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Water balance of Lake Tana and its sensitivity to fluctuations in rainfall, Blue Nile basin, Ethiopia

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Abstract

The annual water budget of Lake Tana is determined from estimates of runoff, rainfall on the lake, measured outflow and empirically determined evaporation. Simulation of lake level variation (1960–1992) has been conducted through modeling at a monthly time step. Despite the ±20% rainfall variations in the Blue Nile basin in the last 50 years, the lake level remained regular. A preliminary analysis of the sensitivity of level and outflow of the lake suggests that they are controlled more by variation in rainfall than by basin-scale forcing induced by human activities. The analysis shows that a drastic (40–45%) and sustained (7–8 years) rainfall reduction is required to change the lake from out flowing to terminal (cessation of outflow). However, the outflow from the lake shows significant variation responding to the rainfall variations. Unlike the terminal lakes in the Ethiopian rift valley or the other large lakes of Tropical Africa, at its present hydrologic condition, the Lake Tana level is less sensitive to rainfall variation and changes in catchment characteristics.

Keywords: Lake Tana; Water budget; Lake level simulation; Sensitivity; Blue Nile; Ethiopia

1. Background

The hydrology of lakes and swamps in Ethiopia and the Nile basin has been studied from the point of view of at least three interdependent interests. One is related to developing hydrological models for water resources utilization (USBR, 1964; Sutcliffe and Parks, 1987; Guariso and Whittington, 1978; Johnson and Curtis, 1994; Conway, 1997; BCEOM, 1999; Sene et al., 2001; Legesse et al., 2004). The second is related to testing the impacts of the natural climate fluctuation such as the ENSO (El Niño Southern Oscillation) or human induced climate changes such as global warming on Lake hydrology (Gleick, 1991; Conway and Hulme, 1993; Conway and Hulme, 1996; Conway et al., 1996; Strzepek et al., 1996; Eltahir, 1996). The third is related to modeling lake levels or outflows to use it later to quantitatively interpret historical lake level records in terms of past rainfall/climate variations (Street, 1980; Nicholson et al., 2000; Nicholson and Yin, 2001; Lamb et al., 2002).

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This work assesses the water budget of Lake Tana, the headwater of the Blue Nile basin (one of the major tributaries of the Nile) from point of view of developing water resources development model and from the point of view of modeling the sensitivity of the lake to climate variations.

Regarding the water resources development there is increasing water utilization along the lower Nile valley (Egypt and Sudan) straining the limited freshwater resources of the basin (Gleick, 1991). Similarly, there is an increasing demand for irrigation and hydropower development in Ethiopia to cope with the recurrent drought and its impacts and to increase agricultural production to cope with increasing population. Currently greater than 90% energy use in Ethiopia depends on the fuel wood. This has resulted in extensive vegetation degradation which by itself partly caused land degradation and reduction of agricultural productivity.

Since the water resources of Blue Nile basin are shared by Sudan and Egypt many previous hydrological studies attempt to come up with hydrological models of the Nile from which exploring scenarios can be used as a basis of agreements on water resources sharing. While some countries emphasize that the current models or the existing data can be used as basis of water resources development others emphasize the need of further hydrological studies. Whatever the case may be, the hydrology of the Nile has been reviewed often (Shahin, 1988; Guariso and Whittington, 1978; Johnson and Curtis, 1994; Sutcliffe and Parks, 1999; Conway, 2000).

Because of the complexity in the climate and hydrological characteristics of the sub basins of the Nile, improvement in the existing water resources models or the development of new models requires sub basin scale hydrological modeling which can be combined to produce sound models for the Nile basin. The hydrology of many large lakes and swamps of the Nile has been relatively well documented. Examples include Lake Victoria (Yin and Nichoson, 1998; Sene, 1998; Sene et al., 2001; Nicholson and Yin, 2001), the Sudd swamp (Sutcliffe and Parks, 1987, 1999; Mohamed et al., 2004) and the Blue Nile basin (USBR, 1964; Conway and Hulme, 1996; BCEOM, 1999). Despite the major importance of the Lake Tana basin (outflow contributes 8% of the Blue Nile flow in Ethiopia) the hydrology of this lake is not well documented in the scientific literature.

From the paleo-climate reconstruction perspective, the Ethiopian lakes and their sediments have been among the best documented in the world and were widely used in paleo climate reconstruction (Grove et al., 1975; Street and Grove, 1979; Le Turdu et al., 1999; Benvenuti et al., 2002; Legesse et al., 2002). Since Lake Tana is located on the headwater of the Blue Nile River and the Blue Nile is the major river that affects the water availability in the lower Nile, using the sediments of the lake to reconstruct the hydrological history of the Nile and North East Africa is more appealing in this historically important region of the world. The capacity of the lake level or its sediment to register past environmental variations depends upon its response to these variations. This in turn depends on the lake geometry, lake water balance, the outflow-lake level relation and the catchment characteristics. Classification of lakes according to sensitivity of their lake levels to climate variation shows that closed lakes are more sensitive ‘amplifier’ than open lakes with large outflows (Street, 1980; Street-Perrott and Harrison, 1985; Bengtsson and Malm, 1997). One of our interests is, therefore, to compute the rainfall reduction that is required to change Lake Tana from out flowing to a terminal lake. This brings not only major ecological or limnological changes but also changes in the sensitivity of the lake to environmental variations.

This paper aims to develop a preliminary hydrological model of Lake Tana. It estimates the water budget component of the lake, simulates the lake level variations (1960–1992) at monthly time steps and make a preliminary sensitivity analysis of lake level and lake outflow to rainfall changes.

2. Site description

Lake Tana occupies a wide depression in the Ethiopian plateau (Fig. 1). The lake is shallow, oligotrophic, and freshwater, with weak seasonal stratification (Wood and Talling, 1988; Wudneh, 1998). At 3156 km^2 in area, it is the largest lake in Ethiopia and the third largest in the Nile Basin. Of more than 40 rivers feeding the lake, Gilgel-Abay,

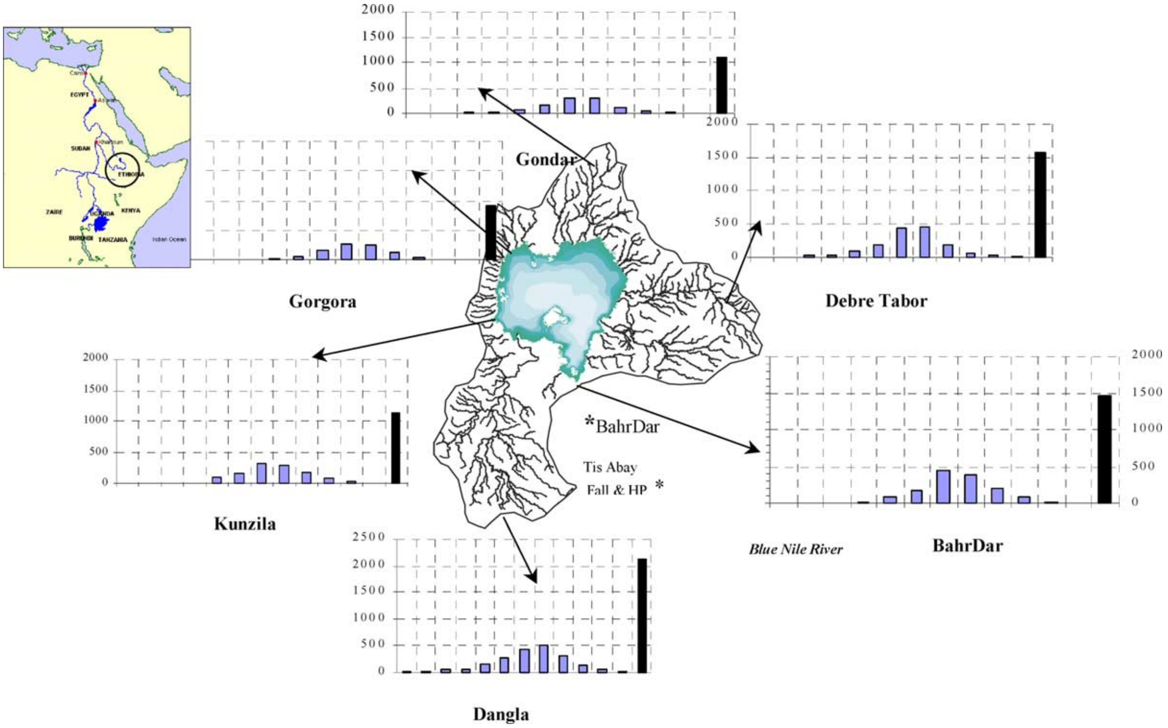

Fig. 1. Location of Lake Tana, drainage map, January to December monthly rainfall histogram and annual rainfall distribution in mm in the Lake Tana Basin. The four large rivers account for 95% of surface water flow to Lake Tana. The TisIsat fall and the hydropower plant is located 35 km downstream of Lake Tana outflow.

Reb, Gumera and Magetch contribute more than 93% of the inflow. The only surface outflow is the Blue Nile, which comprises 7% of the Blue Nile flow at the Ethio-Sudanese border (Shahin, 1988; Conway, 2000). The lake is believed to have been formed due to damming by lava flow during the Pliocene (Mohr, 1962), but the formation of the depression itself started in the Miocene (Chorowiz et al., 1998). The temperature of the lake surface is about 3 °C greater than mean air temperature (Morandini, 1940), perhaps related to the above one year residence time of lake water and the consequent heat storage. The mean annual humidity (1961–2002) at Bahr Dar (the closest station to the Lake) is 0.65 and it varies between 0.50 and 0.80. The morphometric and physiochemical characteristics of the lake are presented in Table 1. Compared to other large lakes in the region, the lake has small catchment to lake area ratio.

The climate of the region is 'tropical highland monsoon' with one rainy season between June and September (Fig. 1). The air temperature shows large diurnal but small seasonal changes with an annual average of 20 °C. The seasonal distribution of rainfall is controlled by the northward and southward movement of the inter-tropical convergence zone (ITCZ). Moist air masses are driven from the Atlantic and Indian Oceans during summer (June–September). During the rest of the year the ITCZ shifts southwards and dry conditions persists in the region between October and May. Generally, the southern part of the Lake Tana basin is wetter than the western and the northern parts.

At least seven irrigation schemes with an overall water demand greater than 600 million m^3/year have been proposed within the watershed of Lake Tana (USBR, 1964; BCEOM, 1999). However, no major water resources development implementation has so far been done in the Lake Basin. The two important water resources development around Lake Tana include the water level regulation weir constructed at the mouth of the lake in 1996 and the TisIsat hydropower development 35 km downstream of the

Table 1
Morphometric and physicochemical characteristics of lake Tana, data from various sources: Morandini, 1940; Wood and Talling, 1988; Shahin, 1988

Morphometric characteristics		Physicochemical characteristics	
Maximum depth (m)	14	Lake temperature (°C)	20–24
Mean depth (m)	9	Electrical conductivity (μS/cm)	220
Lake area (A_L) (km^2)	3156	PH	8.1
Catchment area (A_c) (km^2)	16500	Na^+ (mg/L)	7–9
Lake volume (V_L) (km^3)	28.4	K^+ (mg/L)	1
Water residence time	3 years	Ca^{++} (mg/L)	14
Major water use	Hydropower, navigation	Mg^{++} (mg/L)	12
Altitude (m)	1830	$HCO_3^- + CO_3^{--}$ (mg/L)	91
Latitude	11°35′E–12°18″E	Cl^- (mg/L)	1.25
Longitude (°N)	37	TDS (mg/L)	150
A_L/A_C	0.2	$\delta^{18}O$ (‰)	+4.0
Runoff coefficient (κ)	0.22	δD	34.6 ‰

Lake. The construction of the weir, which was completed in 1996, was intended to augment the dry season outflow to supply water regularly to the Hydropower Plant (TisIsat Hydropower). The low-level water development activities, however, does not mean a low level of environmental impact. The few activities such as the diversion of the water for hydropower generation have significantly reduced the volume of water available for the 35 m waterfall. This natural waterfall was the second most frequently visited tourist destination in the region.

3. Water balance of Lake Tana

3.1. Components of the water balance

3.1.1. Bathymetry, precipitation, river inflow, lake levels and outflows

To estimate precipitation on the lake, we used the monthly series of rainfall (1960–1992) at the Bahrdar station (the nearest station located at the southern shore of the Lake). Using this data, the mean annual lake precipitation is estimated at 1451 mm. Section 4 uses this data to simulate the lake level. A total mean annual surface water inflow is estimated at 1162 mm. This is obtained from the measured river discharge data (1921–1926, 1928–1933 and 1959–1992) and the inflow from the ungauged catchments which is estimated from runoff coefficient (runoff coefficient, $\alpha = 0.22$, Shahin, 1988). The inflow from ungauged catchment contributes less than 7% to total inflow.

Fig. 2 shows bathymetric and lake area-lake depth relations. The lake is characterized by a flat bottom and rapid drop in depth at its margins. In its present day condition a 1m increase in lake depth results in 60 km^2 increase in lake area (Fig. 2), which is negligible compared to the area of the lake. Among the Ethiopian Lakes, Lake Tana has relatively the longest hydrologic records. Mean monthly, outflow from the lake and lake levels are available intermittently since 1921 and continuously since late 1950s. Unfortunately, the datum used by earlier records and the records starting 1950s are not similar and unverifiable. Therefore, this work uses the latest records in water budget estimations. The zero reference datum of the recent lake level record is located at the elevation of 1784.515 masl (JICA, 1977) in the southern part of the lake. Fig. 3 shows the lake level, outflow and the net basin supply[1] series in the period 1960–1992. The figure shows that there is high inter-annual variability in the outflow (and to lesser extent in the net basin supply) than in the lake levels. Lake level varies by about 1.5 m between the rainy and the dry seasons but inter-annual variation is smaller than this. Maximum lake level is attained in October, one month after the end of rainy season. Minimum lake level is attained from May to June.

Unlike the equatorial lakes in East Africa, the mean annual lake levels have been stable over the last century. For example, Lake Victoria's level and

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[1] Net basin supply is the total inflow less the evaporation. It is given as: $N = P(t) + R_{in}(t) - E(t)$

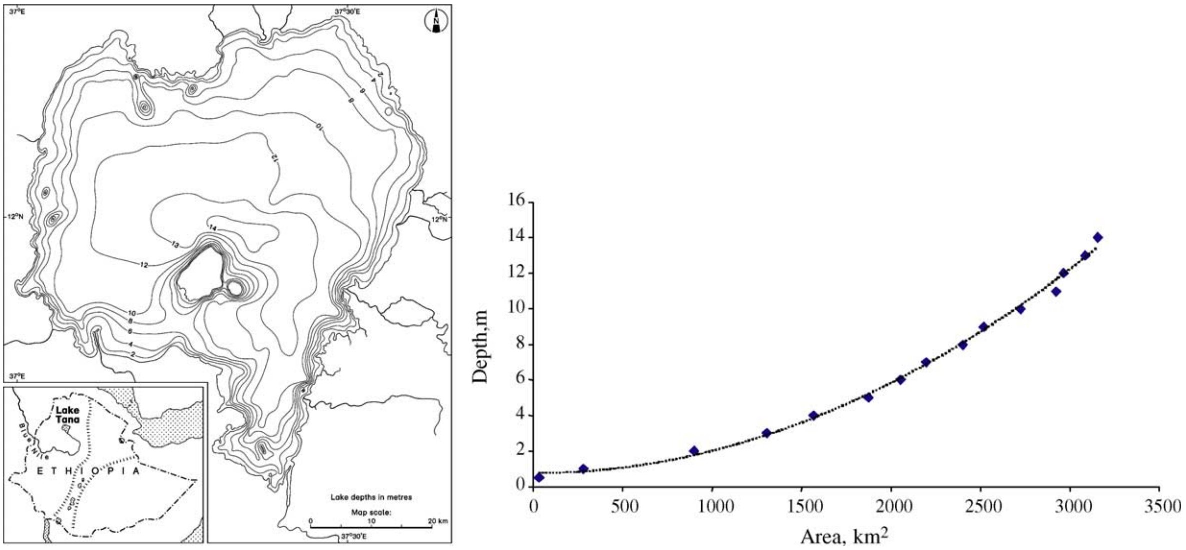

Fig. 2. Bathymetric map and lake level-lake volume relations of Lake Tana, data from Morandini, 1940.

outflow increased dramatically in 1960s (Nicholson et al., 2000). Lake Malawi has showed a series of dramatic lake level changes in the 20th century (Calder et al., 1995) and Lake Abiyata in Ethiopian rift, mainly filled by other lake overflowing, shows a 7 m decline in the last 20 years (Legesse et al., 2004).

Although rainfall behaviour and lake characteristics are different, some slight similar trends can be observed. The abrupt 2 m rise recorded in Lake Victoria between 1960 and 1968 is mirrored by a slight increase in level and a marked increase in outflow of Lake Tana. An exception is the year 1964 in which Lake Tana shows one of the lowest lake level records. We show later that the 1964 lake level data is probably erroneous due to recording failures or reporting mistakes. When the Lake Victoria level shows a decreasing trend (a lake level decline by about 1 m) between 1978 and 1986 (Nicholson and

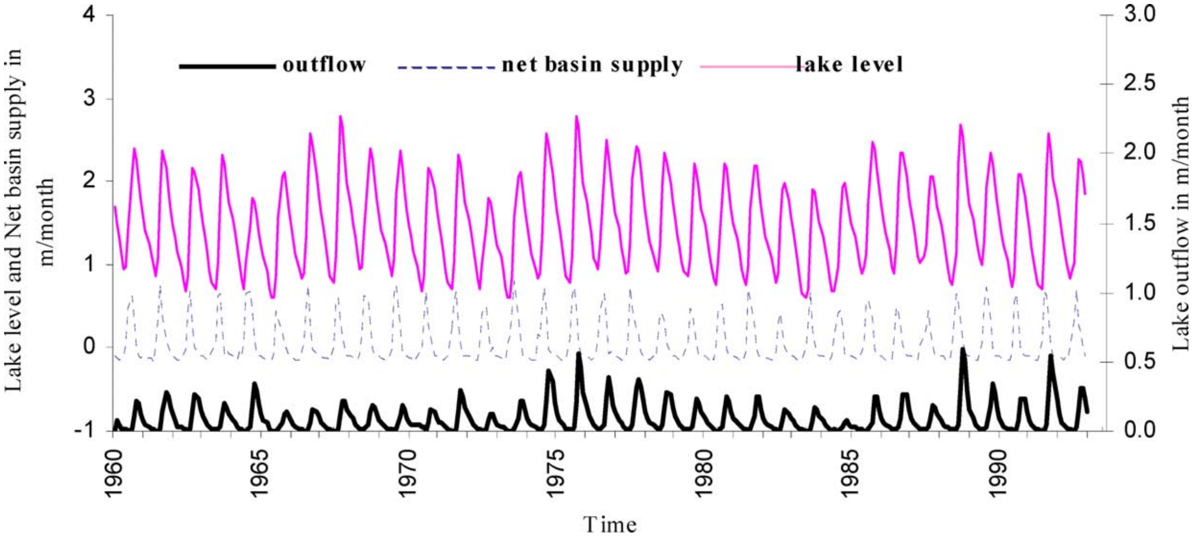

Fig. 3. Monthly series of lake level, lake outflow and net basin supply (1960–1992).

Yin, 2001), Lake Tana also shows a declining lake level trend but the decline is not as pronounced as in Lake Victoria. However, the outflow of Lake Tana shows a marked decline during this time. There is also no evidence of Lake Tana desiccation or cessation of outflow during the last 100 years. One of the regionally consistent variations in the hydrologic parameters is observed between the year 1975 and 1986. The period shows a decline in lake outflow. This period is also marked by decline by 1 m of Lake Victoria (Nicholson and Yin, 2001) and a decline in annual precipitation over the Blue Nile basin (Conway, 2000). In the drought year of 1984, the outflow from Lake Tana shows the lowest record.

Unlike the lake levels, the outflows of Lake Tana show a marked variation reflecting or 'amplifying' the changes in rainfall variation. Lake response to rainfall variation is not only the function of the hydrologic balance condition of the lake but also it depends on the geometry of the lake particularly that of the relationship between outflows and lake levels. The relation between the outflow and the lake levels in turn is the function of the geometry of the lake near its outflow zone. For natural unregulated lakes the relation is often expressed as $R_{\mathrm{out}} = aH^b$. The b-value varies between 0 and 3 in many natural lakes. The value $b = 1$ indicates a lake whose outflows and lake levels are linearly related. The b value close to 0 indicates lakes with somewhat constant outflow. The plot of lake monthly levels vs. lake outflows for the period 1960–1992 (Fig. 4) has the relation: $R_{\mathrm{out}} = 0.0156\mathrm{H}^{3.25}$ ($r^2 = 0.97$). The high value of b means that during high lake conditions a small change in lake level would change the outflow discharge significantly. Therefore, a small change in net basin supply would result in only a small change in lake level but a significant change in outflow. Fig. 4 also shows the discharge lake level relation is some what different for different years. The year 1964–1965 shows the most irregular relation indicating most likely error in recording. Particularly the lake level record of the year 1964 shows major inconsistency.

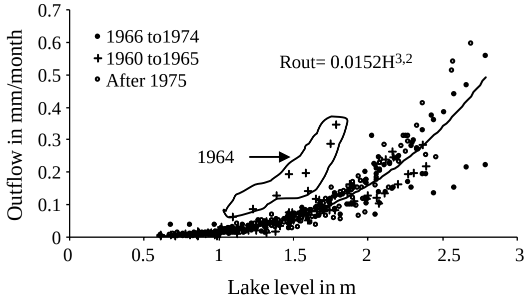

Fig. 4. The relation between lake level and out flow.

3.1.2. Evaporation

Evaporation from lakes is often the largest percentage component of the water budget, so its accurate determination is crucial for a reasonable estimate of the water budget. The Penman method has been found suitable for evaporation estimation under any climatic conditions and for a time scale as long as one month (Jensen et al., 2000). The Penman approach combines the fact that evaporation is a diffusive process and that energy can be expressed in terms of mass. The water advected energy, change in stored energy over the time of observation, the heat exchange by conduction between a lake and the underlying sediment, are all assumed to be negligible in this approach.

The Penman equation can be written as

$$E = \frac{s(T_{\mathrm{a}})(K + L) + \gamma K_{\mathrm{E}} \rho_{\mathrm{w}} \lambda_{\mathrm{v}} V_{\mathrm{a}} [e_{\mathrm{sat}}(T_{\mathrm{a}})](1 - W_{\mathrm{a}})}{\rho_{\mathrm{w}} \lambda_{\mathrm{v}} [s(T_{\mathrm{a}}) + \gamma]} \tag{1}$$

where E is evaporation in cm/day, V_{a} is wind speed in cm/s, W_{a} is relative humidity, T_{a} is average air temperature in °C. $s(T_{\mathrm{a}})$ is the slope of saturation vapor pressure versus air temperature, and $e_{\mathrm{sat}}(T_{\mathrm{a}})$, the vapor pressure of a saturated atmosphere. The later two variables were empirically determined from the meteorological data of Table 2.

K_{E} is a coefficient that reflects the efficiency of vertical transport ($= 1.26 \times 10^{-4}$ cm day^{-1}), ρ_{w} is mass density of water ($= 1$ g cc^{-1}), λ_{v} is latent heat of vaporization of water ($= 560$ cal g^{-1}), and γ is a psychrometric constant ($= 0.66$ mb°C^{-1}) K and L are net short-wave and net long-wave radiation in cal cm^{-2} day^{-1} respectively. The net short-wave radiation data at Addis Ababa Geophysical Observatory (the closest station where measurement is available) have been used in the calculation. Net long-wave radiation can be estimated empirically, using the Stefan–Boltzmann equation adapted for

Table 2
Meteorological data for Bahr Dar station T in °C, W_a in %, C as fraction, V_a in cm sec^{-1}, K in cal cm $^{-2}$ day^{-1} for Addis Ababa Station

	J	F	M	A	M	J	J	A	S	O	N	D
T_a	16.6	18.0	20.4	20.9	21.3	20.0	18.6	18.4	18.7	18.9	17.3	16.3
W_a	57	50	47	46	57	65	78	80	74	68	63	59
C	0.20	0.21	0.25	0.20	0.30	0.40	0.60	0.60	0.45	0.30	0.21	0.21
V_a	170	200	210	200	220	250	210	170	150	110	110	130
K	445	459.2	495.6	471.0	473.0	361.0	302.0	334.5	370.0	561.0	542.6	501.1

open water evaporation (Dingman, 1994). This equation is given as:

$$L = \varepsilon_w \varepsilon_{at} \sigma (T_a + 273.15)^4 - \varepsilon_w \sigma (T_s + 273.15)^4 \quad (2)$$

where ε_{at} is the effective emissivity of the atmosphere, σ is the Stefan–Boltzmann constant ($=1.17\times10^{-7}$ cal cm^{-2} day^{-1} K^{-4}), and T_a and T_s are air temperature and surface temperature of evaporating surface in °C, respectively. The value of ε_w is 0.97. ε_{at} is given as $(0.53+0.065e_a^{0.5})(1+0.40C)$, where C is the fraction of cloud cover per day. Due to the lack of complete kinetic temperature (T_s) measurement over the lake surface, we used the approach of Kohler and Parmele (1967) to estimate the net long-wave radiation. They made the following modification to the Penman equation to avoid the need for the kinetic surface temperature.

Replace L with $L = \varepsilon_w L_{at} - \varepsilon_w \sigma (T_s + 273.15)^4$ and γ with $\gamma + \frac{4\varepsilon_w \sigma (T_a + 273.5)^3}{K_E \rho_w} \lambda^{w} V_a$. L_{at} is the incoming latitude dependent long-wave radiation which is obtained from tabulated data for latitude range from 0 to 90°N (Dingman, 1994).

The daily evaporation in cm/day were then calculated from Eq. (1). The daily evaporation is summed to give monthly and annual evaporation. An annual mean open water evaporation of 1478 mm/year has been obtained for the Lake Tana region (Table 3). Our annual evaporation estimate is greater than that of previous open-water estimates by Morandini (1940); Shahin (1988) by 150 mm. However, it is lower than open water evaporation rate of the Ethiopian rift valley lake which often exceeds 1700 mm/year (Valet-Coulomb et al., 2001).

3.1.3. Groundwater

Since piezometric data is scarce around the lake quantifying groundwater flow around the lake using physical approaches was not possible. The general topography and geology of the region shows a likely groundwater flow towards the lake. However, because of the shallow depth of the lake and the compartmentalization of the groundwater flow paths as it moves from bordering highlands towards the lake by the faults around the lake, the groundwater component of the water balance may be considered of minor importance. Preliminary isotope balance study (study in progress) shows that the groundwater inflow constitutes less than 7% of the total inflow.

3.2. The annual water balance

The annual average water balance is tabulated (Table 3) and presented in Fig. 5. The balance has an error of +22 mm/year. This is small compared to the complexity of the estimation of each of the water budget components. The source of this error can be attributed to the lack of direct measurement of accurate evaporation rate or the fact that we assumed net groundwater flux and inflow from the ungauged catchment to be negligible. We also assumed that rainfall at the closest station to the lake represents the average direct rainfall on the lake—this may incorporate error as the lake is large and areal rainfall distribution is not regular.

4. Lake level simulation

4.1. Model formulation

The water balance of an open lake is normally given as

$$\frac{dH}{dt} = P(t) - E(t) + \left(\frac{R_{in}(t) - R_{out}(t) + G_{net}(t)}{A(h)} \right) + \varepsilon_t \quad (3)$$

Table 3
Monthly and annual water budget of Lake Tana in mm (period 1960–1992)

	J	F	M	A	M	J	J	A	S	O	N	D	Annual
P_L	2.7	2.3	7.0	23.3	83.7	177.2	438.8	394.6	202.3	93.2	23.1	3.4	1451
E_L	108	136	156	162	162	147	114	99.6	113.7	105	92.1	90.3	1478
R_{in}	9.3	6.4	5.1	4.4	9.8	42.2	262.6	422.2	259.1	93.0	41.7	20.0	1162
R_{out}	64	43	27	16	10	8	25	135	268	245	157	99	1113

where H is the level of the lake, A is the depth dependent surface area of the lake, P is the rate of rainfall over the lake, E is the rate of lake evaporation, t is time, R_{in} and R_{out} are surface water inflow and outflow respectively, and G_{net} is the net groundwater flux. The final term ε_t, represents uncertainties in the water balance arising from errors in the data and other terms such as minor abstraction or inflow from ungauged catchments.

4.2. Model solution

The usual approach to solving the differential water balance equation is to simulate the lake level on monthly or longer time step (Nicholson et al., 2000; Calder et al., 1995; Valet-Coulomb et al., 2001). Integrating over a time interval Δt (one month in our case), the differential equation can be rewritten as

$$\Delta H = P(t) - E(t) + \left(\frac{R_{in}(t) - R_{out}(t) + G_{net}(t)}{A(h)}\right) + \varepsilon_t \quad (4)$$

Further simplification can be done to this equation because we assume that the right most term in the equation, ε_t, is negligible, and net ground water flux has been considered as zero. We also assumed a constant area lake, as indicated by the present day relation between lake depth and area (Fig. 2). Under present day conditions, lake with outflow, a 1 m increase or decrease in lake depth results in a change of its area by less than 2%. A simplified equation of the following form has been finally used to simulate the measured lake levels.

$$\Delta H = P(t) - E(t) + \left(\frac{R_{in}(t) - R_{out}(t) + G_{net}(t)}{A(h)}\right) + \varepsilon_t \quad (5)$$

The solution of this equation is not straightforward because at any given time there are two unknowns: the lake level at the time (H_t) and the outflow that corresponds to this lake level ($R_{out}(t)$). The simplest approach to approximate the lake level is to use the previous months outflow ($R_{out}(t-1)$) in the Eq. (5) and assuming the initial H equal to the mean of the measured H. In lakes and linear reservoirs with the relation $R_{out} = aH^b$ with $b \ll 1$, the lake level

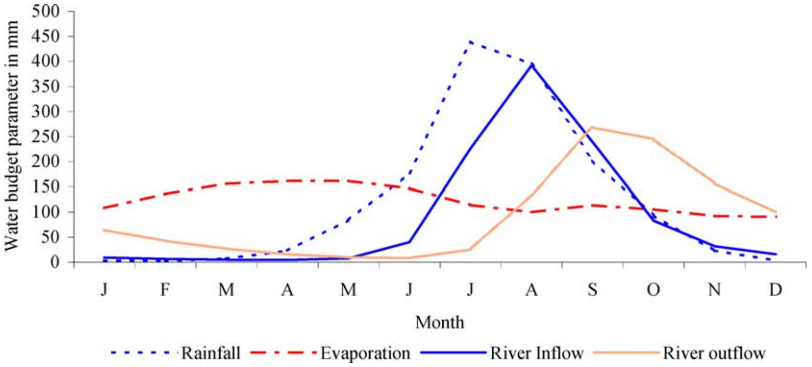

Fig. 5. Mean monthly water budget of Lake Tana (1960–1992).

simulated by using previous months outflow may very well simulate the measured lake levels. Some examples of such approach that give good results include simulation of Lake Malawi levels (Calder et al., 1995) and simulation of Lake Ziway levels (Valet-Coulomb et al., 2001). Fig. 6(a) gives the comparison between the calculated lake level using previous months outflow and the measured lake level. Although it is suitable as a rapid approach to check the validity of water budget estimates the use of previous months outflow to simulate the current month lake level, it is not strictly valid for lakes with variable outflows. The apparent discrepancy between the measured and the simulated is because of the high variability of the outflow of Lake Tana, inducing a higher b value compared to the Lakes Malawi and Ziway. The specific discrepancy of the period 1974–80 could be explained by a stonger monthly variability due to a larger rainfall amount.

A sounder approach of simulating the lake level is to solve the water budget equation iteratively so that the right hand part and left hand side of Eq. (5) are equal. We used an Excel SOLVER environment to perform the iteration. The calculated lake level is compared with the measured lake level in Fig. 6(b) and Fig. 7. During the running the iteration we optimised the value of b, evaporation, rainfall and initial lake level, a couple of times by trial and error. The final selection of the best simulation is based on the Nash criteria (Nash and Sutcliffe, 1970), regression coefficient and root mean square error (RMSE). The best Nash ($=0.75$) regression coefficient ($r^2=0.75$) and the root mean square error (RMSE $=0.27$ m) is obtained for evaporation rate 5% greater and rainfall 5% lower than the measured values, b fixed at 2.7 and initial lake level H_0 estimated at 1.5 m. Given that the rainfall decreases north and westwards on the lake the monthly rainfall series at Bahrdar may overestimate the simulated lake level. Therefore better simulation using 5% reduction in rainfall is justifiable. If one eliminates the points that depart from the major trend in Fig. 4 (the early 1960s lake levels), the b value would be lower than the one estimated from measured ($b=3.25$) lake levels and outflows. This justifies the selection of new b value estimated from optimisation ($b=2.7$) as representative of Lake Tana.

The disagreement in between the measured and the calculated values in the year 1964 reflects most likely an error in lake level record. The general agreement between the measured and the simulated lake level shows that the catchments scale changes during the last four decades which is not accounted in the model (forest cover changed is subject to discussions (Nyssen et al., 2004) depending of cultivation) is not detected in the lake level records. Variation in rainfall alone explains well the lake level history. The lack of large fluctuation in the lake level shows that because of the size of the lake and the high b value only a small change in lake level should be enough to cause the excess rainfall to be lost by increased outflows.

5. Lake level and outflow sensitivity to rainfall variations

One of our objectives is to determine the sensitivity of the lake level and its outflow to sustained changes

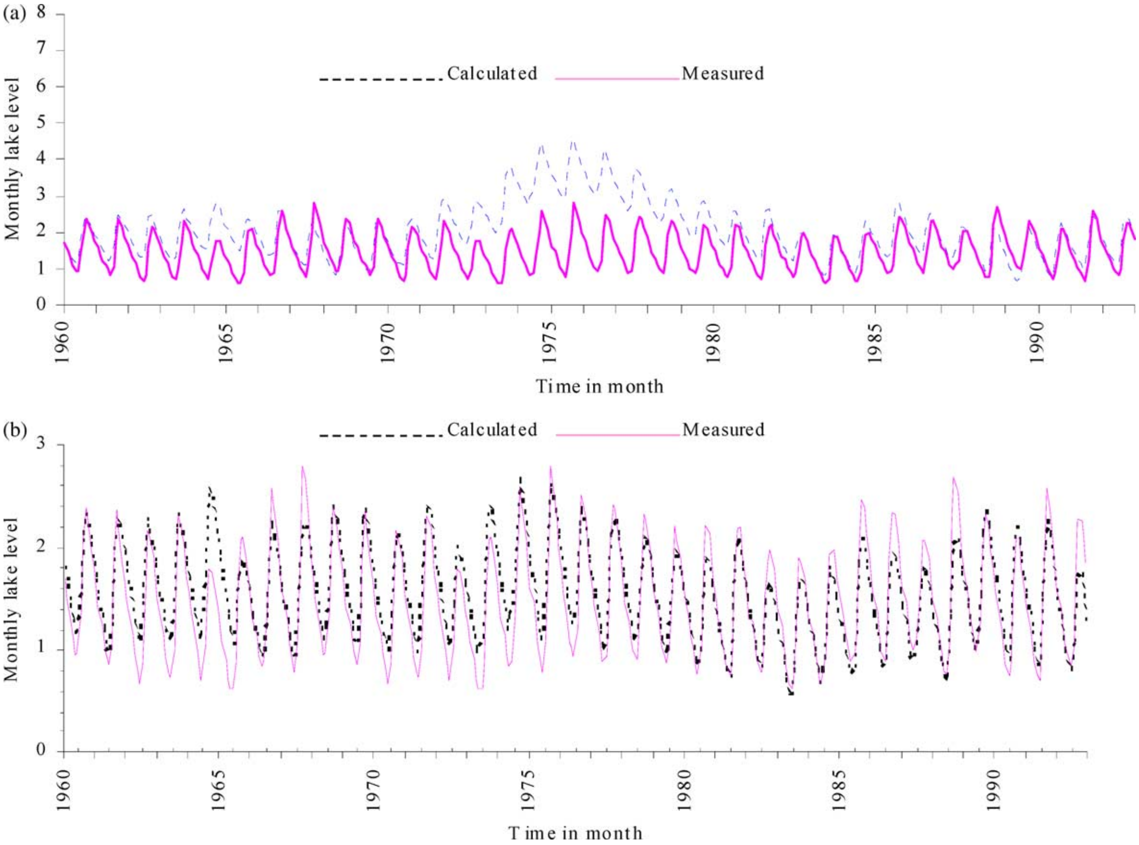

Fig. 6. (a) Comparison between measured lake level and lake level computed from previous months calculated outflow using the relation: $H_t = H_{t-1} + P(t) + R_{in}(t) - E(t) - R_{out}(t-1)$. (b) Comparison between measured lake level and simulated lake level between 1960 and 1992 using the relation: $H_t = H_{t-1} + P(t) + R_{in}(t) - E(t) - R_{out}(t)$ assuming the initial level ($H_0 = 1.5$ m).

in one or more of its water budget components: rainfall, net basin supply, abstraction for irrigation, or land use. We used two simple approaches: tangent line approximation and graphic method. A detailed mathematical foundation of sensitivity analysis is found in McCuen (1973). Sensitivity is a measure of change in one factor, x_i, on another factor, y; where y is any function of x_i, $i > 0$ which can be expressed as:

$$y_0 = f(x_1, x_2, \ldots, x_n) \tag{6}$$

The change in factor y_0 resulting from change in one of the factors x_i can be expressed in mathematical form by using a Taylor series expansion (tangent line approximation) of the explicit function:

$$f(x_i + \Delta x_i, x_{j,j\neq i})$$

$$= y_0 + \frac{\partial y_0}{\partial y_i}\Delta y_i + \frac{1}{2!}\frac{\partial^2 y_0}{\partial y_i^2}\Delta y_i^2 + \ldots \tag{7}$$

For naturally regulated lakes, the instantaneous outflow term R_{out} can normally be related to the instantaneous lake level term H by an expression of

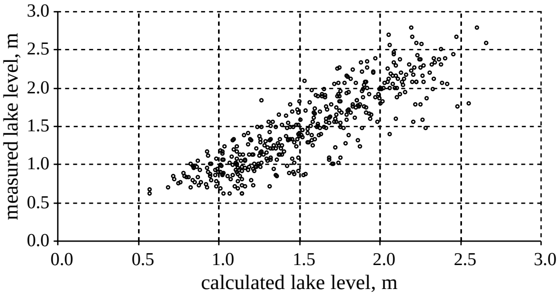

Fig. 7. Relation between the calculated and the measured lake level.

the form

$$R_{\mathrm{out}} = aH^{b} \tag{8}$$

This equation is a standard non linear reservoir relation which is widely used in reservoir hydraulic routing (Klemes, 1978) and lake level modeling (Sene, 1998, 2000). As our interest is to see the sensitivity of the equilibrium lake level to change in rainfall or change in water use, we examined the annually integrated values of water budget parameters. For Lake Tana, the nearest value of b that is obtained from the relation between lake level and the corresponding out flow after optimization is $b=2.7$.

The equilibrium level of the lake, corresponding to the long-term mean value for the net basin supply, can therefore be given by Eq. (9), because at equilibrium the left hand side of Eq. (1) assumes a value of zero.

$$(H_{\mathrm{e}}) = \left(\frac{A_{\mathrm{e}}N_{\mathrm{e}}}{a_i}\right)^{\frac{1}{b_i}} \tag{9}$$

where the net basin supply or the free water yield N is given as $N = P(t) + R_{\mathrm{in}}(t) - E(t) = P(t) + \alpha P(t)\frac{A_{\mathrm{c}}}{A_{\mathrm{L}}} - E(t)$. The subscript e denotes an equilibrium value and α represents the runoff coefficient of the watershed under consideration.

Using Eqs. (8) and (9) as objective functions, applying the sensitivity analysis approximation using Eq. (7), and after eliminating the non-linear terms, a simplified and practical relationship of the following form (Eq. (10)–(13)) can be derived. These equations are similar to a simplified model suggested for Lake Victoria (Sene, 1998; Sene et al., 2001) to gain an estimate of the impact of changes in rainfall variation on outflow or lake level. The results of these models are more accurate for small (fractional change) changes in the parameter to be changed.

The fractional change in lake level which results from fractional change in precipitation is obtained first by calculating the fractional change in lake level due to fractional change in net basin supply

$$\Delta H = \frac{H_{\mathrm{e}}}{b}\,\frac{\Delta N}{N_{\mathrm{e}}} \tag{10}$$

If change in the net basin supply is solely cause by change in rainfall

$$\Delta H = \frac{H_e}{b}\,\frac{\Delta P(1+\kappa)}{N_e} \quad \text{where} \quad \kappa = \alpha\frac{Ac}{A_{\mathrm{L}}} \tag{11}$$

If the change in the net basin supply is solely caused by change in basin runoff which in turn is caused by diversion of water for irrigation.

$$\Delta H = \frac{H_{\mathrm{e}}}{b}\,\frac{\Delta R_{\mathrm{in}}}{A_{\mathrm{L}}N_{\mathrm{e}}} \tag{12}$$

Changes in lake outflow are related to change in lake level by the equation of the form

$$\Delta R_{\mathrm{out}} = (R_{\mathrm{out}})_0\frac{b}{H_0}\Delta H \tag{13}$$

Considering $b=2.7$, for annually integrated lake level and outflow, Eq. (9) through 13 reveals that a sustained 30% decrease in precipitation leads to an absolute fall of the equilibrium lake level by 0.5 m. This in turn leads to a 75% decrease in lake outflow. A sustained 10% decrease in precipitation leads to an absolute fall of lake level by 0.25 m which in turn results in a decrease of lake outflow by 24%. If all the irrigation schemes proposed by USBR (1964) within the watershed of the Tana basin are implemented, the lake level would fall by 0.2 m and the lake outflow decreases by 20%. A sustained 45% decrease in rainfall leads to a permanent closure of the lake (cessation of the outflow). These equations also demonstrate that the lake level is less sensitive to change in runoff coefficient. Isotope balance evidence (Kebede and Travi, 2004) shows that the steady state oxygen isotopic composition of the lake increases by a factor of 3‰ for the lake changing from outflow condition to a closed lake.

The mathematical approach discussed above does not show the time-scale within which the lake level reaches a new equilibrium after a sustained change in one of the hydrologic parameter is induced. The equilibrium response of the lake depends on the value of b and on the amount of change in the water budget components.

We used a simplified graphical approach to demonstrate this. In the graphical approach, we used Eq. (5), and we forced one of the water budget components, namely monthly rainfall, to change by the required amount and then observe the lake level until it reaches a new equilibrium. The graphic approach is similar to the simulation of the lake level (Eq. (5)) but we reduced the mean monthly rainfall of each month by the required amount (10, 25, 40 and 45%) and run the iteration in the Excel. Since the runoff to the lake also changes with rainfall, we used a simple runoff-rainfall relation to estimate the changed runoff corresponding to the changed rainfall. The new runoff is estimated from rainfall as: $R_{\mathrm{in}} = 0.2PA_c/A_L$.

Some examples of the impacts of rainfall variation on lake outflow and lake level and the associated equilibrium time are demonstrated in Fig. 8. The graph shows that the equilibrium time depends on the change in rainfall. For small changes the equilibrium response time is short. The figure shows that it is only under a sustained 45% decrease in rainfall that the lake changes from out flowing to a terminal. The strict validity of the results depends on the validity of the assumption that the runoff coefficient remains constant under any rainfall condition. Normally when rainfall decreases the runoff coefficient also decreases. So one can logically assume the 45% rainfall decrease required to cease the lake is the maximum value.

The time required for the lake to reach new equilibrium is observed visually from the output of the computations under the changed condition. Fig. 8 shows for small changes in rainfall the equilibrium response of lake Tana is consistent with previously estimated response time using mathematical approaches. Using a mathematical approach Sene (1998) showed that the response time of Lake Tana is in the order of 2–3 years, far less than the response time of other large East African lakes, which is in good agreement with the graphical approach.

6. Discussion and conclusion

This preliminary work estimates the water budget of Lake Tana and its sensitivity to rainfall variations. Unlike many tropical lakes of Eastern African and that of Ethiopian rift valley lakes, the level of the lake remained regular over the last 40 years or more. However, the lake outflow has significantly varied mirroring the changes in rainfall in the region. Unlike other East African lakes, which show significant lake level variation to small changes in rainfall (order of less than 20% increase or decrease), a drastic change in the rainfall variation is required to bring Lake Tana to cessation of outflow. The low sensitivity of Lake Tana's level is a typical characteristic of lakes with significant outflow. In such lakes, lake levels by themselves give little information about local and regional hydrological conditions unless they are related to lake area and river basin area (Bengtsson and Malm, 1997) or unless their outflow is used. The high *b* value in the discharge-lake level relation shows a small change in lake level results in a significant change in outflow. However, once it ceases to flow after a sustained drastic climate change, its lake levels behave similarly to other sensitive closed basin lakes.

The overall agreement between prediction and observation of the hydrological model at the monthly time step confirms the validity of the annual water budget of Lake Tana obtained from the average of the monthly values. The fact that the measured lake level is less sensitive to change in catchment characteristics may indicate that, an extreme change in land use would be required for its effect to be detectable beneath the changes caused by natural variations in rainfall.

Precipitation on the lake is balanced by evaporation, so a complete utilization of all the rivers entering the lake is required for complete cessation of river outflow. Our preliminary sensitivity analysis gives an initial insight into the impact of water resources development and variation in rainfall on lake level and outflow. Although a drastic amount of change (40–45% decrease in precipitation) is required to change the lake from open to closed conditions, because of the short response time (less than 8 years) lake Tana might have passed through a series of changes between a closed lake and an open lake hydrology during short lived climate shocks of the Holocene. The lake chemistry and isotopic composition changes significantly during changes from an open lake to a closed lake condition. Therefore the sediments of Lake Tana may preserve a record of climate change. The 2‰ increase in the steady state oxygen isotopic composition during the change from to closed lake conditions is big enough to leave its signature in the sediments of the lake, so the hydrological history of the lake may be obtained from authigenic lake sediments. Our results show that, at least for the Lake Tana basin, variations in climate plays a far greater control on lake hydrology than

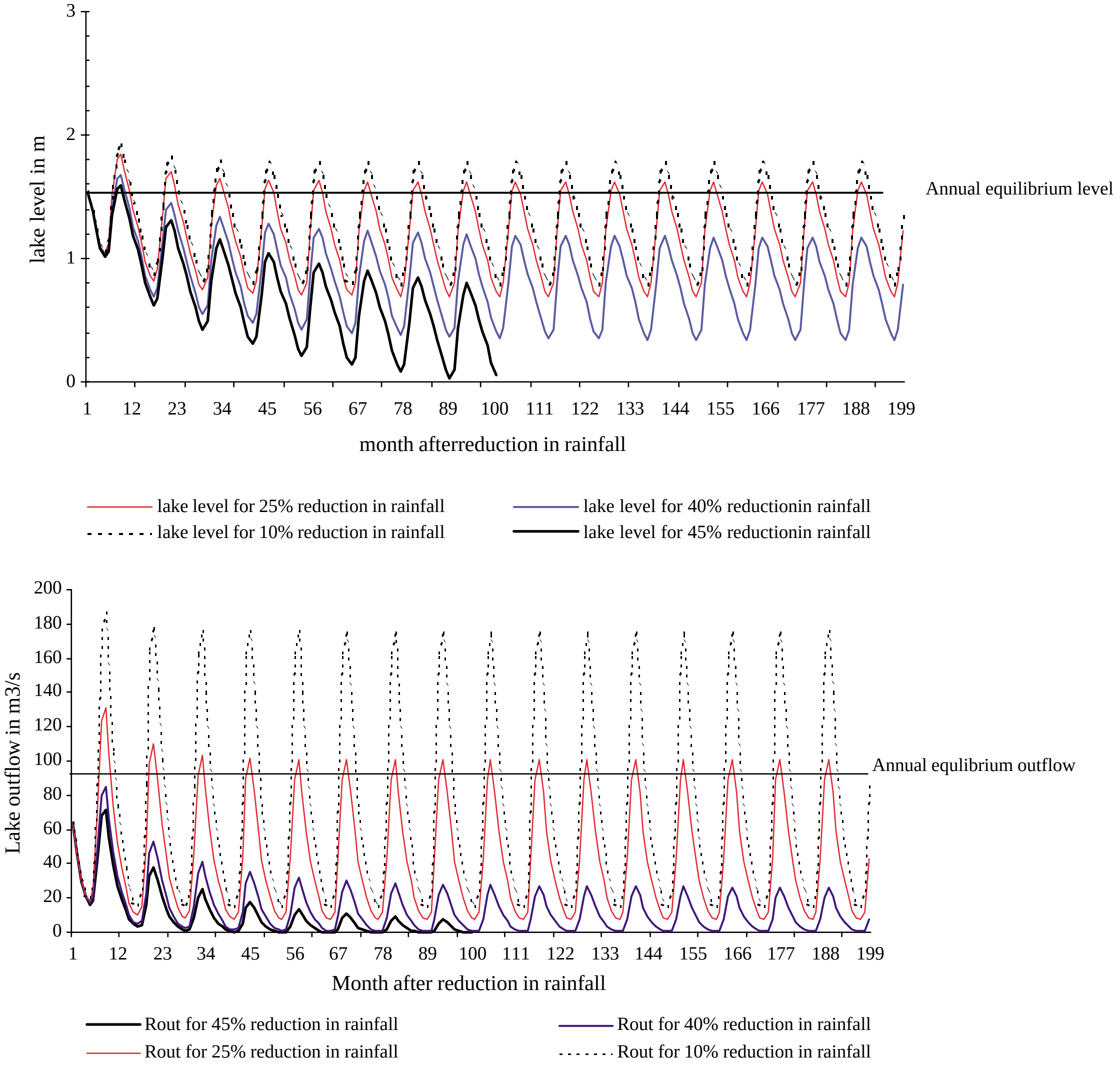

Fig. 8. Equilibrium response of lake level (above) and lake outflow (below) to sustained changes in rainfall. The changes are forced on the mean monthly precipitation and the response of the mean monthly lake level and the mean monthly outflow to the changes are demonstrated. The horizontal lines are the current mean annual lake level and the mean annual lake outflow.

human impact or local forces such as deforestation and accompanied change in runoff, and diversion for irrigation during the last century. However, the lake level is less sensitive to short lived term variation such as the ENSO. Therefore, in analyzing the impact of the ENSO the best record is the lake outflows than the lake levels.

In the sensitivity analyses the selection of the scenarios was somewhat arbitrary. Under natural condition this is much more complex and changes are irregular. However, the model gives a general behavior of the lake. More precise modeling of the lake should consider the rainfall variability on the lake surface and coupling catchment model with lake model. The lake level model by the graphical approach can be used as a simple tool to predict the impact of the water resources development around the lake.

Currently it seems lake level regulation, from the weir constructed at the outlet of the lake in 1996, is somewhat intuitive and arbitrary than based on mathematical models.

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