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Towards an understanding of human impact upon the hydrology of Lake Naivasha, Kenya

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Abstract

The water balance of Lake Naivasha, has been calculated from a model based upon the long-term meteorological data of rainfall, evaporation and river inflows. The lake is Kenya's second Ramsar site because of its international importance as a wetland, but supplies drinking water to Nakuru and irrigation water to the nationally important industries of horticulture and power generation. Groundwater flows into and out of the lake are estimated from the model's success in predicting water level fluctuations over the same period. 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 and gauging stations. The model estimated a current annual abstraction rate of 60×10^6 m^3 ann^{-1}, a figure perhaps six-times higher than that calculated as a 'safe' yield in the 1980s. There is an urgent need to accurately measure all abstractions and provide consistent, reliable, hydrological and meteorological data from the catchment, so that a 'safe' yield may be agreed upon by all stakeholders and sustainable use of the lake waters achieved.

Introduction

Lake Naivasha is situated on the floor of the Eastern Rift Valley, at its highest elevation 1890 m, in Kenya (0° 45′ S, 36° 20′ E). The faulting which produced the Rift Valley has led to extensive, and often intense, volcanic activity associated with it, evidence for which is widespread (Fig. 1.) The valley floor is composed of a complex stratigraphy of volcanic and fluvio-lacustrine deposits laid down in Pleistocene times from a larger lake (Butzer et al., 1972; Richardson & Richardson, 1972). The underlying rocks are a complex and fractured mosaic as a consequence of this tectonic activity, and include a deep and wide aquifer. Water from the lake seeps into this (Gaudet & Melack, 1981) and moves through it, probably both southwards towards Longonot and northwards towards Gilgil (Clarke et al., 1990). The lake has no surface outlet.

This underground outflow is maintained by inflow from the higher altitudes of the Rift's flanks (because on the Rift floor, evaporation exceeds rainfall). The catchment on the north and north-eastern side consists of two long axial river systems, draining into Naivasha as a result of past intra-rift faulting and of recent volcanic activity (Clarke et al., loc. cit.), the Gilgil and Malewa (formerly Melewa). Their high altitude origin (>2500 m; rainfall 1100 mm ann^{-1} compared to 600 mm ann^{-1} at Naivasha) makes them permanent, feeding Lake Naivasha mainly through surface flow (input calculated as 85% surface and 15% subsurface, Gaudet & Melack (1981)).

On the eastern, western and north-western and southern side of the catchment, no surface water reaches the lake (Fig. 2). Rivers, often clearly incised into the landscape, flow seasonally. Only the eastern stream, the Karati, reaches the lake in high rains. Others end before the lake, such as the Marmonet from the Mau Escarpment on the western Rift flanks, which recharges the Ndabibi Plains (Clarke et al., loc. cit.)

The outflow water from Lake Naivasha has been detected in the north (estimated 30% contribution to the warm springs on the northern edge of Lake Ele-

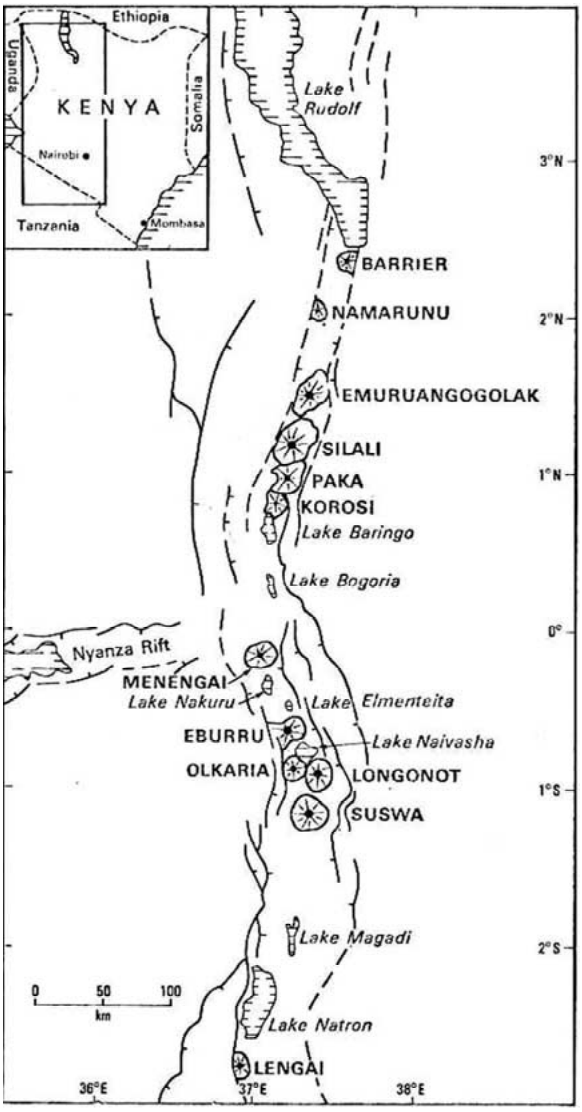

Figure 1. The Eastern (Gregory) Rift, showing the evidence of tectonic activity and the location of Lake Naivasha. Modified from Clarke et al. (1990).

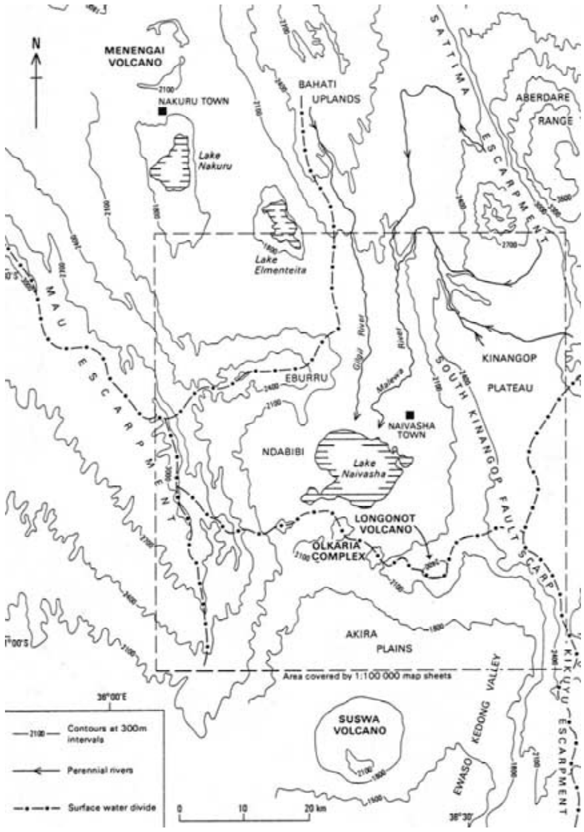

Figure 2. The catchment of Lake Naivasha showing the surface-water drainage pattern. Modified from Clarke et al. (1990).

menteita) and in the south (an estimated 60% contribution to the Olkaria well-field and a lower contribution to fumaroles east of this) (Clarke et al., loc. cit.).

The water balance of Lake Naivasha has been of wider interest for over 100 years; initially because of scientific curiosity about the causes of its extreme fluctuations but latterly for its economic value for irrigation and supply of potable water to Nakuru.

The scientific interest was strengthened by the archaeological evidence from the 1930s onwards from raised shorelines, which showed that Naivasha was part of a much larger lake (Leakey, 1931; Nilsson, 1932), (Fig. 3), either including present-day Elmenteita and Nakuru, or just the former (Åse et al., 1986). This realization then led to suggestions of synchrony between the major ice ages in the Northern Hemisphere with pluvials (wet periods) in the tropics. Palaeolimnological analysis did not support this hypothesis (Richardson, 1972; Richardson & Richardson, 1972). The lake level fluctuations have attracted analysis because their dependence upon the high-altitude rainfall makes them also dependent upon the Inter-Tropical Convergence Zone (ITCZ), which brings annual rainfall to the East African highlands in two rainy seasons as a consequence of its march northwards then southwards in a pattern controlled by the meeting of the westerly winds from the Indian Ocean with the easterly winds from the Atlantic. This large-scale climatic influence was confirmed by Vincent et al. (1979), who showed the similarity of Naivasha and Turkana level fluctuations in contrast to Lake Victoria's. These fluctuations were correlated with the altitude fluctuations of the snout of the Lewis glacier on Mount Kenya.

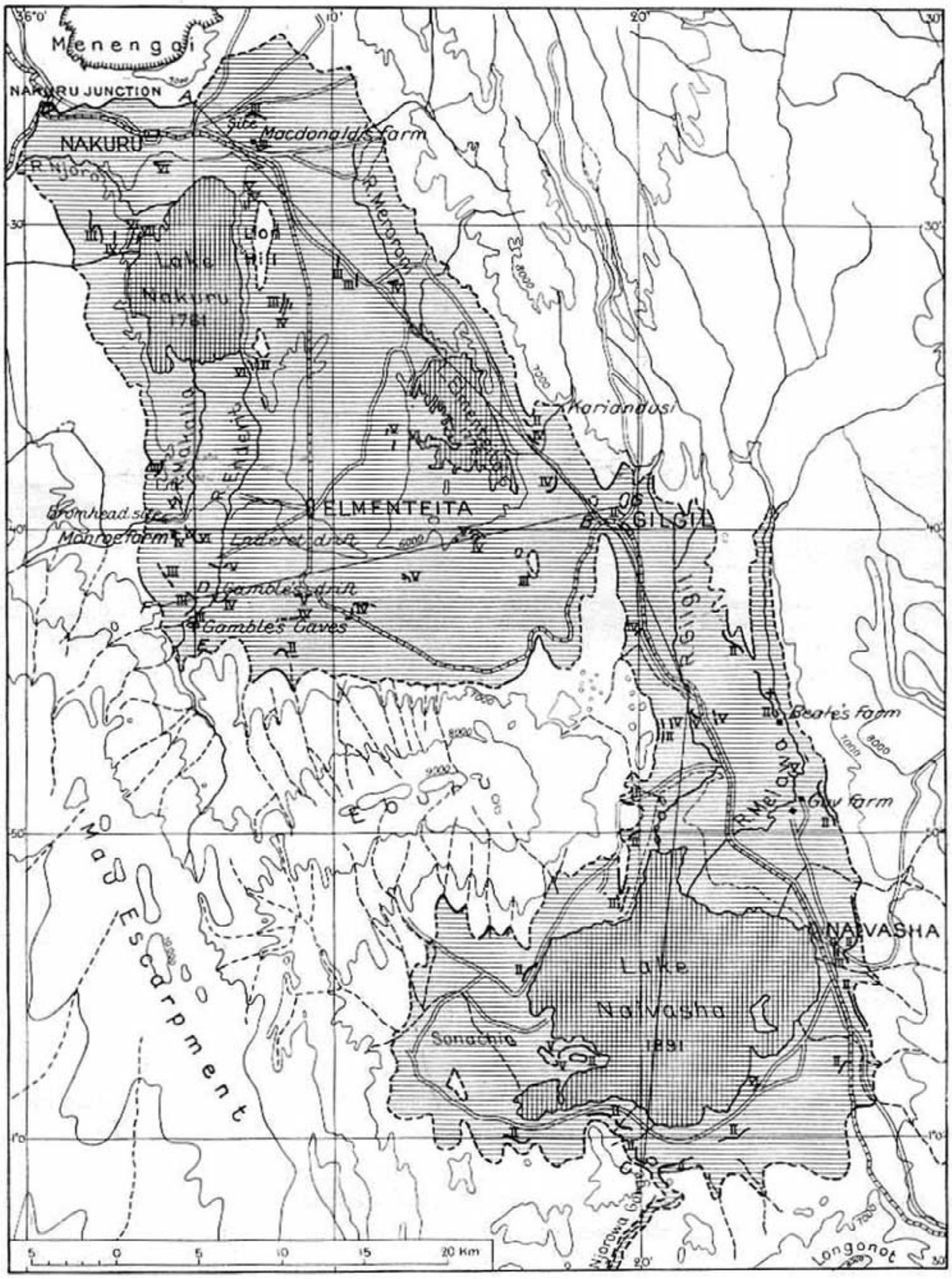

Figure 3. Pleistocene lakes in the Rift Valley. Modified from Nilsson (1932).

Searches for causes in lake level fluctuations have focused upon sun spot cycles, which showed a good correlation early in the 20th century but a weak one latterly (Åse et al., loc. cit.). Vincent et al., (loc. cit.) found strong evidence for an approximate 7-year periodicity, similar to the interval of El Nino events in the Southern Pacific. These apparent cycles of short-term lake level rises and falls have occurred against a longer-term pattern of lake level decline, which has been in evidence throughout the 20th Century (Fig. 4) with the exception of the decade 1955–65 when the decline was temporarily reversed.

Figure 4. The level of Lake Naivasha over the past 130 years (reconstructed from several sources).

In the 1970s the first scientific evaluation of the lake's water budget was carried out to try to establish why it remained fresh (Gaudet & Melack, loc. cit.). The freshness was attributed to very dilute inflows combined with sediment uptake and loss of water with some solutes by seepage out. The water balance, compiled for three years 1973–75, showed the major inputs to be river discharge and direct rainfall while the main outflows were evaporation and seepage.

The economic interest in the lake's water balance has been driven by a desire to utilize the 'available' freshwater with calculations appearing at approximately 10-year intervals over 60 years (Sikes, 1936; Tetley 1948; Brind & 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 (Anon, loc. cit.). This latter consideration suggested 16.5×10^6 m^3 ann^{-1} as a 'safe yield' although it did not relate this to any inflow. These studies (by government hydrologists and engineers) had assumed that catchment abstractions were minimal on an annual basis because the existing licenced abstraction volume was 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 (Johnson et al., 1995) whose output is air-freighted to Europe. This land use change, dramatic in itself, has brought even greater social changes in the rise in population of estate-labourers and their dependents.

The Lake Naivasha Riparian Owners' Association (LNROA) (until recently a closed organization which existed to settle disputes between members whose land ownership ends at the 1906 lake level contour but who have a legal right to cultivate lake bed below this), articulated the environmental concern about these changes (Enniskillen, 2002). Two consultants' reports summarized all the scientific knowledge about Lake Naivasha and its conservation status (Goldson 1993, Khroda 1994). The Association's subsequent lobbying led to Lake being declared Kenya's second Ramsar site in 1995 followed by the production of its management plan and strategy for implementation (Anon, 1996, 1997). The Association changed its constitution and name to become the Lake Naivasha Riparian Association (LNRA) and its organizational work was recognized by the award of the Ramsar Prize in 1999.

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, 10 km to the south, 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–early 1990s was estimated by Goldson (loc. cit.) at 37, 39 and 15 $\times$; 10^6 m^3 ann^{-1} respectively, a total of 91 $\times$ 10^6 m^3 ann^{-1}.

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 an hydrological model which allows hypothetical scenarios to be evaluated. One hydrological model was produced in the 1990s (Stuttard et al., 1999), but it was based on satellite imagery and sophisticated GIS packages, which make it less suitable for field use in Africa. The relatively short calibration period during a period that large-scale abstractions were increasing on a yearly base make it less suitable to evaluate the long-term waterbalance. This paper addressed the need for an hydrological model with a simple and usable one based upon a Microsoft Exel™ programme.

Methods

Model construction

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 seepage (groundwater outflow) 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 is expressed as:

$$\text{lake volume change} = \text{inflow} + \text{rainfall} - \text{evaporation} \pm Q_{\text{aq}} - Q_{\text{out}}, \qquad (1)$$

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

$$Q_{\text{aq}} = \text{C}\ (\text{H}_{\text{lake}} - \text{H}_{\text{aquifer}})\ \ \text{m}^3\ \text{month}^{-1}, \qquad (2)$$

where C is the hydraulic conductance of the 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:

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

and

$$H_{\text{aquifer}^{\text{new}}} = H_{\text{aquifer}^{\text{old}}} + H_{\text{aquifer}}(m),$$

where A is the surface area and Sy is the specific yield (porosity) of the aquifer.

Q_{out} (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 inflow, the evaporation of riparian vegetation and a systematic over or underestimate of the inflow, rainfall and evaporation are a part of this term.

Inflow is the river inflow, expressed as $\alpha \times$ gauged inflow (m^3 month^{-1}), where α is a factor to modify the inflow for a systematic error in the data. *Rainfall and Evaporation* are as named, input in mm month^{-1} from the meteorological records.

The model was optimized by minimizing the sum of squared differences between observed and simulated monthly water levels. The optimizing model parameters were the constant outflow, the hydraulic conductance of the lake aquifer system and the specific yield of the groundwater reservoir.

Input data and limitations

Meteorological data were obtained from the Ministry of Environment and Natural Resources (MENR), Government of Kenya, which is the custodian of all meteorological data collected in the country, some dating back to the beginning of the 20th Century. Lake level data have been recorded at Naivasha throughout the century as feet or metres above sea level (discussed more fully in Åse, 1986). The latter data are derived from a confusing and conflicting range of absolute levels. For the model it was decided to use the old data collected by the erstwhile Ministry of Works and using the Cassini Projection after Laws & Flintoff (1950). Data since 1983 have been recorded by Sulmac, a large horticultural company, whose level has been authenticated by a professional surveyor on behalf of LNRA.

Lake bathymetry has been recorded on several occasions since the first government survey in 1928. The most recent are Åse, in 1983 (Åse 1986), Hickley in 1993 (Hickley et al., this volume) and WRAP/MNR&E, in 1997. The flow data for the rivers Malewa, Gilgil and Karati have been used, starting from 1932 with missing data infilled from the nearest data by statistical correlation to give a continuous monthly record to 1998.

The 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 1958–94.

The rainfall data of Naivasha (District Office). and Kinankop Forest Station have been recorded from 1901 and 1915, respectively, to present. Evaporation data are derived from the measured pan evaporation data have been used for the period 1960 to 1998. For the period 1901 to 1960, mean monthly values of the 1960–98 period have been used.

Model calibration

The model parameters which can be optimized are α, hydraulic conductance, specific yield, initial water level and most important the constant outflow, Q_{out}. In the calibration of the model α, the inflow correction factor, was set to one. The initial water level was set to the water level in January 1932.

None of the optimized parameters were time variant. This means that the parameters were not optimized for intervals to get a better fit but always for the full calibration period. The optimalization was carried out using the data from 1932 to 1978. because it was assumed that the abstraction rates during this period were low and that the overall quality of the flow data was good.

Water budget

An average annual natural water budget of the lake was estimated for a reliable period prior to industrial abstraction. In February 1932 and again in June 1981 the lake was at 1889.2 m and the area 164 km^2, and so the average of this period was taken. The purpose of understanding the water balance of Lake Naivasha 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. An ‘equilibrium lake area’, Aeq$_w$ was calculated, where

$$(\text{rainfall} - \text{evaporation}) \times A_{\mathrm{eq}_w} + \text{inflow} - \text{outflow} = 0. \tag{3}$$

The relation between lake area and lake level defines the long term equilibrium lake level. This concept is important discussing 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 is in water balance terms in an equilibrium and therefore a sustainable state. The problem of what is the safe yield, is rather a political and ecological question than an hydrological one.

Results

The first model runs made it clear that simulation of the lake levels was possible, but that data after 1978 were not of high enough quality (Fig. 5). The model was re-run using only Malewa discharge data from 1932–1950 and Turasha from 1950–1990 as these were considered the most reliable sets. Figure 6 shows a better match between simulated and actual levels was achieved. 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 in the past two decades is distinct and indicates the magnitude of industrial abstraction. Since the model (Equation (1)) does not contain an abstraction component the divergence of the curves from 1983 onwards is caused by the abstractions from the basin. Using the monthly differences between observed and simulated lake levels allows an estimate of lake volume used for industrial abstraction starting from January 1983. This has risen to 60×10^6 m^3 ann^{-1}, a value close to estimates derived from the area under irrigation and the irrigation requirement of the crop pattern. The calculated abstraction has resulted in a lake which might have been 3–4 m higher than was observed in November 1997 before the rapid rise caused by the ‘El Nino’ rains (Fig. 7).

Mean monthly local rainfall (Naivasha D.O.), lake inflow and lake level rises show an approximately monthly time lag (Fig. 8), indicating the natural catchment response for the time taken to restore soil moisture deficit after the dry season. Naivasha local rainfall does not directly influence the lake, because of the positive dominant influence of the high-altitude rainfall and the negative influence of evaporation. Nevertheless, there are four reasons why a lake level model based on local rainfall would be valuable:

1. Rainfall data exist from 1900 for Naivasha town and can be used to model the lake levels from 1900 to present.
2. If rainfall data can be used to accurately predict lake levels for the period before exploitation

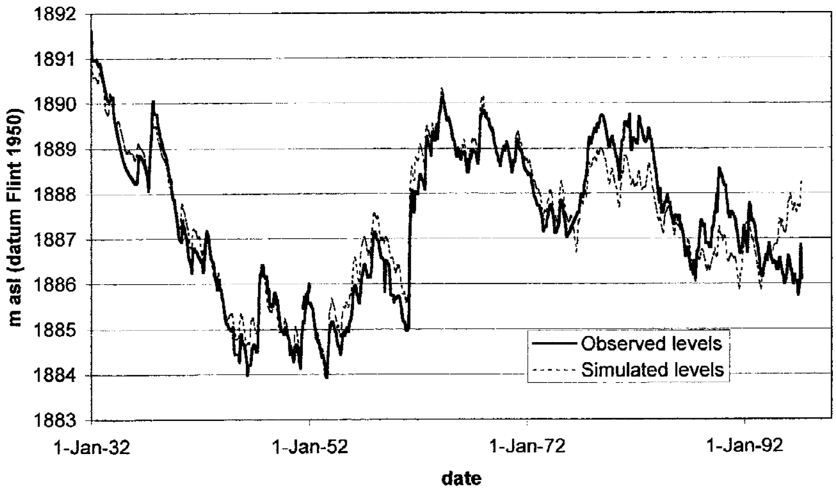

Figure 5. The simulation of Lake Naivasha water levels from 1932 to present, based upon measured inflows from the Malewa, Gilgil and Karati rivers compared to recorded levels.

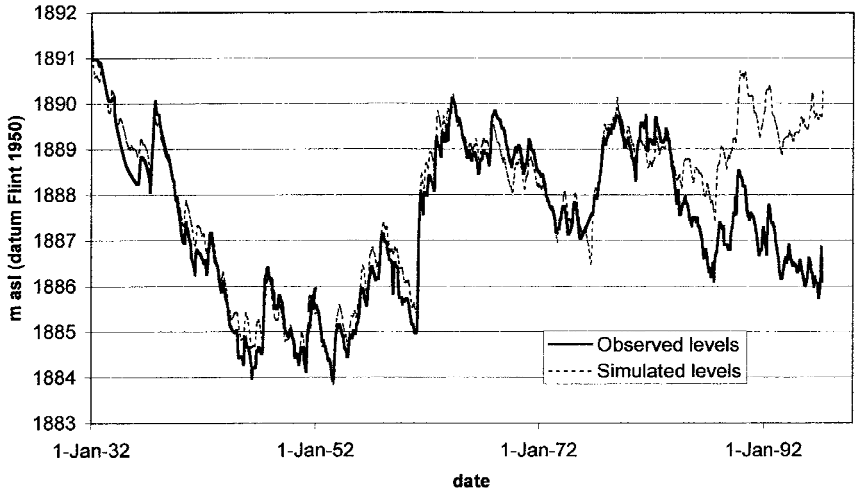

Figure 6. The simulation of Lake Naivasha water levels from 1932 to present based upon measured inflows from the Turasha river compared to recorded levels.

of water resources started, this model can show the effect of abstractions in the whole Naivasha catchment.

3. If a reliable rainfall runoff model exists it renders the model independent of the availability of flow data.
4. If the model is physically based it can be used to predict the hydrological effect of changes in the catchment and climate.

Figure 9 shows the output of this model, constructed through correlation of monthly inflow volume with monthly rainfall. The accuracy of this model is lower than the fuller hydrological model (a lake level confidence of 2 m compared with 0.52 m).

It is peculiar that the rainfall data from Naivasha town should give slightly better results than the rainfall data from Kinankop Forest Station, which is in the middle of the water-generating upper catchment. This indicates that the large fluctuations are driven by long-term overall drier and wetter periods.

Sustainable water resource exploitation

The average annual water balance of the lake for the period February 1932 to June 1981 (Table 1) was estimated with an error of 1.36×10^6 m^3 (equivalent to

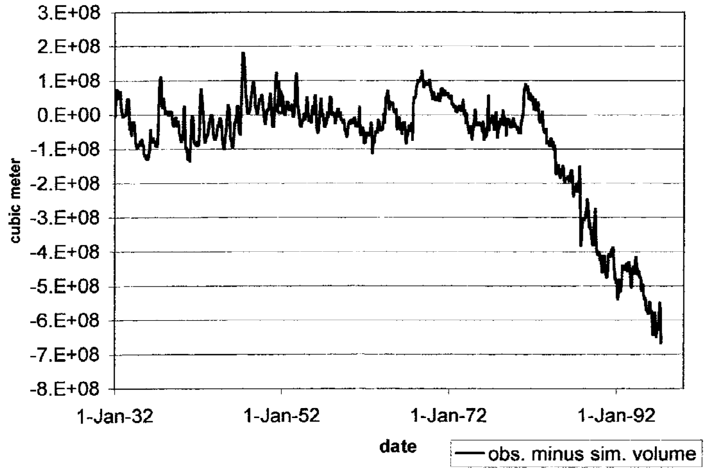

Figure 7. The difference in lake volume between observed and simulated levels, based upon a composite flow series (1932–1952 Malewa; 1952–1997 upscaled Turasha).

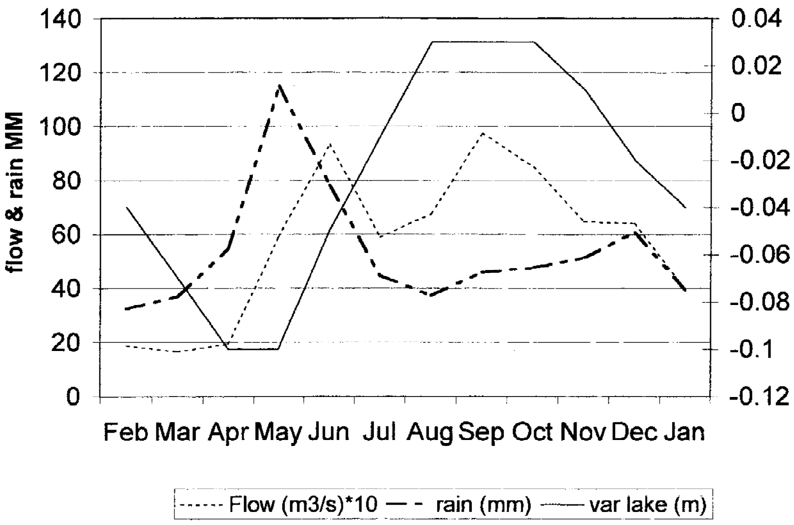

Figure 8. The mean monthly rainfall at Naivasha, inflow of the Malewa river and level of lake Naivasha, 1932–1997.

Table 1. The long-term average annual water balance from the model, prior to irrigation abstraction

Surface water inflow	217.4	$\times 10^6$ m^3
Rainfall	93.9	$\times 10^6$ m^3
Evaporation	256.3	$\times 10^6$ m^3
Water loss	56	$\times 10^6$ m^3
Sum (error)	1.36	$\times 10^6$ m^3

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 abstractions of 60×10^6 m^3 ann^{-1} on the new equilibrium lake level and area, using Equation (4), gave a level of 1883.4 m, which corresponds to an area of 82 km^2. Figure 10 shows the hypothetical effect of an exploitation of 60×10^6 m^3 ann^{-1} from 1932 to present. The average lake level has been reduced from approximately 1988 to approximately 1984.5 m. The simulation also shows that it takes some 10 years before a new equilibrium has reached.

The rise of the simulated water level after 1993, and the almost equal simulated and observed water levels at the end of 1997, are due to three effects:

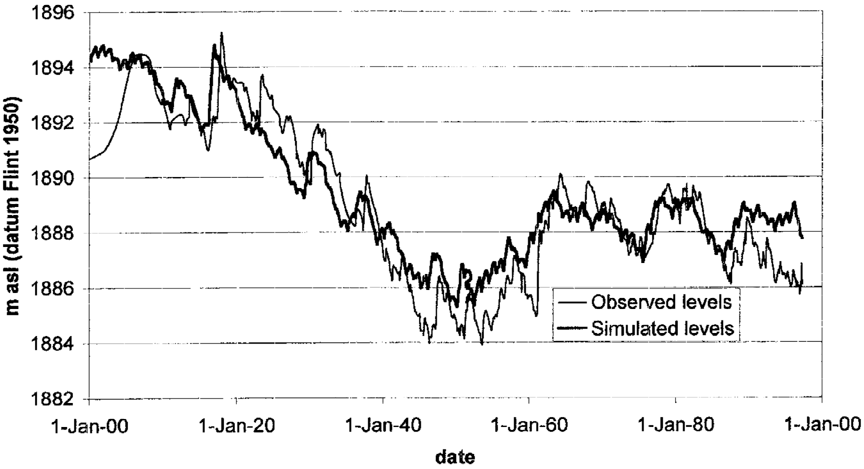

Figure 9. The simulation of lake Naivasha water levels through the 20th Century based upon rainfall at Naivasha D.O. compared to recorded levels.

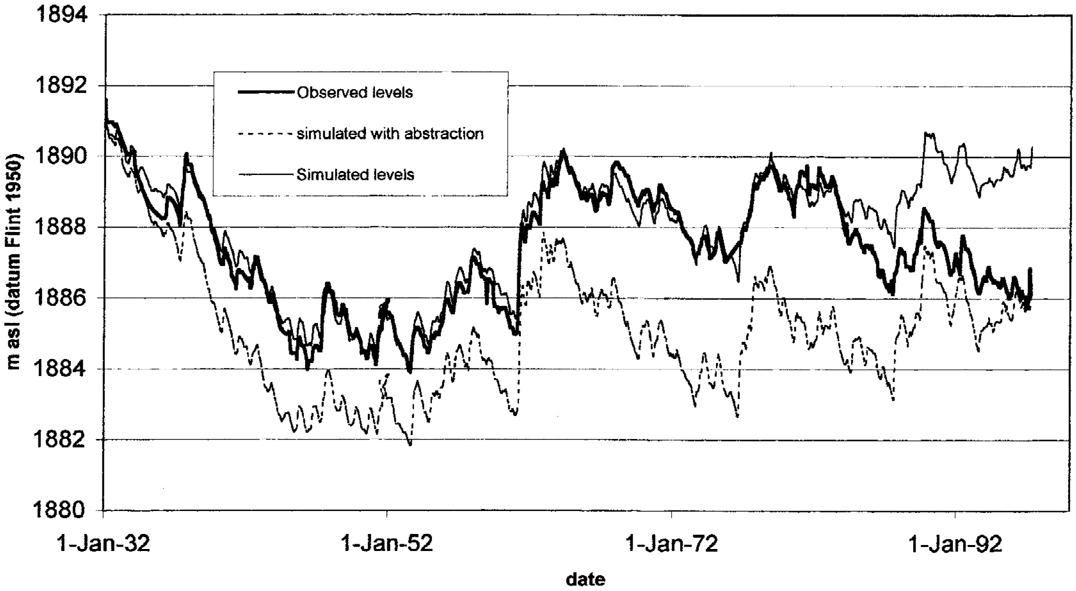

Figure 10. The simulation of lake Naivasha water levels from 1932 based upon measured inflows from the Turasha river with, and without, abstraction of 60×10^6 m^3 ann^{-1}.

1. The simulated lake is in long-term equilibrium between in flows and out flows and will therefore, have a lower response to a wet period.
2. The actual abstraction is probably higher than 60 $\times 10^6$ m^3 ann^{-1} now.
3. If all assumptions are correct the two curves will always converge to the new equilibrium level.

Comparison of exploitation of 60×10^6 m^3 ann^{-1} commenced in 1932 with a similar exploitation in 1961 as is shown in Figure 11. Here again the system needs a considerable time span to finds its equilibrium, from 1932 to the mid 1940s and from 1971 to 1990. Simulation experiments with the time-to-equilibrium have shown that this is not a fixed period but depends on the onset time and the climatic condition at the time exploitation starts. This is relevant for the interpretation of the present situation since it is not possible to predict how close or distant the lake is from a new equilibrium. However, since the simulations use a constant rate of abstraction, whereas in the real situation the abstraction rate has been constantly increasing over the last 15 years due to the expanding

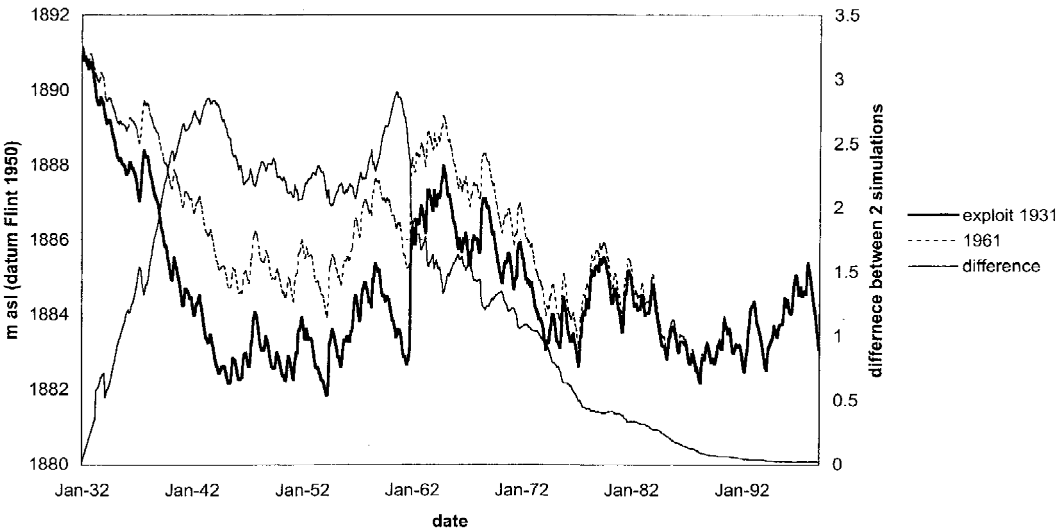

Figure 11. The simulation of Lake Naivasha levels under exploitation starting in 1961 compared to 1932 demonstrating the time taken to reach an 'equilibrium level'.

Table 2. The long-term average water balance figures used for the calculation of equilibrium lake levels and areas

Naivasha DO rainfall 1900–1998	648 mm
Evaporation Naivasha MoWD 1959–1990	1788 mm
Inflow Malewa 1932–1980	217.4×10^6 m^3
Groundwater outflow	56×10^6 m^3

area under irrigation we may safely assume that the lake is not in an equilibrium state.

Discussion

The abstractions from the Naivasha catchment are not known and can only be estimated from abstraction permits or from the known area of cropland and known requirements of the crops. Groundwater, abstracted from boreholes, may or may not be contiguous with lake or with inflow water. Goldson (1993), after discussing all the uncertainties and inaccuracies, estimated an abstraction figure for the 1990s six times what was considered the safe yield in the early 1980s. The present model suggests an abstraction in the mid-1990s at two-thirds of Goldson's estimate, but still three to four times the original concept of 'safe'. Some of the permits for river abstraction may well have influenced the long-term flow data, since the total permitted abstraction accounts for approximately 17% of the estimated long-term surface inflows to the lake (Table 2). There is thus an urgent need to accurately measure all the abstractions from river, lake and groundwater, in order to build an accurate water balance. Equally, there is an important requirement to scientifically and logistically establish an accurate and reliable hydrological and meteorological data base, as is evidenced by the accuracy of the model when run with only the time series and the gauging data considered to be the most accurate.

The other important need is to understand what a 'safe yield' means in terms of a sustainable lake, which can be interpreted in two ways. The first is the lake in terms of its water quality and quantity for irrigation. As the lake level (and area) decrease, water may increase in the short-term (as it becomes closer to dilute river water) but may decrease in the long-term (from greater algal activity in a more nutrient-rich environment, for example). The costs of using lake water for sensitive horticultural crops increase. The second is in terms of the biodiversity, ecology and conservation of the lake. No one has yet tried to predict the way in which the myriad aspects of the lake's ecology will change with either a declining lake level or an 'equilibrium', more predictable, lake level.

Encompassing both the uncertainty over the economic use of the lake and the unpredictable ecological response, is the concept of the 'Tragedy of the Commons' (Hardin, 1968) and the real prospect of its appearance at Lake Naivasha. At present, the waters in the Naivasha catchment, like the waters in many parts of the developing as well as developed world, are treated as common property, to be exploited by each and every individual, company and para-statal according only to their needs and ability to utilize them (i.e., wealth). With no measurement of ‘how much’, no concept of what is a sustainable/safe yield, and no policy on how to match what is used with what is sustainable, Lake Naivasha has a bleak long-term future in a continent with a bleak future (Ashton, 2002) unless drastic action is taken soon. This paper is a small step in trying to define a sustainable yield for Lake Naivasha and facilitate that action.

Acknowledgements

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