Groundwater links between Kenyan Rift Valley lakes

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Abstract

The series of lakes in the bottom of the Kenyan Rift valley are fed by rivers and springs. Based on the water balance, the relative positions determining the regional groundwater flow systems and the analysis of natural isotopes it can be shown that groundwater flows from lake Naivasha to lake Magadi, Elementeita, Nakuru and Bogoria.

Introduction

The African Rift system is an extensive graben system extending from the Red Sea to Southern Africa. The drainage can be described as a chain of closed drainage basins with inflow from the flanks of the rift. The Kenyan Rift valley lake basins from North to South are: Turkana, Logipi, Baringo, Bogoria, Nakuru, Elementeita, Naivasha and Magadi.

Lake Logipi, L. Bogoria, L. Elementeita and L. Magadi receive a considerable part of the inflow from springs. Lake Turkana, Baringo, Nakuru are mainly fed by rivers. Only Lake Naivasha and Lake Baringo are freshwater lakes.

The lakes have been subject to various studies. Numerous studies address the ecology of the lakes (Harper, 2002). The size of the lakes correlate well the climatic conditions and therefore the coverage and sediment cores have been used the reconstruct the past climatic conditions over East Africa ({Olago, 2000 #24}Verschuren 2002).

Especially the water balance of the economically important Lake Naivasha has been studied for more than half a century. The outflow of Lake Naivasha has been debated since the lake is studied. Due to its freshness the existence of outflow has hardly been doubted. However, the magnitude and direction of outflow is been subject of discussion.

Previous studies of exploration of the Naivasha area began as early as 1880's by European explorers. Thompson of the Royal Geographical Society of England noted the freshness of the lake water and attributed it to being either of recent origin or the lake having an underground channel. Gregory (1892) suggested that the lakes freshness was due to undiscovered underground outlet. Nilsson (1938) proposed that the Lake's freshness was a result of water both entering and leaving the Lake via underground seepage.

In 1936, Sikes made the first statistical attempt to estimate monthly and annual water budget for Lake Naivasha and magnitude of the proposed underground seepage. It is uncertain which methods he used, but he estimated that water was seeping out of the lake at a rate of 43 million m^3 $year^{-1}$.

In his note on Lake Naivasha the hydraulic engineer acknowledged outflow and assumed it would be between 0 and 46 million m^3 $year^{-1}$ (Tetley, 1948). The higher figure tallies remarkably well with more recent estimates.

The first attempt to address the direction of flow in the Naivasha area is made by Thompson *et al* (1958). They constructed a basic piezometric map with inferred flow directions.

Mcann (1992) was the first to attempt to look at the integral water balance of lakes Naivasha, Elementaita, Nakuru, Solai, Baringo and Bogoria.

He estimated a subsurface outflow to the Nakuru and Elementeita catchment to be about 37 million m3 year-1 using Darcys law. Based on the Naivasha lake water at least 34 million m^3 $year^{-1}$ infiltrates to Naivasha groundwater reservoir. He further estimated that about 14 million m3 year-1 and 23 million m3 year-1 of groundwater inflow is required to maintain constant lake water level for Lake Elemeinteita and Lake Nakuru respectively.

Gaudet and Melack (1981), extensively studied the chemical and water balance of Lake Naivasha. They concluded that there is a subsurface water outflow from the Lake Naivasha but that this plays a minor role to explain the freshness of the lake. The water balance for 1973-1975 show equal groundwater in and outflow. The outflow constitutes 20% of the total outflow.

Åse *et al* (1986) worked on the surface hydrology of the lake and mass balance equation to derive possible subsurface outflow from the lake. He doubted however the possibility of an outflow due to the thick impeding clay layer covering the lake bottom Clark *et al* (1990) and others used groundwater hydraulics and isotope methods to determine the water flow. They refer to a previous water balance study suggesting an outflow of 50 million m^3 $year^{-1}$. The flow to the south is via relatively shallow aquifers less than 500 m depth, and these may account for 50 to 90% of the total flow. Estimate of the northerly flow by the same authors was 11.3 mcm/yr.

Darling *et al* (1990) and others were able to determine the direction, quantity and character of the underground flows in and out of the lake. They used stable isotopic composition of the fumaroles steam from volcanic centres in the areas to infer groundwater composition. Using simple modelling techniques they traced the outflow from the lake up to 30 km south. Lake water has also been detected in Olkaria steam. The work confirmed that of Allen (1989) that most of the water leaving the lake goes out between Olkaria and Longonot, whilst a smaller portion goes north between Eburru and Gilgil.

Suttard *et al* (1992) in a study commissioned by the European Union derived an outflow from Lake Naivsha of 45 mcm/year.

Ojiambo (1992) deduced from piezometric surfaces that the subsurface outflow from Lake Naivasha originates from the southern shores of the lake, and then flows southerly and southwesterly toward Olkaria. And that the main lake outflow fluxes ranges from 18 and 50 mcm /yr.

Becht *et al* (2002) calibrate a water balance model for Lake Naivasha simulating the monthly water levels from 1932 to 2000 and derive a groundwater outflow is 55 m^3 $year^{-1}$

Lake Baringo is likely to have groundwater outflow to explain its freshness. The flow from Lake Bariningo is exclusively directed towards the North feeding the perennial hot springs of Kapedo and Lurosio. (Darling, 1996) (WRAP, 1987).

Odhiamdo *et al* (2005) have published the water balance of Lake Baringo.

In Ethiopia the ground water link between Rift valley lakes and the water balances has been described by several authors Legesses (2004), Ayenew (1998), Darling (1996).

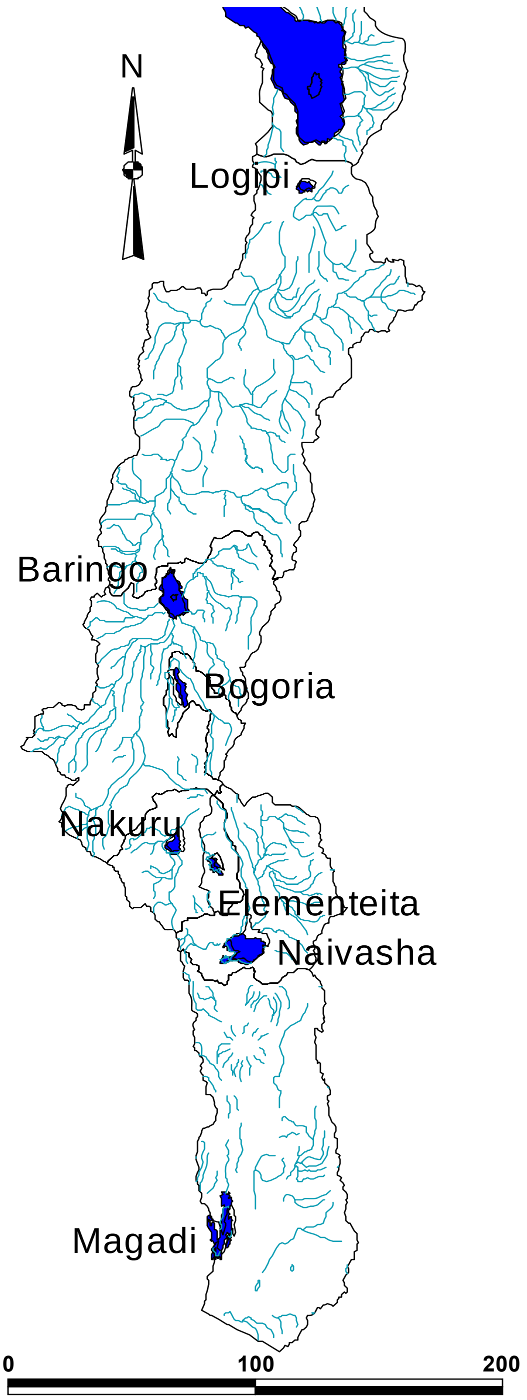
Physical setting

The Southern Rift Valley Lakes (SRVL) in Kenya are from North to South the Lakes Nakuru, Elementeitata, Naivasha and Magadi. Of these lakes Lake Naivasha is fresh. This is explained by its location at the culmination of the rift valley floor (1885 m asl) provoking the outflow of groundwater. This refreshes the lakes and prevents the accumulation of salts.

To the North Lakes Elementaita and Nakuru have elevations of 1776 and 1755 m asl, respectively. Lake Magadi has an elevation of 550m asl and acts as an absolute sink of water and solutes. This is manifested by the thick soda deposits covering most of the lakes surface.

The climate of the rift valley bottom is semi arid with average rainfall of 400-600 mm year^{-1}. The open water evaporation is in the order of 1700-2500 mm year^{-1} , leaving a water deficit of more than 1 m yr^{-1}. To replenish this deficit the lakes are fed by surface or groundwater.

Lake Naivasha and Lake Nakuru are mainly recharged by perennial rivers and ephemeral streams during the rainy season. The surface water inflow into Lake Magadi is limited and the main recharge comes from a series of springs. Lake Elementeita is fed by rivers and springs. The perennial rivers originate from the eastern and western flanks of the rift with rainfall up to 2000mm year^{-1}



Groundwater links: the regional picture

The regional picture of groundwater flow between the RVL can partly be deduced from lake properties. In a lake with only inflow all dissolve solids accumulate and the lake turns salt. The most extreme example of this is Lake Magadi that acts a final sink for large drainage area, and contains thick deposits of soda. In contrary, fresh water lakes are flushed by either surface water overflow or groundwater outflow.

The position of the lake with respect to topography and other lakes plays a dominant role in the regional hydrogeology. In general the lakes at the topographic high elevation are fresh through an outflow of groundwater (eg. Naivasha) and lakes in the low parts act as the final collector (eg. Magadi). The relative position of the lakes will thus govern the regional flow patterns, where Naivasha constitutes the main recharge area and Magadi and Baring/Bogoria the main discharge areas.

The long-section of the rift valley topography shows the position of the lakes. In the Naivasha are elevation of the deep aquifer is known from geothermal wells. In this area the top of the geothermal aquifer is at approximately 1500 m asl. In the next valley South of lake Naivasha (Kedong valley) no water has been found in boreholes at an elevation of 1400 m asl. This observation constraints the outflow mechanism of lake Naivasha to the South to the deep regional (geothermal) aquifer. Such a deep flow system could also feed lake Bogoria and Lake Baringo. Flow further to the North is unlikely. The deepest point of the Northern part of the rift valley is at the Logipi swamp, just South of Lake Turkana. If this area would be the terminal of groundwater flow towards the North, similar soda deposits as in the Magadi area would be deposited here, which is not the case. A rather shallow flow system from Lake Baringo feeding the Kapedo Springs to the North is likely.

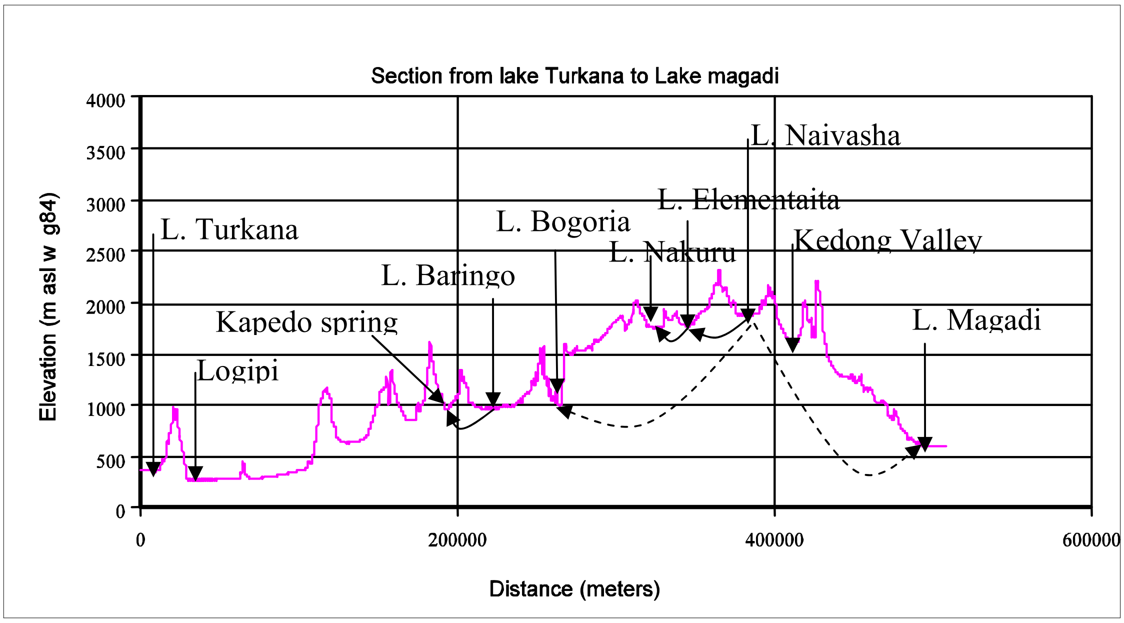


Figure 1

The water balances of the lakes show groundwater outflow from the fresh lake Naivasha and lake Baringo and groundwater inflow for all others.

Isotopes play an important role in deciphering the flow path between the lakes. The natural ^{18}O and ^{2}H stable isotopes occur in all natural waters. The isotopic composition is given as a deviation in ‰ from the international standard, the Standard Mean Ocean Water (SMOW).

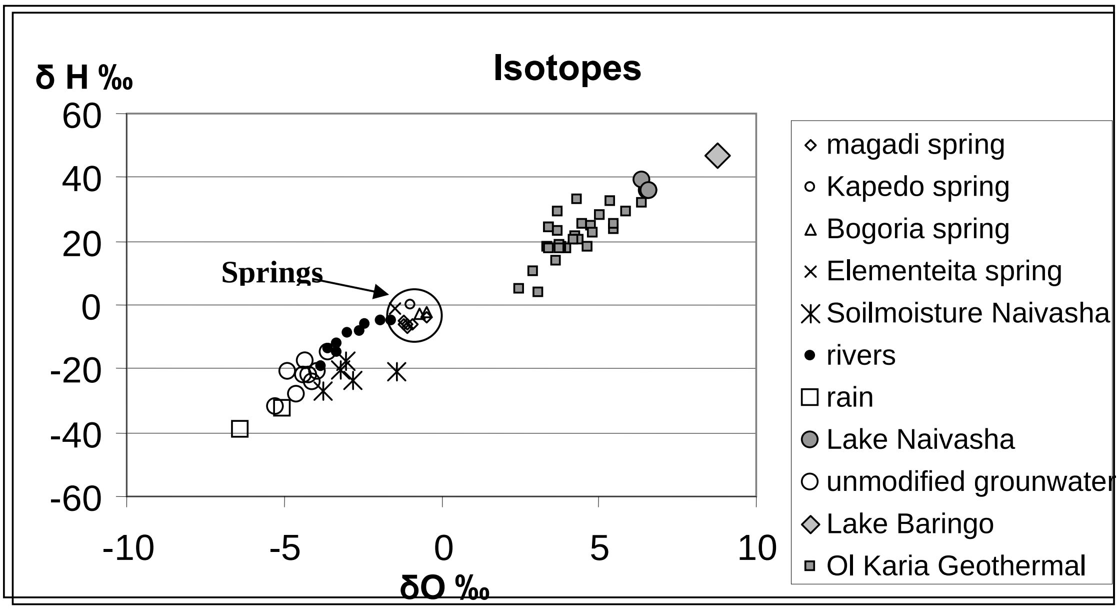


Figure 2

The isotopic composition of natural waters from the rift valley is shown in figure 2. The natural rain is most depleted in the natural isotopes with a mean value of -5 ‰ ^{18}O and -30 ‰ ^{2}H form the lower limit whereas the lake water form the upper limit. The isotopic composition of the enriched lake water (Naivasha 6.6 ‰ ^{18}O and 35 ‰ ^{2}H) provides an effective tracer for axial groundwater movement. The isotopic composition of the geothermal water from the Naivasha area clearly shows a large distribution of lake water. The unmodified groundwater forms a cluster with a mean isotopic composition of
(-4.6 ‰ ^{18}O and -28 ‰ ^{2}H. The springs presented in the graph (Magadi, Elementeita, Bogoria, Baringo, and Kapedo) all have a rather similar isotopic signature
(-1.5/0 ‰ ^{18}O and -5/0 ‰ ^{2}H). The cluster is indicated by an enclosing circle in figure 2. This composition can be explained as a mixture of 70 % unmodified groundwater and 30 % lake water. It has to be stressed that other factors such as variation of the isotopic composition of the local rainfall and the evaporation from the hot underground reservoirs (fumaroles) may equally affect the isotopic composition of the deep rift valley groundwater.

The water balances of Southern Rift Valley Lakes (SRVL)

Assuming that the lakes are hydraulically linked by groundwater flow, this flow is reflected in the individual water balances of the SRVL.

The outflow from Naivasha (elevation: 1886 m asl) cannot disappear. Possible exit mechanisms are: Lake Magadi towards the South, the Lakes Elementaita, Nakuru, Bogoria and springs towards the North and in the form of steam in the geothermal areas. Mcann (1972) estimates the steam discharge in the Naivasha area in the order of 5 million m^3 $year^{-1}$. This is only 10 % of the total outflow from the lake.

The water levels of the SRVL can be simulated using a lake water balance model.
The model is based upon the monthly change in a simplified water balance. Components used are inflow from rivers, rainfall on the lake surface, evaporation from the lake surface, a constant groundwater flow and a dynamic groundwater component to take into account the interactions with the aquifer surrounding the lake. The lake Level–Area–Volume relationship is built into the model and allows the calculation of the rain and evaporation as a volume. The model uses a monthly time step, and is expressed as:

$$\text{Lake volume change} = \text{inflow} + (\text{rainfall} - \text{evaporation}) * \text{lake\_area} + \text{regional groundwater flow} + Q_{aq} \quad (m^3\ month^{-1}) \qquad \textbf{(1)}$$

where Q_{aq} is the inflow to or outflow from a hypothetical dynamic groundwater aquifer linked to the lake. It is derived as:

$$Q_{aq} = C\,(H_{lake} - H_{aquifer}) \quad (m^3\ month^{-1}) \qquad \textbf{(2)}$$

where C is the hydraulic conductance between the lake and aquifer (m^2 $month^{-1}$) and H is the water level (m). The water level in the aquifer is updated using the in/outflow calculated for the previous month:

$$H_{aquifer} = Q_{aq} / A \times Sy \ (m^3\ month^{-1}) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ \ldots\ldots\ldots \textbf{(3)}$$

and

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

where A is the surface area and Sy is the specific yield (porosity) of the hypothetical aquifer.
On the long term the balance of Q_{aq} is zero; if the lake rises lake water will recharge the aquifer and water is released from the aquifer to the lake during recession.
The regional groundwater flow is the discharge or recharge the lake and is set to a constant for each model run. It is the main calibrating parameter determining the overall groundwater loss or gain. It also lumps and to a certain extent and balances out all missing parts and errors in the water balance.
The above model has been used to evaluate the water balances for the Lake Naivasha, lake Elementeita and lake Nakuru.

Lake Naivasha

The inflow data for Lake Naivasha are available since 1932 and therefore the model is calibrated for the period 1932 to 2001. The data set is of good quality as demonstrated by the good match between modeled and observed lake levels. The deviation between the modeled and observed series starting in 1980 is attributed to the abstractions from the basin mainly for irrigation.

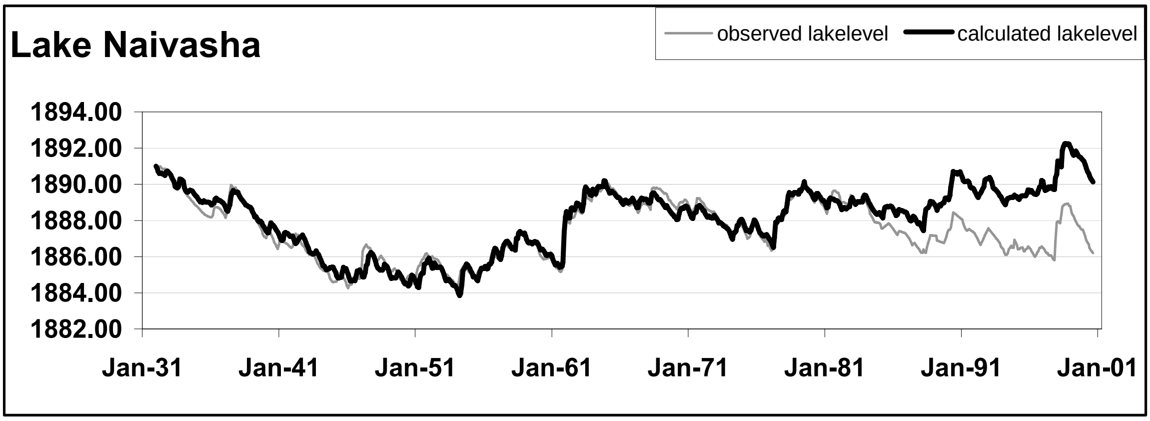


Figure 3

The groundwater outflow, the main calibrating parameter of the model, is 54 million m^3 $year^{-1}$.

Lake Elementeita

Lake Elementeita (elevation: 1776 m asl) is the first lake to the north of Naivasha and more than 200 m below lake Naivasha is the most logical place to intercept the northerly outflow of Lake Naivasha. The lake is situated in shallow pan floored by rather coarser salt impregnated sedimentary material. The lake receives inflow from the Mereroni, Kariandusi streams and groundwater sources. The Maji Moto spring on the south-eastern end of the lake is a major contributor to the lake. This spring is associated with a large N-S oriented fault system, most likely acting as a conduit between Naivasha and Elementeita. A model of the water balance is calibrated for the period 1958-1998.

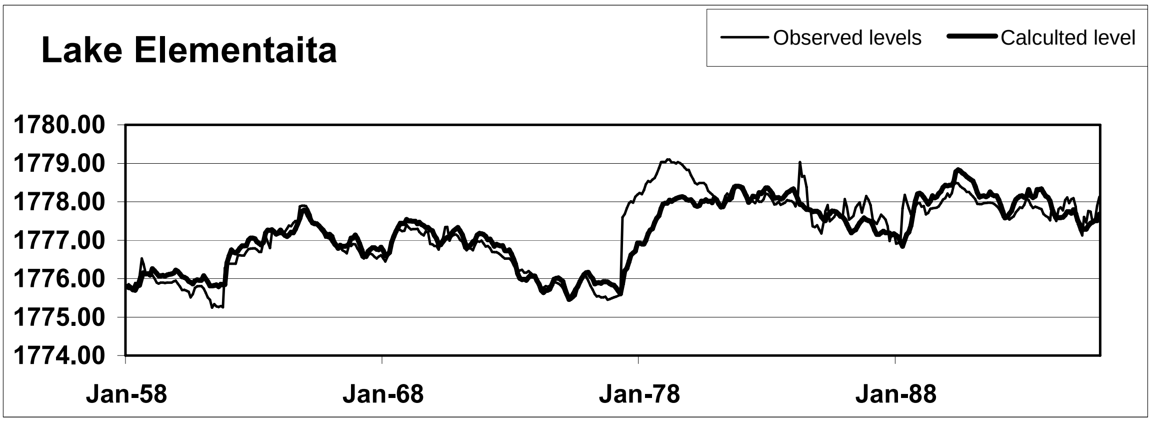


Figure 4

The groundwater inflow to achieve optimal calibration is 16 million m^3 $year^{-1}$.

This inflow corresponds to a mean flow of 0.5 m^3 sec^{-1}, much more than the measurable flow of the springs along the southern shores of the lake. In September 2005 the flow of these springs was 0.2 m^3 sec^{-1}, and locals confirmed a very constant flow. A large portion of the groundwater inflow to the lake seems to occur under the water surface as diffuse inflow.

The isotopic composition of the springs shows a Lake Naivasha water contribution of 30 percent. (Darling, 1996). Combining the water balance and isotopic indicators one may conclude that 4.8 million m^3 year^{-1} flow from Naivasha to Lake Elementeita.

The levels of Lake Nakuru (elevation: 1758 m asl) are modelled for the period 1952 - 1996. During the period 1932 - 1952 only a few lake level observations exists but oral records indicate the lake only contained water after rains. In the early 1950's plans existed to construct a across the lake retaining the water of Njoro river and the springs. In the framework of this project hydrological surveys where carried out. Under the lake a shallow artesian aquifer exists indicating some groundwater recharge. The fact that the lake goes regularly dry indicates that the amount of upward flow to small to prevent the lake from falling dry.

Lake Nakuru

The modelled levels using the water balance model is shown in figure 3.

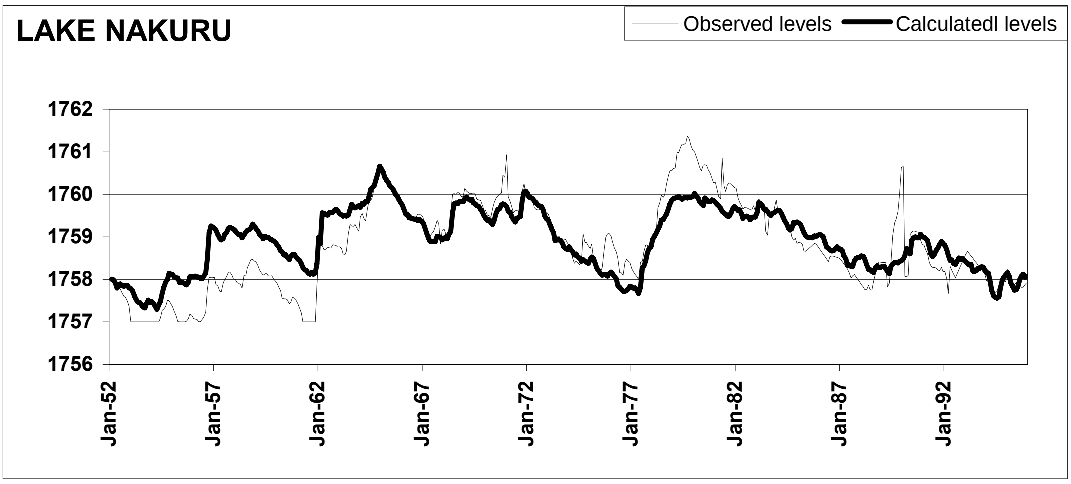


Figure 5

The calculated groundwater inflow based on the WBM is 24 million m^3 year^{-1}. This translates in an upward flow in the order of 0.5 m year^{-}1.

The origin of the groundwater flow is yet unknown. Along the North Western shore of lake Elementeita the groundwater gradient is sloping away from the lake indicating some flow from Elementeita towards Nakuru. Also Lake Naivasha may be directly linked to Nakuru. Most likely however the bulk of the water originates from the flanks of the Rift Valley. Isotope samples taken in 2004 from the area South of lake Nakuru did not indicate mixture with lake water, excluding a shallow connection between the two lakes.

Lake Magadi
Very few data on the water balance is available for Lake Magadi. A large part of the lake is covered with a thick crust of soda, reducing evaporation. Based on the open lake and the soda covered lake a approximate water balance has been established.

The evaporation rate from an open body of water is partly a function of the degree of salinity. It is well known that the evaporation rate from a saline water surface is lower than the freshwater surface (Salhotra *et al* 1985) due to vapour pressure reduction.

Several researchers (Allison *et al* 1985; Ullman 1985; Jacobson and Jankowski 1989; Malek *et al* 1990 Chen and Zawislanski *et al* 1992) carried out measurements of evaporation rates on salt lakes in various locations in United States and Australia. They reported that the actual evaporation rates from salt-crusted surfaces are as low as a few percent to 25% of the potential or pan evaporation rate in the same area. The three mechanisms which are considered responsible are: the high shortwave reflectivity of the dry salt crust, vapor density depression due to salinity and high salt crust resistance to moisture transfer.

During the dry season the water level of Lake Magadi does not change much, so one can assume that the evaporative loss is balanced by groundwater inflow. Figure 6 shows the monthly rain and evaporation data. Average yearly rainfall is 472 mm and yearly evaporation is 2433 mm, giving a water deficit of almost 2000 mm year^{-1}. Assuming that the fluctuations of the lake are driven by local run-off

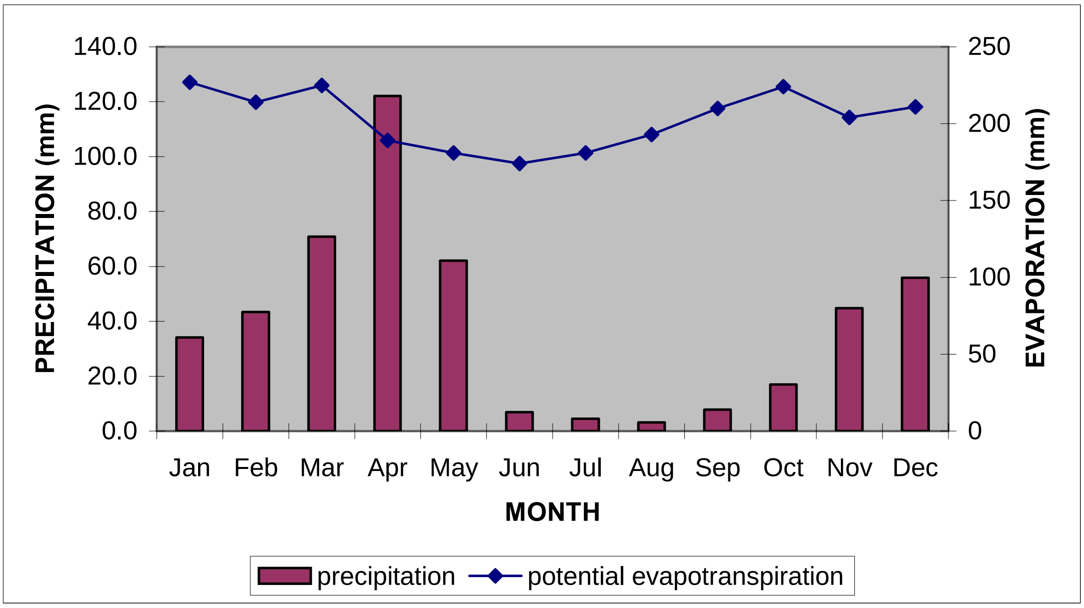


Figure 6

The crusted surface area covers approximately 144 km^2 of the total surface area. The remaining surface was approximated to be of brine nature and covered the remaining 20 km^2 of the lake surface. The water deficit over the period June to September is 0.7 m, or

0.175 m month^{-1}. The open water deficit during the dry season is 3.5 million m^3 month^{-1}, or 42 million m^3 year^{-1}. The salt crust is wet until a few centimetres below the surface. Therefore we assume that the evaporation through the crust is 10% of the open water evaporation. This translates in an evaporative loss of 30 million m^3 year^{-1} through the trona crust. The total inflow is estimated at 72 million m^3 year^{-1}.

The Ewaso Ngiro river looses water through infiltration that is assumed to discharge in Lake Magadi. The springs along the Western side of the lake have the isotopic signature of rainwater. Furthermore several streams originating from the flanks of the rift valley infiltrate. Therefore it is unlikely that the discharge from Lake Naivasha constitutes a large portion of the inflow.

Lake Bogoria

Onyando *et al* (2005) estimates the groundwater inflow in Lake Bogoria at 28 million m^3 year$^{-1.}$

Conclusions

Due to the reliable long-term data the outflow from Lake Naivasha can be reliably established at 55 million m^3 year^{-1}. This flow can only leave the groundwater system through springs and seepage zones associated with lakes and in the form of steam from the geothermal area. Based on water the water balance Lake Elementeita needs a groundwater inflow of 16 m^3 year^{-1}, Nakuru requires an inflow of 24 m^3 year^{-1}, Bogoria has an estimated groundwater contribution of 28 m^3 year^{-1}, and the Magadi groundwater component is in the order of 71 m^3 year^{-1}.

The combined groundwater flow towards these lakes is 139 m^3 year^{-1}. The outflow of Naivasha represents 40 % of this flow.

The isotopic composition of the spring water is similar and indicates a contribution of 30 % lake water. This is rather close to the factor calculated based on the water balance where the Naivasha outflow represents 40 % of the total inflow to the receiving lakes.

Water balance, hydrogeologic and isotope considerations all favour a considerable distribution of Naivasha water to the recharge of Lake Elementeita. The origin of the Lake Nakuru groundwater is most likely derived from local recharge with possibly a small contribution from Lake Naivasha water. The bulk of the infiltrated lake water is emerging in Lake Bogoria and Lake Magadi. There are no reasons to maintain the in previous literature postulated distribution of 80% Southerly flow and 20 % Northerly flow. More likely the flow to the North is equal or larger than the flow toward the South. Based on geometric considerations he Southerly flow is exclusively through the deep regional aquifer system. The Northerly flow to Bogoria is also through the deep aquifer whereas the flow towards Elementeita and Nakuru is in a shallow system.

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