopian rift revealed that groundwater is one of the major components of the water balance of many Ethiopian lakes (Ayenew, 1998; 2001). When this study was started little was known of the hydrogeologic cycle and the role of groundwater in the water balance. A basic question was whether a substantial part of the lake water depend on groundwater flux. This paper tries to illustrate both the long-term water balance and the importance of groundwater.

Description of the areas

What makes the Ethiopian and Kenyan rift similar is the existence of a string of lakes occupying volcano-tectonic depressions separated by ridges and volcanic hills often associated with geothermal fields and fed by rivers originated from adjacent highlands characterized by high rainfall. The existence of these lakes is due to the numerous Late Quaternary central volcanic structures, which often separate the lakes from each other. Many of them are alkaline and their water is highly concentrated sodium bicarbonate type (Wood and Talling, 1988; Tudorancea and Taylor, 2002). This situation is partially caused by the high alkalinity from the surrounding volcanic rocks, their terminal topographic position and the limited fresh surface water input from the catchments (Talling and Talling, 1965; Woldegebriel et al., 1990; Ayenew, 2003) coupled with poor surface water drainage outlets due to the steep sides of the valley and lack of drainage outlets. The evaporation of the terminal lakes also plays a role in the high concentration of sodium carbonate, which in turn creates an ideal breeding ground for algae. Several species of fish thrive in the rift. As a result, millions of birds flock to these lakes to feast on the abundant food supply of algae and fish.

In contrast to many East African lakes Awassa and Naivasha are the major dilute fresh crater lakes with closed drainage system located around the culmination of the Ethiopian and Kenyan rift floors respectively. The low salinity is owing to the underground seepage of groundwater from the lakes (Talling and Talling, 1965; Wood and Talling, 1988; Darling et al., 1996; Becht and Harper, 2002; Ayenew, 2003; Gebreegizabher, 2005). The two lakes occupy volcano-tectonic depression at the floor of the centre of the rift (Fig. 1, Table 1). Brief description of the physiography, climate and geology of the two catchments is given.

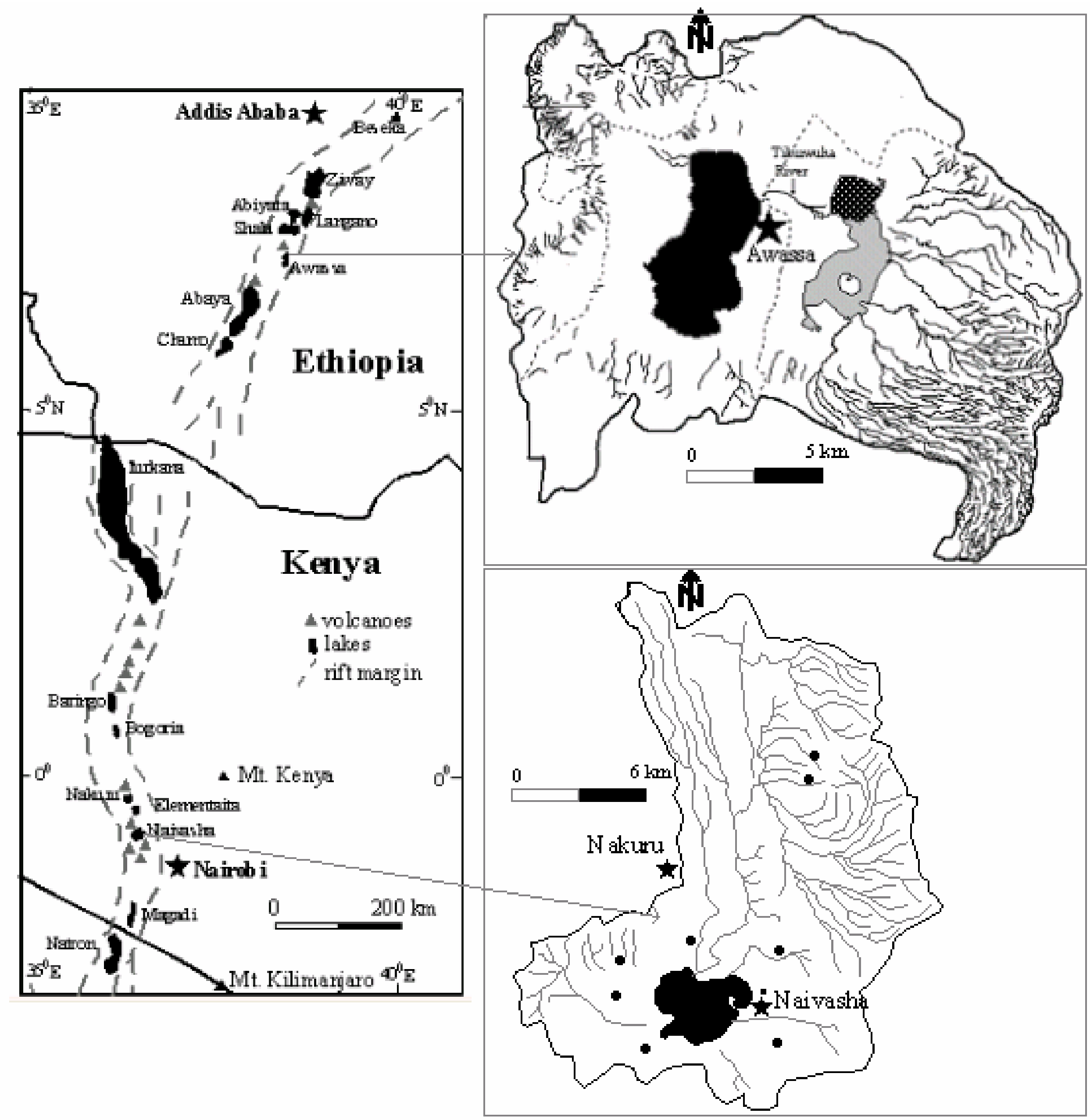


Figure 1.Simplified location map of the two catchments (circles represent sites of major water demand and diversion)

Table 1. Basic morphometric data of the lakes

Lakes	Altitude (m.a.s.l)	Area (km^2)	Max. depth (m)	Mean depth (m)	Catch. area (km^2)	Volume (km^3)	Residence .time (year)
Awassa	1680	100	22	11	1455	1.3	1.3
Naivasha	1887	145	16	4	3388	4600	1.5

Awassa catchment

Lake Awassa is one of the few fresh closed lakes (electrical conductivity = 802 µS/cm, pH = 8.6) in the Main Ethiopian Rift (MER) situated at an altitude of 1680 meters above sea level (m.a.s.l). As compared to all Ethiopian rift lakes, it is located at the highest topographic position. It is a vital source of livelihood for millions of people. The inhabitants depend on the lake for fishing and recreation. At the national level it is a major source of income through tourism and is one of the biggest bird sanctuary in the rift.

The Awassa area has a sub-humid climate and receives mean annual rainfall of around 960 mm (FAO, 1984). The mean annual pan evaporation at Awassa town is 2140 mm (WWDSE, 2001). The long-term mean annual temperature is around 19 ^{0}C. The rainfall is much higher (around 1250 mm annually) in the surrounding highlands.

Lake Awassa catchment has overlapping pair of calderas; namely Awassa and Corbetti containing lakes Awassa and Cheleleka respectively. The total catchment area is 1455 km^2, of which Lakes Cheleleka (7°06'N, 38°33'E, altitude 1685 m.a.s.l) and Awassa (7°04'N, 38°26'E) account 14.5 and 100 km^2 respectively. Swamps surrounding Lake Cheleleka located right to the northeast of Awassa occupy a further 63 km^2 (Telford, 2000). The Awassa caldera is of Pliocene age (Woldegabriel *et al*., 1990) underlain by ignimbrites. Joints and faults enhance the permeability of the ignimbrite; major fault-controlled springs feed the lake. The main rock units are volcano-lacustrine deposits and acidic volcanics (Di Paola, 1972). The recent acidic volcanics consists of obsidian, which forms the northern watershed boundary (Corbetti geothermal field) and pyroclastic products covering the foot of the highlands encroaching towards the lake from the northern recharge area. There are also scoraceous deposits of unconsolidated fragments of volcanic origin. Locally they are good unconfined aquifers covered with volcano-lacustrine deposits (Chernet, 1982; Nidaw, 1996; Dessie and Tessema, 2003). The faulting which produced the rift valley has led to extensive fracturing of the rocks. Recently reactivated very wide faults are evident in the floor of the caldera.

The caldera has five independent tributary rivers that drain ultimately to the lowest Lake Awassa. The bordering scarps and volcanic complexes have an elevation difference varying from 200 to 900 m. Runoff from the eastern wall of the caldera feeds Lake Cheleleka. Overflow from Lake Cheleleka drains into Lake Awassa through the Tikur Wuha River, which is the only major affluent river. The catchment on the north and northeastern side consists of perennial streams, draining into Lake Cheleleka. On the eastern, western, northwestern and southern side of the catchment, no perennial river flow reaches the lake. Many of the ephemeral streams terminate in wide-open faults before they reach the lake.

Lake Awassa is anomalously dilute (Wood and Talling, 1988); despite being located in a topographically closed system. Various mechanisms have been suggested to explain the low salinity of the lake and other low-salinity closed-basin lakes in the East African Rift system. The simplest explanation for the low salinity is overflow, but there is no evidence that Lake Awassa overflowed into neighboring basins during extreme wet years. Wood and Talling (1988) suggest that Lake Awassa may have more dilute inflowing rivers than other lakes, but the rivers flowing into Lake Awassa are as dilute as those flowing into the more saline open Lakes Langano and Ziway located in the northern adjacent basins (Richardson and Richardson, 1972). Groundwater outflow towards the low-lying and deep Lake Shala, as demonstrated by Darling *et al.* (1996) using isotopic evidence and groundwater flow modeling (Ayenew, 2003), remains the most plausible mechanism for maintaining the low salinity.

Naivasha catchment

Naivasha is the largest freshwater lake in the complex central Kenyan rift, whose southern shore area has become the focus of the country's horticulture. It is located right south of the alkaline lakes of Elmenteita and Nakuru. The alkaline lakes are often in volcanic areas with hot springs and in a terminal position. There are no known surface water outlets for Lake Naivasha, yet the water remains fresh (EC = 330 μS/cm) like Awassa, thus leading to suggestions of possible intricate hydrogeological mechanisms involving underground seepage.

The floor of the rift incorporates the lake, the Ndabibi Plains to the west and the Ilkek Plains immediately north of Naivasha. The Mau escarpment on the western fringe rises up to a maximum of 3080 m.a.s.l with a SSE-NNW orientation and is over 3000 m for 36 km of its entire length. The escarpment is rugged and deeply incised with numerous fault scarps. There is a rise of topography to the south towards the Olkaria volcano of up to 2430 m.a.s.l. To the east is the broad Kinangop Plateau that rises to a maximum altitude of 2740 m.a.s.l. The NNW-trending Kinangop fault scarp separates the plateau from the plain in a series of normal step faults.

Naivasha's wetlands receive inflow from two perennial and several ephemeral streams. The main rivers are the Gilgil, Karati and Malewa. The rainfall in the highlands maintains the perennial flow of the rivers. The Malewa and Gilgil rivers drain from the northern part of the catchment while Karati River drains from the northeastern part. Flow in the Karati river and other streams are seasonal and often don't reach the lake as surface water. The Malewa river accounts for about 90% of the river discharge into the lake.

The rainfall patterns in the region are subject to great spatial and temporal variation and is a product of both the location of the area in the East African tropics (macro-climate) and the particular topography of the region (meso-climate). The macro-climate gives a regime of two rainy seasons, the "long rains" occurring in April and May and part of June; sometimes these rains begin in March, the "short rains" in December and January, occasionally beginning in November (Fig. 2). In the rift valley this pattern is distorted by relief, with very much more rain falling at higher altitudes (1250-1500 mm annually) than on the valley floor. Within the rift mean annual rainfall is relatively low; which is around 750 mm annually (Meteorological Department data 1931-1980). On the rift escarpments and highlands rainfall values are much higher varying between 1250 and 1500 mm annually. Also evapotranspiration rates at these altitudes are lower at about 1400 mm annually. The annual average temperature ranges from 8^{o}C to 30^{o}C.

There is striking similarity in geology between the Kenyan and Ethiopian rift around the lakes. The rift floor is mainly composed of a succession of late Tertiary and Quaternary volcanics in places intervening lacustrine beds and alluvium principally of reworked volcanic debris. Plio-Pleistocene trachyte lavas and ignimbrites occupy nearly all the floor of the central and southern rifts and occur in places on the marginal plateaux. The lower part of the group consists of trachytic tuffs with prominent ignimbrite units. Further east ash flows are found on the flank of the highlands. West of the rift Plio-Pleistocene ignimbrites form most of the Mau Range and extend northward (Mmbui., 1999). On the rift floor trachyte and some basalt occurs within the ignimbrite succession. The Late Quaternary phase of mainly trachyte caldera eruptions occurred along the floor of the rift and is represented by the large central volcanoes in places with geothermal manifestations.

The floor of the rift valley is covered by young volcanics and lake sediments, which forms unconfined aquifer with high permeability. It consists of reworked volcanic sediments and forms the major part of the Naivasha area. Estimated average hydraulic conductivity and well yield is 10 m/day and 3 l/s/m respectively. However Clarke *et al*. (1990) indicated from an inventory of boreholes in the lake sediments and volcanics, estimated permeability of 12 - 148 m/day northeast and northwest of the lake. The fractured volcanic rocks often form confined or semi-confined aquifers at greater depths with low storage coefficients (Stuttard et al., 1999). Tuffs on the east of the lake are reported to have average conductivity of 0.8 m/day and the trachytes to the south east and in the west with 1.1 m/day. Average well yield for the tuffs, basalts and trachyte is around 0.2 l/s/m. In both catchments the main aquifer is the volcano-lacustrine deposits usually associated with fractured or reworked volcanics.

The hydrological model

The hydrological model used here is spread-sheet based. It was developed at the International Institute for Geo-Information Science and Earth Observation (ITC) in the Netherlands (Becht and Harper, 2002). The model requires known recorded hydrometeorological data and tries to estimate the unknown components of the water balance (often groundwater and/or water abstraction) as a residual by comparing recorded and simulated lake levels. The same model provided reliable information on groundwater inputs and outputs for the Kenyan rift lakes on the basis of known surface water balance components (Mmbui, 1999; Oppong-Boateng, 2001; Nabide, 2002)

The methodology is centered on optimization, calibration and validation of a deterministic quasi-distributed hydrological model. The calibration parameters were based on estimates derived from available data sources. The model is calibrated against historical measurements of lake levels, river discharge and evaporation. The water balance components used are inflow from rivers, rainfall on the lake surface, evaporation from the lake, and indirectly inflow from ungauged catchments and a dynamic groundwater component that takes into account the interactions of the lake with the surrounding aquifer.

In the model the available recorded hydrologic data are given in the basic data file (arranged in excel columns). The model tries to estimate the unknown net groundwater flux by comparing the simulated and recorded lake levels. After evaluating the equilibrium conditions of the lake on the basis of long-term records of the major water balance component, simulation is made to study the response of the lake under different abstraction/diversion scenarios for Lake Naivasha. In cases when fit is not obtained within reasonable range between the simulated and observed lake levels, an attempt is made to explain the divergence in terms of natural and anthropogenic factors on the basis of field observations. In the course of simulation the model uses the various sums and adjustments to arrive at the unknown net groundwater flux. The observed values are rainfall, lake evaporation, gauged river discharge and surface runoff from ungauged catchment estimated using runoff coefficients (for Awassa r_c= 0.14; and for Naivasha r_c= 0.13). The net evaporation volume estimate is calculated from the monthly average lake surface area multiplied by the net open water evaporation depth.

In the simulation result, columns are provided for monthly-observed lake level, calculated lake level, surface area and volumes. The calculated surface area and volume are derived from stage volume/surface area relationships. Another column is provided for the square difference between the observed and calculated levels and areas. The monthly change in storage is calculated from the total inflows and outflows (showing the temporal variations of lake levels). Abstraction from the lake is assumed to be negligible for Awassa; for Naivasha limited records are available.
The lake level-area-volume relationship is built into the model and allows the calculation of the water balance components (expressed in depth of water) as a volume. The model uses a monthly time step, and the water balance is expressed as:

Volume change = Surface water + Rainfall + Q_{in} - Evaporation – Q_{out} -Abstraction
where, Q_{in} is the inflow to or outflow (Q_{out}) from a hypothetical dynamic groundwater aquifer linked to the lake. The difference between the two (Q_{in} - Q_{out}) is the net groundwater flux. It is derived from the following relation

$$Q = C\,(H_{lake} - H_{aquifer}) \text{ in } m^3\ month^{-1}$$

where, C is the hydraulic conductivity of the aquifer (m^2 $month^{-1}$) and H is the water level in the lake and aquifer (m).

The water level in the aquifer is updated using the inflow and outflow calculated for the previous month (H_{pre}):

$$H_{pre} = Q/A \times S_y\ (m^3\ month^{-1})$$

and

$$H_{\ aquifer\text{-}new} = H_{in\text{-}old} + H_{in}\ (m)$$

where, A is the surface area and S_y is the specific yield of the aquifer obtained from hydrogeological maps and pumping test data (Oppong-Boateng, 2001; Nabide, 2002**;** Dessie and Tessema, 2003). Q (m^3 $month^{-1}$) is the water balance deficit, set to a constant for each model run. It lumps and to a certain extent balances out all missing parts and errors in the water balance. The major component is the outflow from the lake, but also the long-term unknown inflows from direct runoff and groundwater, and a systematic over or underestimate of the inflow, rainfall and evaporation are a part of this term.

The model is optimized by minimizing the sum of squared differences between observed and simulated monthly lake levels. The optimizing model parameters were the constant outflow, the hydraulic conductivity and specific yield of the aquifer in direct link with the lakes.
The lake water balance is computed by estimating all the lake's water gains and losses, and the

corresponding change in volume over the period Δt. The water balance of the lakes is given by:

$$\Delta V = P - E - W + S_{in} + G_{in} - G_{out}$$

where, P is rainfall over the lake, W is withdrawal or abstraction for irrigation, E is lake evaporation, S_{in} is the surface water inflow (including the gauged river discharge), G_{in} and G_{out} are the inflows and the outflows of groundwater, respectively, ΔV is the change in the amount of water stored in the lake during Δt.

The water balance equation can be rearranged to solve for the net groundwater flux (G_{net})

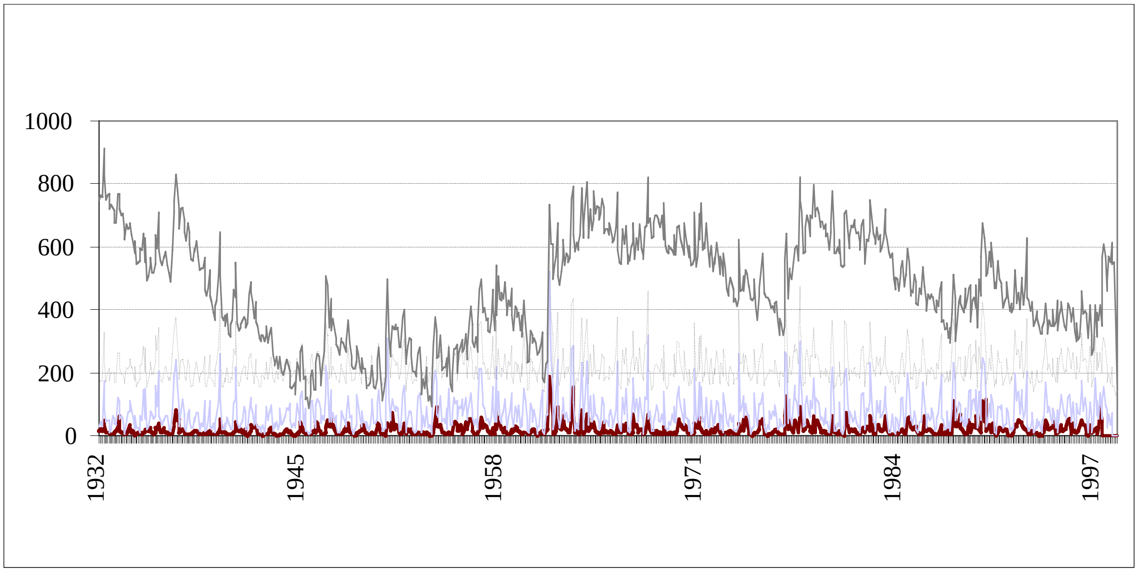
$$G_{net} = G_{in} - G_{out} = \Delta V + P + S_{in} - E - W$$

When G_{net} is positive, groundwater inflow exceeds outflow, and this value can be considered as the minimum amount of groundwater inflow in the lake water budget, similarly, when G_{net} is negative, groundwater outflow occurs from the lake.

Model input parameters and calibration

The model requires historical hydrometeorologiical data. Figure 2 shows the historical records showing the temporal variations of some of the water balance components. The record indicates strong seasonal and interannual variations of rainfall, river flow and lake levels. Unlike Lake Naivasha recent level rising trend is evident for Lake Awassa. High water levels in the early 1970's flooded parts of Awassa town (Makin *et al.,* 1976). Water levels were high again in late 1996 following a prolonged wet season (Telford *et al.*, 1999). The flow data for the Tikur Wuha River gauged close to the lake and the pan evaporation at Awassa town was used. Lake evaporation was obtained from pan evaporation (Colorado class A pan) by using a pan coefficient of 0.75. This value was found to give realistic result in the MER (Ayenew, 2002; Legesse *et al.*, 2003).

The Naivasha catchment has more long-term and continuous records for the major water balance components. Meteorological data were obtained from the Kenyan Ministry of Environment and Natural Resources; some dating back to the beginning of the 20th Century. Lake level data have been recorded at Naivasha town throughout the 20th century. For the initial Lake Naivasha model run it was decided to use the old data collected by the Ministry of Works. Data since 1983 have been recorded by Sulmac, a large horticulture company. The river flow data are reliable until the mid-1970s, after which the frequency of missing data increases. Malewa data were not recorded after 1985 and so the flow has been calculated using the Turasha (Malewa main tributary) data, which had good quality data from 1950 to 1990 and the Gilgil from 1958 to 1994. The rainfall data of Naivasha (District Office) and Kinankop Forest Station have been used at different stages of the modeling. Evaporation data (1960-1998) has been derived from the pan evaporation record.



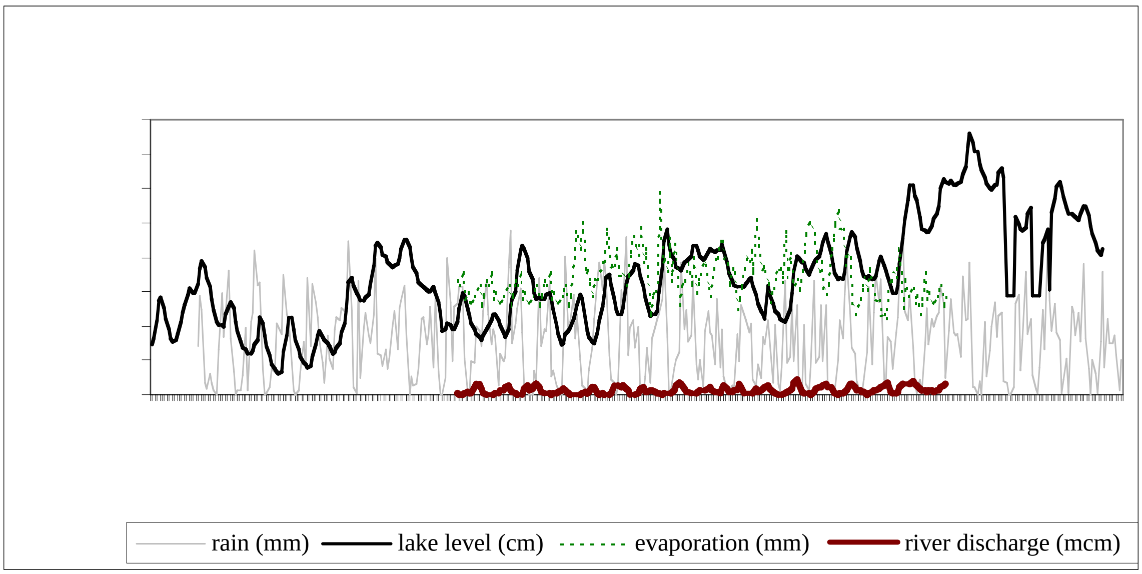


Figure 2. Historical records of some water balance components of the lakes

The lakes Awassa and Naivasha bathymetric maps were established in 1999 by WWDSE (2001) and Ase et. al. (1986) respectively. The historical stage records were used to establish the lake level-volume relationship which is crucial to accurately convert the change in the lake's storage into the corresponding lake level in the model. The water level-surface area rating curve is vital for accurate dynamic calculation of direct rainfall falling on the lake and evaporation from the lake during model simulations.

The model is caliberated by ”trial and error” approach. A graph of observed and calculated lake levels versus time was plotted under different simulation scenarios by making slight adjustments in the aquifer parameters and groundwater flux. The plot was automatically updated whenever chosen model parameters were adjusted. The probable ranges of the parameter values to be determined during the calibration were set on the basis of optimization and from the experiences

obtained from adjacent similar catchments and historical records. Visual inspection of the plot of observed and computed water levels provided a qualitative evaluation of the calibration effort. To quantify the error in the calibration, a column was included in the model to compute the sum of the square difference between the calculated and observed lake levels.
Optimization was made using known and observed hydraulic parameters using the solver function available in the Excel. Optimization was done each time with a view to minimizing the sum of square difference between the observed and calculated lake levels. The model parameters which have been optimized are head diffrences between the lake and the groundwater level, hydraulic conductivity, specific yield and most importantly the groundwater outflow (G_{out}). After optimization the sum of square differences did not exceed a maximum of 0.3.

Results and Discussion

The main purpose of the modeling in the case of Lake Awassa is to quantify the net groundwater component of the water balance under the existing condition where abstraction of water from the lake and its tributary rivers is negligible. In the case of Lake Naivasha emphasis is given to the hydrodynamics or the response of the lake under different abstraction conditions and changes in the hydrological input variables. This exercise is believed to have practical value for optimization and water management of Lake Awassa for future abstraction of water for irrigation. Therefore, the discussion starts from the simplest case of Lake Awassa to the relatively more complex condition of Lake Naivasha.

Simulation of Lake Awasssa

The first model run was done without groundwater component. The calculated water levels followed the same trend as observed lake levels but was on average higher than the observed. The higher calculated lake level implies that the total observed lake storage is higher than what is expected as if the lake did not have groundwater outflow. After the first model runs, very few erroneous data inputs became apparent and these errors were adjusted accordingly by changing the runoff. The simulation results improved significantly. Later groundwater outflow value was introduced. The specific yield and hydraulic conductivity used was based on published values for similar aquifer materials in the Ethiopian rift (Ayenew, 2001) and limited pumping test data (Dessie and Tessema, 2003). The average hydraulic conductivity, transmissivity and yield of wells is 4.2 m/day, 43.6 m^2/day and 8 liters/sec respectively. Finally with a runoff coefficient of 0.14 and the constant annual groundwater outflow of 58×10^6 m^3, a reasonable agreement between the measured and simulated lake level is achieved for the simulation period (Fig. 3).

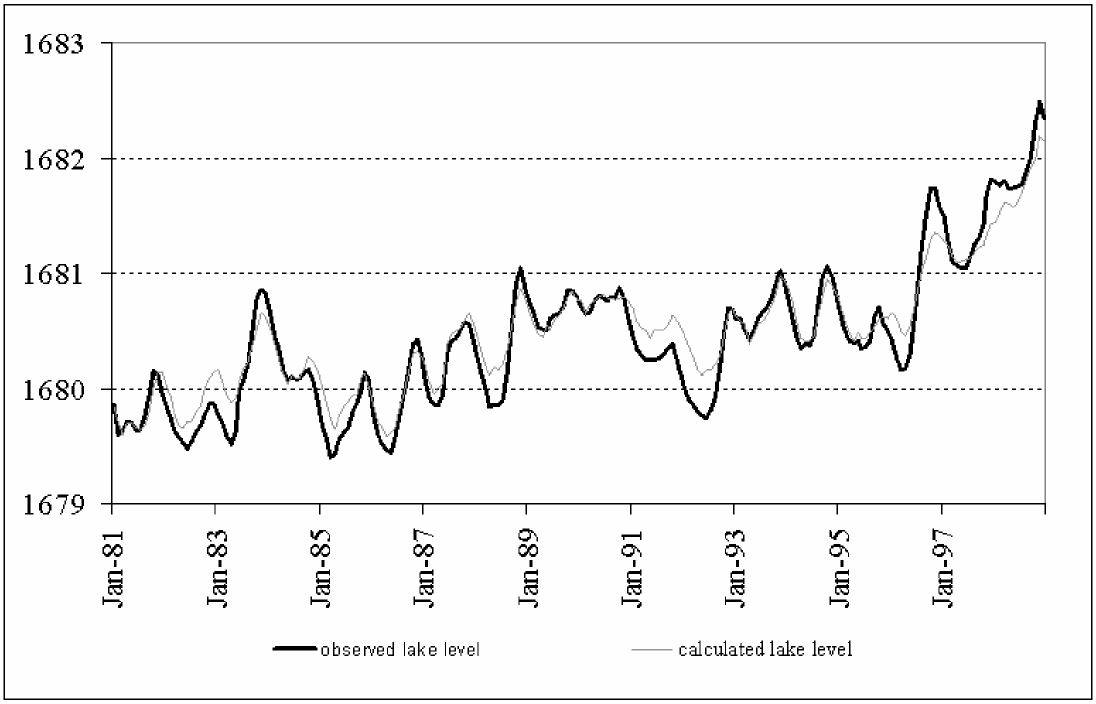


Figure 3. Observed and simulated lake levels of Awassa

As in the case of lake levels the observed and calculated lake volumes show a good fit for much of the simulation period. Lake storage values are obtained from observed lake levels using the lake level-volume relationship. The observed and calculated lake volume have similar regression coefficient except some divergence during the years 1989 to 1991 and 1997 onwards. The period after the mid 1990s have shown relatively poor fit. The recent misfit between the measured and simulated lake levels is related to land use and climatic changes and neotectonlnism. According to the studies made by the Ministry of Water Resources in the Awassa catchment, there is drastic land use changes, erosion and subsequent siltation of the lake. Based on the comparison of multi-temporal aerial photographs and the land use map of 1965 and 1998 of the Awassa cacthment; open bush land, cultivated fields, grazing land and urban area have shown spatial increment of 136.2, 50.7, 7.2 and 185.7 percent respectively (WWDSE, 2001). Whereas dense bushy woodland and open bushy wood land decreased by 55 and 73.8 percent respectively. The size of lake Awassa has shown an increment of around 4.5 km^2 in size during this time. Large open faults created by recent earth movements favor groundwater inflow in to the lake (Gebreegziabher, 2005). The study made in the adjacent Ziway-Shala basin revealed the importance of land use changes on lake levels (Legesse et al., 2003). Many of the Ethiopian rift lakes respond significantly to climatic changes (Ayenew, 2004; Legesse et al., 2004). The largest Lake Tana in the highlands was also found to be sensitive to climate (Kebede et al., 2006). Although, the relative importance of the various natural and anthropogenic factors are not discriminated well, lake Awassa seems to be also influenced by climatic changes. According to Geremew (2000) the sharp rise of the level of Awassa from 1996 onwards is partly attributed to high rainfall during the years 1996, 1997 and 1998, which is 16, 7 and 12 percent above catchment average respectively. The resulting Tikur Wuha river discharge during these years is also 13 to 70 percent higher than long-term average.

The long-term annual water balance component was estimated after model calibration. In decreasing importance the major water balance components of the lake are evaporation, rainfall and river discharge (Table 2). For some of the water balance components the modeling result coincides with previous estimates made on the basis of conventional methods (Nidaw, 1996; Halcrow, 1989; WWDSE, 2001). However, the annual groundwater outflow estimated by the spreadsheet model is higher than the 45 million cubic meter estimated by Ayenew (1998) using groundwater models.

Lakes	Rainfall	Evaporation	Surface runoff	Net groundwater outflow	Remark
Awassa	106	132	83.7	58	Groundwater inflow and outflows are not separated
Naivasha	93.9	256.3	217.4	56	Estimation under equilibrium (without pumping for irrigation)

Table 2. Long-term annual volumetric water balance components (expressed in10^6 m^3)

Simulation of Lake Naivasha

An average annual water balance of the lake was estimated first for a reliable period prior to large-scale irrigation/industrial abstraction (Table 3). The purpose of understanding the water balance of Lake Naivasha for this period is, as has been for 70 years, to estimate a 'safe yield' of water from the lake. An estimate of this 'safe yield' was made starting from this long-term annual average in the absence of abstraction. An equilibrium lake area (A_{eql},) was calculated based on the following relation:

$$(\text{Rainfall} - \text{Evaporation})\ A_{eql} + (\text{Inflow} - \text{Outflow}) = 0$$

The relation between lake area and lake level defines the long-term equilibrium lake level. This concept is important for addressing the sustainable or safe yield. It should be realized that a constant abstraction from the system translates in a reduced lake area and therefore lake level. For every rate of abstraction (smaller than the total inputs) a long-term equilibrium level will be established and the system in water balance terms is in an equilibrium and therefore under sustainable state.

The first model runs made it clear that simulation of the lake levels was possible and shows a good fit between the simulated and observed lake level; but that data after 1978 were not of enough quality as illustrated in the divergence (Fig. 4). The model was run using Malewa River discharge data from 1932–1950 and Turasha River discharge from 1950–1990 as these were considered the most reliable data sets.

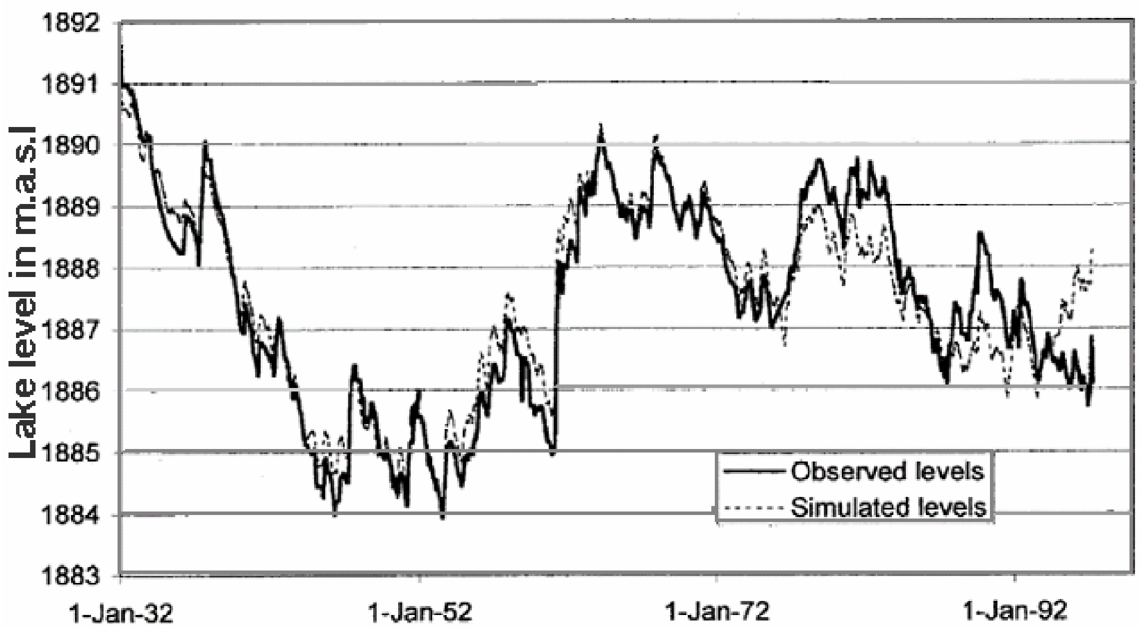


Figure 4. The simulation of Lake Naivasha water levels from 1932 to present based upon measured inflows from the Malewa, Gilgil and Karati rivers compared to recorded levels.

Figure 6 shows a better match between simulated and recorded lake levels with the exception of the later two decennia. The standard deviation of the difference between the two was 0.26, which means that 95% of all monthly levels differ 0.52 m or less. The deviation of simulated from observed water levels after the 1980s is distinct and indicates the magnitude of industrial abstraction.

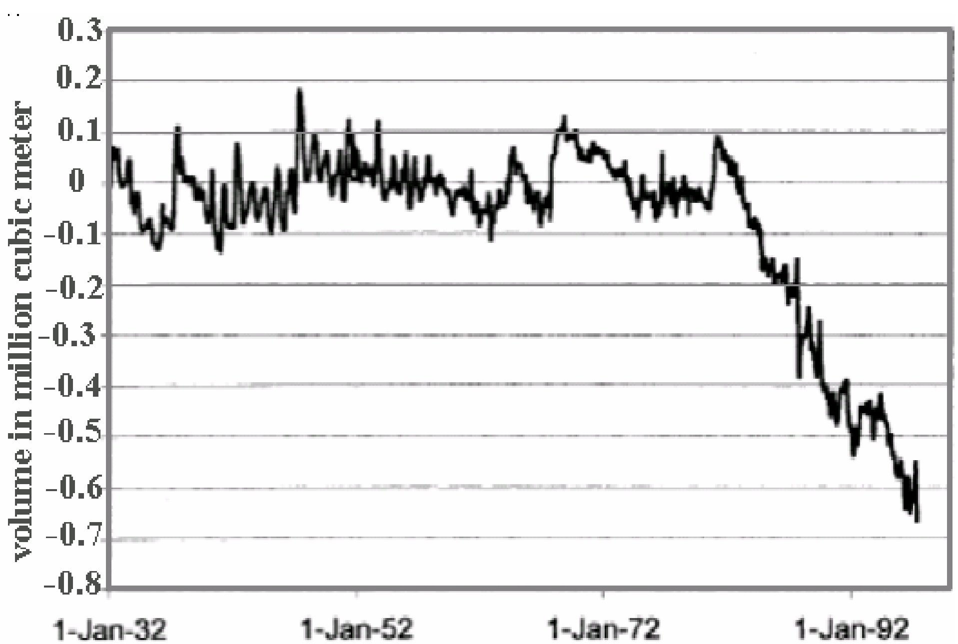


Figure 5. The simulation of Lake Naivasha water levels since 1932 using measured inflows from the Turasha river compared to recorded levels.

Since the model does not contain an abstraction component the divergence of the curves from 1983 onwards is caused by the large-scale pumping and diversion of water from the lake and feeder rivers. Using the monthly differences between observed and simulated lake levels allows an estimate of lake volume used for industrial abstraction starting from January 1983 (Fig. 6). This value has become 60×10^6 m^3 annually, a value close to estimates derived from the area under irrigation and the irrigation requirement of the crop patterns of the area (Becht and Harper, 2002). The calculated abstraction has resulted in a lake, which might have been 3 to 4 m higher than the value observed in November 1997 before the rapid rise caused by the 'El Nino' rains. Recent short field visits revealed much higher abstraction rate in the Naivasha catchment.

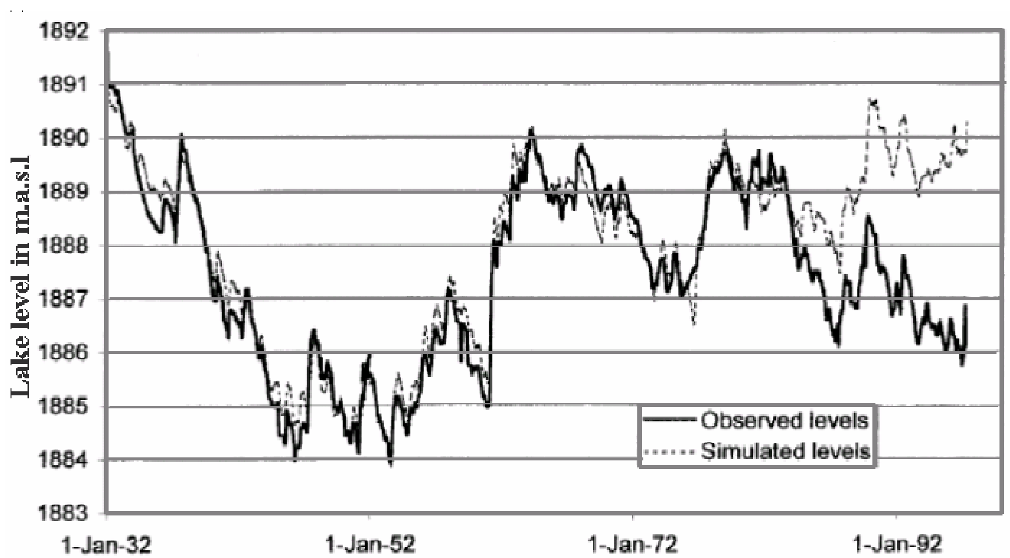


Figure 6. The difference in lake volume between observed and simulated levels, based upon a composite flow series (1932–1952 Malewa; 1952–1997 up scaled Turasha).

The average annual water balance of the lake for the period February 1932 to June 1981 (Table 3) was estimated with an error of 1.36×10^6 m^3 (equivalent to 8 mm of water level). The equilibrium water level was estimated at 1886.5 m, corresponding to a long-term equilibrium lake area of 140 km^2. Abstraction from the lake will result in a reduction of this equilibrium lake level and area. Simulating the effect of estimated annual abstractions of 60×10^6 m^3. The new equilibrium lake level and area gave a level of 1883.4 m, which corresponds to an area of 82 km^2. The average lake level has been reduced from approximately 1988 to 1984.5 m since 1932. The simulation also shows that the lake takes some 10 years before a new equilibrium has reached. This model simulation result clearly illustrates how the lake dimensions changes if excessive abstraction continues.

Table 3. The long-term average water balance figures used for the calculation of equilibrium lake levels and areas.

Water balance components	Recording period	Estimated value
Rainfall over the lake	1900-1998	648 mm
Lake evaporation	1959-1990	1788 mm
Malewa river inflow	1972-1980	217.4×10^6 m^3
Net groundwater outflow	Residual	56×10^6 m^3

Sensitivity analysis

Generally the model result shows a good correspondence between the behaviour of the model and the reality. Aside from comparing observed and simulated lake levels, validation of the model was carried out by comparing lake level, volume and surface area. The scatter plot of the observed and simulated lake levels covering the entire calibration period gave a correlation coefficient of 0.91 and 0.88 for lakes Awassa and Naivasha respectively.

Lake area obtained by digitizing the lake perimeter from Landsat satellite 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 the ground in Awassa area. 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 percent error. This difference could be attributed among other things to the resolution of the digital elevation model (DEM) used to extract the lake area and uncertainties on the lake bottom morphology from which the lake level area/capacity expressions is derived.

Sensitivity analysis was made for further set of model runs. Starting from the base model, a certain number of changes are performed for each single variable according to a defined number of intervals and ranges. The sensitivity analysis was performed on the input variables thought to be of significance in the model calculation such as rainfall, evaporation, discharge and as well as the established plausible calibrated values including the net groundwater flux, specific yield, hydraulic conductivity and aquifer area.

The model is more sensitive to evaporation and rainfall (Table 2). Ten percent 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 34 cm on the simulated lake level is obtained. The variable to which the model is least sensitive is aquifer area and lake aquifer conductance.

Conclusions and recommendations

According to the spreadsheet model simulation result the most important water balance components that play very important role in the fluctuation of the lakes are evaporation, rainfall, and runoff. Groundwater outflow is quite significant and accounts more than 30% of the total outflow in both lakes.

When the model is run based only on the surface water balance components (in the absence of groundwater) there is a progressive separation between observed and calculated lake levels. The calculated levels implying that the lake should accumulate more storage than is actually observed. This separation could not be pinned down to systematic errors in surface runoff, rainfall and evaporation measurements. It is a clear indication of subterranean outflow of groundwater from both lakes. The best fit in the model is obtained when a net annual groundwater outflow of 58×10^6 m^3 and 56×10^6 m^3 is accounted for lakes Awassa and Naivasha respectively.

The recorded and calculated lake levels agree within acceptable limits up to the mid 1970s; afterwards there is an increasing divergence between observed and calculated lake levels. This is mainly attributed to land use changes resulting in high surface runoff and saltation in Lake Awassa and progressive increase of pumping water from Lake Naivasha and its tributary rivers. Field evidences also indicate the positive role of newly formed faults that act as conduit to groundwater inflow from the elevated areas to Lake Awassa.

It has been shown that the model simulated and conventionally computed water balance components agree reasonably only if the groundwater component is accounted. This means that estimating the groundwater fluxes using appropriate methods such as seepage meters and tracers will allow a better understanding of the hydrodynamics. Leveling the existing water points to know the exact elevations of the surface and the groundwater level and knowledge of detail hydrogeological behavior of the lake catchments is vital.

It is known that the rift floor is disturbed with multi-directional fault systems, thus their relationship with the surface and groundwater flow systems and recording of neotetconic activities together with detailed hydrogeological mapping needs to be considered.

The accuracy and applicability of such models for water management depends on how correctly multi-temporal hydrometeorological data and water withdrawals rates are recorded. At present, the waters in many parts of the East African rift are being abstracted without control and systematic recording. Without proper monitoring and measurement, it is not possible to understand the safe yield of a given lake and come up with sustainable water resources utilization practices. Therefore, effort has to be made in quantifying all the water balance components in detail including groundwater.

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Naivasha.

References

Almendinger, J.A., 1990. Groundwater control of closed-basin lake levels under steady-state conditions. Journal of Hydrology. 112:293-318.

Anon, 1984. Lake Naivasha Studies. File WD/4/4/231, 23/10/84. Ministry of Water Development, Nairobi: 4 pp.

Ase, L.E., Sernbo, K and Syren, P., 1986 Studies of the Lake Naivasha, Kenya, and its drainage area. Stockholms Universitet Naturgeografiska Institutionen. Forskningssrapport 63, ISSN 0346-7406. pp 80.

Ayenew T., 1998. The hydrogeological system of the Lake District basin. Central Main Ethiopian Rift. PhD Thesis, Free University of Amsterdam. The Netherlands. 259 pp.

Ayenew, T., 2001. Numerical groundwater flow modelling of the Central Main Ethiopian Rift lakes basin, SINET: Ethiopian Journal of Science 24(2):167-184.

Ayenew, T., 2002. Recent changes in the level of Lake Abiyata, central main Ethiopian Rift. Hydrological Sciences Journal. 47(3): 493-503.

Ayenew, T., 2003. Environmental isotope-based integrated hydrogeological study of some Ethiopian rift lakes. Journal of radio-analytical and nuclear chemistry. 257 (1): 11-16.

Ayenew, T., 2004. Environmental implications of changes in the levels of lakes in the Ethiopian Rift since 1970. Regional environmental changes. 4:192-204.

Becht, R.. and Harper, D., 2002. Towards an understanding of human impact upon the hydrology of lake Naivasha Hydrobiologia 488:1-–12, 2002.

Brind, W. and J. Robertson, 1958. The Hydrology of Lake Naivasha. Hydrology Section, Ministry of Works, Nairobi: 9 pp.

Chernet, T., 1982. Hydrogeologic map of the lakes region (with memo). Ethiopian Institute of Geological Survey. Addis Ababa, Ethiopia. **[**

Clarke, M. C. G., D. G. Woodhall, D. Allen and G. Darling, 1990. Geological, Volcanic and Hydrological Controls on the Occurrence of Geothermal Activity in the area surrounding Lake Naivasha, Kenya. Ministry of Energy, Nairobi: 138 pp.

Crowe, A.S. and Schwartz, F.W., 1981. Simulation of lake watershed systems. I. Description and sensitivity of the model. Journal of Hydrology. 52: 71-105.

Crowe, A.S., 1990. Numerical modeling of the groundwater contribution to the hydrological budget of lakes. In: Selected Papers on Hydrogeology. (Simpson, E.S. and Sharp, J.M., eds.). IAH Pub.1:283-294.

Darling, W.G., Berehanu Gizaw, and Arusei, M.K., 1996. Lake-groundwater relationships and fluid-rock interaction in the African rift valley: Isotopic evidence. Journal of African Earth Sciences. 22: 423-431.

Dessie, T. and Tessema, Z., 2003. Hydrogeology and Engineering Geology of Awassa Lake Catchment. Geological survey of Ethiopia, Addis Ababa.

Di Paola, G.M., 1972. The Ethiopian Rift Valley (between 7°00' and 8°40' lat North). Bulletin vulcanologique 36: 517-560.

FAO, 1984. Agroclimatological data for Africa. Food and Agriculture Organization of the United Nations, Rome.

Gaudet, J. and J. M. Melack, 1981. Major ion chemistry in a tropical African lake basin. Freshwat. Biol. 11, 309–333.

Gebreegziabher, Y., 2005. Assessment of the Water balance of lake Awassa catchmen, Ethiopia. M.SC thesis, International Institute for Geo-Information Science and Earth Observation (ITC).Enschede, The Netherlands.92pp.

Gebremariam, Z., Westhead, K., and Desta, Z., 2002. Long termchanges in chemical features of waters of seven Ethiopian rift-valley lakes. Hydrobiologia 477: 81-91.

Geremew Z., 2000. Engineering geological investigation and lake level changes in the Awassa basin. M.Sc thesis. Addis Ababa University, Department of Geology ad Geophysics. 185 pp.

Goldson, J., 1993. A Three Phase Environmental Impact Study of Recent Developments around Lake Naivasha. Lake Naivasha Riparian Owners' Association, Naivasha, December 1993: 109 pp

Halcrow, 1989. Master plan for the development of surface water resources in ten Awash basin, vol.6. Ministry of Water Resources, Addis Ababa.

Kebede, S., Travi, Y., Alemayehu, T., marc, V., 2006. water balance of lake Tana and its sensitivity to fluctuations in rainfall, Blue Nile Basin, Ethiopia. Journal of Hydrology. 316 (1-4):233-247.

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.

Legesse, D. Christine Vallet-Coulomb, Francoise Gasse, 2004. Analysis of hydrological response of a tropical terminal lake, Lake Abiyata (Main Ethiopian Rift Valley) to changes in climate and human activities. Hydrological Processes 18:487-504.

Makin M.J., Kingham, T.J., Waddams, A.E., Birchall, C.J., Eavis, B.W., 1976. Prospects for irrigation development around lake Ziway, Ethiopia. Land Res. Study. Division, Ministry of Overseas Development, 26. Tolworth, UK. 270 pp.

Mmubi, S.G., 1999. Study of Long-term Waterbalance of Lake Naivasha, Kenya. Unpublished M.Sc thesis. ITC, The Netherlands.

MoWR, 1999. Ethiopian Water Resources Management Policy. Ministry of Water Resources (DHV). Addis Ababa, Ethiopia.

MoWR, 2002. Water Sector Development Program (2002-2016). Strategic plan document. Ministry of Water resources. Addis Ababa, Ethiopia.

Nabide, 2002. Development of 3-D Conceptual Hydrogeological Model for Lake Naivasha area Based on the Integration of Geology, Hydrochemistry, Isotopic Analysis, and Boundary Conditions. ITC MSc thesis. 132 pp.

Nidaw, D., 1996. Hydrogeology of Awassa Area. M Sc thesis. Addis Ababa University , Department of Geology ad Geophysics. 106 pp.

Oestergaard, P., 1974. Abstraction of water from Lake Naivasha. Files WRH 206 vol IV/131, 5/4/74: 2 pp and WRH 206 vol. III/132, 28/5/74: 5pp, Ministry of Water Development, Nairobi.

Oppong-Boateng, R., 2001. Assessment of Groundwater for Irrigation in the Southern Part of Lake Naivasha, Kenya. M.Sc thesis, International Institute for Aerospace survey and Earth Sciences, Enschede.

Richardson, J. L. and A. E. Richardson, 1972. History of an African Rift lake and its climatic implications. Ecol. Mongogr. 42, 499–534.

Sikes, H. L., 1936. Notes on the hydrology of Lake Naivasha. Journal of the East African and Uganda Natural History Society, 13, 73–89.

Sikes, H. L., 1936. Notes on the hydrology of Lake Naivasha. Journal of the East African and Uganda Natural History Society, 13, 73–89.

Street-Perott, F.A., S.P. Harrison, 1985. Lake levels and climatic reconstruction. In: A.D. Hecht (ed.), Paleoclimatic analysis and modelling. New York. John Wiley pp. 291-340.

Stuttard, M., J. B. Hayball, G. Narciso, M. Suppo, L. Isavwa and A.Oroda, 1999. Modelling lake level changes: examples from the Eastern Rift Valley, Kenya. In Harper, D. M. and A. Brown (eds.), The Sustainable Management of Tropical Catchments. J. Wiley and Sons, Chichester: 337–358.

Talling, J.F. and Talling, I.B., 1965. The chemical composition of African lake waters. Int. Revue. ges. Hydrobiol. 50:421-463.

Telford, R. J., Lamb, H. F. and Mohammed, M. U., 1999. Diatom-derived palaeoconductivity estimates for Lake Awassa, Ethiopia; evidence for pulsed inflows of saline groundwater. *J. Paleolimnol.* 21, 409-421.

Telford, R.J., 2000. Diatom stratigraphies of Lakes Awassa and Tilo, Ethiopia: Holocene records of groundwater variability and climate change. Unpublished PhD thesis. University of Wales. UK

Tetley, A. E., 1948. Notes on Lake Naivasha by the Hydraulic Engineer. Directorate of Water Development, Nairobi: 9 pp.

Tudorancea, C., Taylor, W.D. (Eds.), 2002. Ethiopian rift lakes. Backhuys Publishers. Leiden, The Netherlands. 289pp.

Woldegebriel, G., Aronson, J.L. and Walter, R.C., 1990. Geology, geochronology, and rift basin development in central sector of the Main Ethiopian Rift. Geological Society of America Bulletin, 102 (1990):439-458. [B34.022].

Wood, R.B. and Talling J.F., 1988. Chemical and Algal relationship in a salinity series of Ethiopian inland waters. Hydrobiologia 158:29 67.

WWSDE, 2001. The study of lake Awassa level rise. Southern Nations Nationalities and Peoples Regional State. Water, Mines and Energy Resources Development Bureau. Unpublished report of the Water Works Design and Supervision Enterprise (main report volume II), Addis Ababa, Ethiopia. 291 pp.