

## Water balance of Lake Victoria: update to 2000 and climate change modelling to 2100

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**Abstract** An annual water balance model of Lake Victoria is derived for the period 1925–2000. Regression techniques are used to derive annual inputs to the water balance, based on lake rainfall data, measured and derived inflows and estimated evaporation during the historical period. This approach acknowledges that runoff is a nonlinear function of lake rainfall. A longer inflow series is produced here which is representative of the whole inflow to the lake, rather than just from individual tributaries. The results show a good simulation of annual lake levels and outflows and capture the high lake level in 1997–1998. Climate change scenarios, from a recent global climate model experiment, are applied to the lake rainfall inflow series and evaporation data to estimate future water balances of the lake. The scenarios produce a potential fall in lake levels by the 2030s horizon, and a rise by the 2080s horizon. A discussion of the application of climate change data to this complex hydrological system is presented.

**Key words** water balance; climate change; rainfall–runoff model; regression; Lake Victoria

### Bilan hydrologique du Lac Victoria: mise à jour jusqu'en 2000 et modélisation des impacts du changement climatique jusqu'en 2100

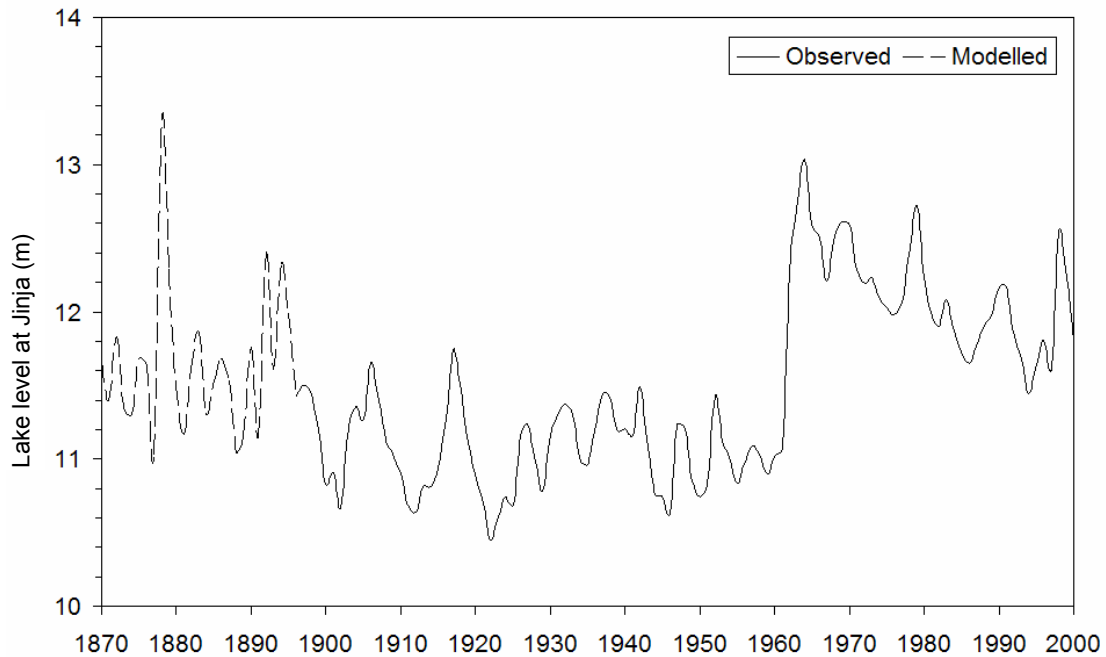
**Résumé** Un modèle annuel du bilan hydrologique du Lac Victoria est développé pour la période 1925–2000. Des techniques de régression sont utilisées pour déduire les entrées annuelles du bilan hydrologique, à partir de données de précipitation directe sur le lac, d'écoulements entrants mesurés et estimés, et d'évaporation estimée pour la période historique. Cette approche reconnaît que l'écoulement est une fonction non-linéaire de la précipitation sur le lac. Une plus longue série de données d'écoulements entrants est générée, représentative de l'ensemble de l'écoulement entrant dans le lac, plutôt que d'affluents individuels seulement. Les résultats montrent une bonne simulation des niveaux annuels et des écoulements sortants du lac, et ils reproduisent le haut niveau du lac de 1997–1998. Des scénarios de changement climatique, tirés d'une expérience récente de modélisation climatique globale, sont appliqués à la série d'entrées pluviométriques et aux données d'évaporation afin d'estimer les futurs bilans hydrologiques du lac. Les scénarios montrent un abaissement potentiel des niveaux du lac à l'horizon des années 2030, et une montée à l'horizon des années 2080. Une discussion de l'application des données de changement climatique sur ce système hydrologique complexe est présentée.

**Mots clefs** bilan hydrologique; changement climatique; modèle pluie-débit; régression; Lac Victoria

## INTRODUCTION

The historical contribution of the White Nile to Egypt, as the provider of the dry season flows, lent urgency to the search for its source in Lake Victoria and its

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**Fig. 1** Lake Victoria levels, modelled (1870–1895) and observed (1896–2000) (Tate *et al.*, 2001).

tributaries. However, the physical source was not located by explorers until the middle of the 19th century. Thereafter, scientists took up the search for the causes of its unusual behaviour: periods of steady levels interrupted by sudden changes.

Although Lake Victoria is fed by a large number of tributaries, drawing inflows from a wide variety of terrains, it has become clear that the bulk of the lake's inflow is drawn from the rainfall over the lake, enhanced by the combination of lake-shore interaction with wider meteorological processes. As Flohn & Burkhardt (1985) pointed out, it is the nocturnal cloud over the lake which is the true source of the White Nile. Tate *et al.* (2001) extended the observed lake level series back to 1870 using a water balance model, which captures the high lake level in 1878 (Fig. 1).

At the same time, the perceived importance of the lake outflow has spread from the dry season flow into Egypt, which has lost its pre-eminence with the construction of the Aswan High Dam, to the main source of hydroelectric power in Uganda and the factor controlling the behaviour of the Sudd wetlands in the southern Sudan. Since the construction of the Owen Falls Dam in 1954, the flow of the Nile below Lake Victoria has controlled the hydroelectric power available to Uganda, and further projects depend on the same basic resource at other locations. Although seasonal fluctuations in river flow, derived from rainfall within the Lake Victoria basin or downstream, have important secondary effects, it is the damped flow controlled by inflow and storage in Lake Victoria which determines the level of power available and the area of permanent swamp in the Sudd.

From a climate change and hydrological perspective, Lake Victoria is interesting because, during the historical record, it has displayed large and rapid changes in level in response to rainfall anomalies. This paper presents a refinement and update of the historical water balance of Lake Victoria and a case study of the possible effects of climate change on this complex hydrological system.

## THE LAKE INFLOWS

The area of Lake Victoria is relatively constant at around 67 000 km<sup>2</sup>. The area draining to the lake is 194 000 km<sup>2</sup>, of which almost 80% has been gauged during some period (Fig. 2).

The main contributions to the lake inflow are from (a) the Kagera basin, where rainfall and runoff are relatively high, but inflow is delayed and reduced by lake and wetland storage, and (b) the northeastern tributaries, where the rainfall is also high and the season more prolonged, with the basins steep and the runoff relatively fast. The southeastern tributaries have lower rainfall and runoff, and this makes for greater variability. The northwestern sector contributes less runoff because of wetland losses. Details of the five main tributaries, which together provide approximately 50% of the total tributary inflow, are given in Table 1.

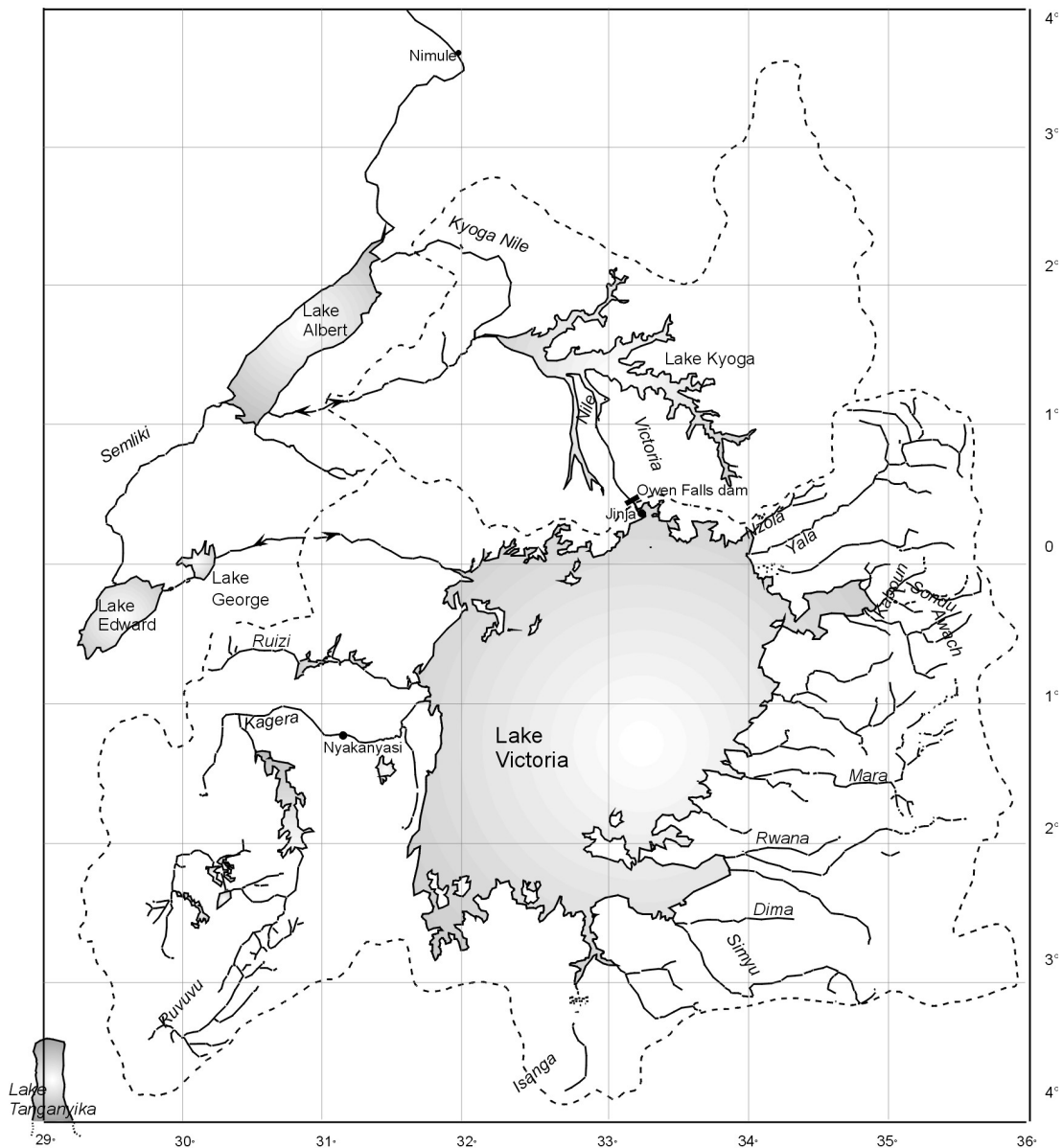


Fig. 2 Map of Lake Victoria and its basin (Sutcliffe & Parks, 1999).

**Table 1** Details of Lake Victoria's main tributaries.

Tributary	Gauged period	Catchment area (km <sup>2</sup> )	Mean annual flow (10 <sup>6</sup> m <sup>3</sup> )	(mm)	CV of annual flows
Kagera	1940–77	55800	6279	113	0.32
Nzoia	1956–79	11900	2486	209	0.36
Yala	1956–79	2650	1068	403	0.28
Sondu	1956–79	3230	1383	428	0.32
Awach Kaboun	1956–77	610	189	310	0.30

CV: coefficient of variation.

Although tributary inflow is small compared with direct rainfall on the lake surface, its greater variability is important in the fluctuations of the basin supply (Piper *et al.*, 1986). Since lake rainfall is almost balanced by the lake evaporation, which varies little from year to year, the net basin supply is unstable. Whereas the variability of lake rainfall is 13% and that of tributary inflow 29%, the resulting net basin supply has a variability of 64% (Institute of Hydrology, 1984). Over the past century, the lake has been in constant transition between a succession of equilibrium states; over the period of the observational record, the lake appears to have passed through several periods of quasi-constant levels, each lasting for up to one to two decades (Sene, 2000). Since 1961–1964 the lake level shows a long-term decreasing trend with higher frequency variability superimposed.

The lake rainfall series is much longer than any of the individual tributary flow records, which in any case represent only part of the surface runoff for most of the period (Piper *et al.*, 1986). Through deriving inflows from lake rainfall, a longer inflow series can be produced which is representative of the whole inflow to the lake, rather than just from individual tributaries. The mean tributary runoff coefficient is highly sensitive to mean catchment rainfall; thus, if catchment rainfall is proportional to lake rainfall, then tributary inflow is a nonlinear function of lake rainfall. Although the percentage runoff from the rainfall around the lake is relatively low (up to 25%), the rainfall–runoff process is very sensitive to changes in rainfall. Hence the runoff is more variable than the rainfall itself. Although average runoff into the lake is small in total volume compared with direct rainfall on the lake surface, its variability from year to year is greater and its impact on the water balance is significant (Piper *et al.*, 1986).

The approach taken here is to improve on previous estimates of net basin supply based solely on direct lake rainfall, using the assumption that runoff is a nonlinear function of lake rainfall, unlike previous studies that have used a linear relationship between rainfall and runoff (Sene, 2000). Climate change scenarios are then applied to the model, to examine the sensitivity of Lake Victoria levels and outflows to climate change.

## PREVIOUS WORK

The water balance of Lake Victoria has been modelled many times, using different approaches, with various aims in mind. In general, the studies show that direct rainfall over Lake Victoria is the key factor controlling its outflow; that this outflow is of major importance for the whole length of the Nile; and that climate change could have

a marked impact on the sensitive link between lake rainfall, inflow and evaporation which controls this complicated water balance.

Piper *et al.* (1986) were able to explain a significant rise in lake level between 1961 and 1964 through rainfall and resulting tributary inflows. They used rainfall records from gauges around the lake shore and completed a tributary inflow record using ratios to other gauged records, then extended the series back to 1925 using a net rainfall–soil moisture model. Sene & Plinston (1994) used two new water balance models to extend the modelling period to 1990 and to investigate trends in levels and outflows in the later years. They concluded that levels have remained relatively high since the early 1960s due to a sustained increase in lake rainfall. Analysis of rainfall events reinforces this: persistence of high lake levels is related to the combined effects of large catchment size and potential for storage, the wettest October–November on record in 1961, very high rainfall in 1963 and an increase in rainfall between 1931–1960 and 1961–1990 of about 8% over much of the basin (Conway, 2002).

Sene (2000) investigated the influence of Lake Victoria on flows in the upper White Nile using a model that represented the main river channel by a series of interconnected lakes and wetlands. The results confirmed the extreme sensitivity of river flows to changes in Lake Victoria levels and outflows, and in particular to direct rainfall on the lake. For example, a level increase of one metre under low-flow conditions was calculated to cause increases of 70–80% in flows throughout the system. Nicholson *et al.* (2000) developed a water balance model of Lake Victoria that can be used to assess rainfall from lake level. The model was first used to reproduce historical fluctuations of the lake from catchment rainfall and estimated lake evaporation. It was then inverted to predict rainfall from lake levels, with a small margin of error. The authors concluded that the lake is a sensitive indicator of climatic change.

Lake Victoria has also been the subject of climate change studies; indeed, one of the earliest attempts to evaluate the impact of climate change on runoff was on the Nzoia River, a tributary of Lake Victoria (Kite & Waititu, 1981). The Sacramento model was used to investigate the sensitivity of river flow to varying rainfall and evaporation. Conway & Hulme (1996) investigated the potential impacts of climate change on Nile discharge. They used a Lake Victoria water balance model similar to the Piper *et al.* (1986) version, which was driven with climate change scenarios from three global climate models and produced changes in Lake Victoria outflows ranging from –9.2% to +11.8%. Sensitivity analysis showed that a 10% increase in Lake Victoria rainfall causes a 31% increase in runoff, and a 4% increase in potential evaporation causes an 11% decrease in runoff. Various modelling approaches were used and assessed by Sene *et al.* (2001) to test the sensitivity of White Nile flows to potential climate change; this raised a number of interesting issues regarding strategies for modelling climate change impacts, summarized later in this paper.

## DEVELOPMENT OF THE MODEL

“Net basin supply” is a term commonly used to describe the total net contribution to the water balance of a lake, expressed thus:

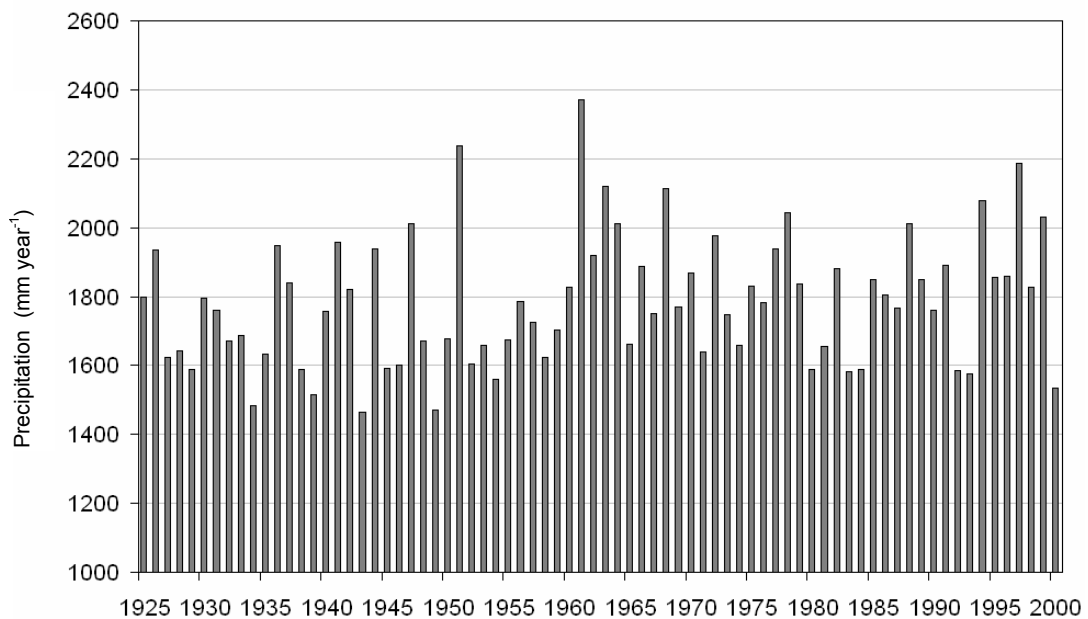
$$NBS = P - E + \frac{Q_{in}}{A} \quad (1)$$

where  $P$  and  $E$  are direct rainfall and evaporation at the lake surface, respectively,  $Q_{in}$  is inflow to the lake, and  $A$  is lake surface area.

The main input to the water balance is direct lake rainfall. The secondary input is tributary inflow which is a function of tributary rainfall, which in turn is related to lake rainfall. Therefore tributary inflow can be described as a function of lake rainfall; this can be done empirically by comparing the two, but is more logically done in two stages: first, individual tributary rainfall is described as a function of lake rainfall, then tributary runoff is described as function of tributary, and thus lake, rainfall. The total predicted inflow of the five major tributaries is then scaled up to represent the total lake inflow. Finally, lake outflow can be predicted from the Agreed Curve (Institute of Hydrology, 1984), the rating curve used to control outflows from the lake since the construction of the Owen Falls Dam, which ensures that the natural storage–outflow relationship for Lake Victoria is maintained.

The key to the whole procedure is the Lake Victoria direct rainfall series, developed by Sene & Plinston (1994). Using the lake system as a giant raingauge during years when the other factors were known, a relationship was obtained between rainfall at the long-term lakeside stations and net rainfall over the lake, which was then applied up to 1990. This series was extended to the year 2000 in this study using rainfall data for the remaining six of the original eight lake shore stations from which data were available. Any gaps were infilled using an isopercentile-style method (Christian & Parsons, 1959), based on data from the nearest neighbour, then the series average was calculated and the lake net rainfall series extended. The complete series, plus estimated constant evaporation (1595 mm), is illustrated in Fig. 3.

From this Lake Victoria rainfall series, subcatchment rainfalls, for each of the five main subcatchments, were estimated using regressions of annual total data. All regressions were based on the common rainfall data period 1956–1990. Regression coefficients are given in Table 2.



**Fig. 3** Derived rainfall series for Lake Victoria, 1925–2000.

**Table 2** Regressions of rainfall (for period 1956–1990).

Catchment	Regressions	Correlation, $R^2$
Nzoia	$P_c = (0.685 \times P_l) + 154.5$	0.52
Yala	$P_c = (0.951 \times P_l) + 64.7$	0.61
Sondu	$P_c = (0.666 \times P_l) + 302.6$	0.39
Awach Kaboun	$P_c = (0.785 \times P_l) + 337.4$	0.29
Kagera	$P_c = (0.556 \times P_l) + 142.8$	0.60

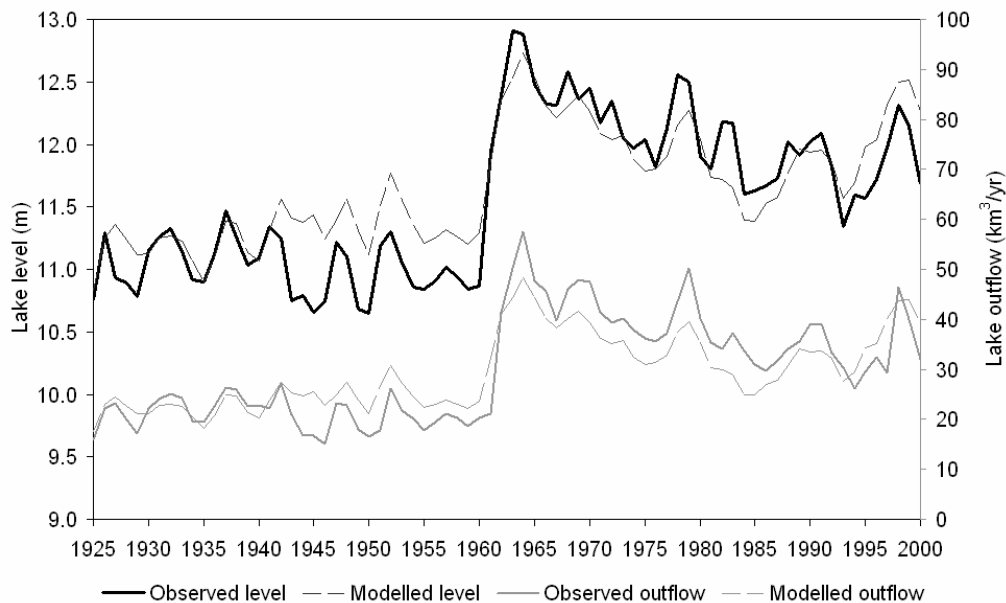
$P_c$  = catchment rainfall;  $P_l$  = lake rainfall.

Each tributary's runoff is estimated from the subcatchment rainfalls via a linear regression between the runoff coefficient ( $r_c$ ) and subcatchment rainfalls ( $P_c$ ) (from Sutcliffe & Parks, 1999, Figure 3.5a), derived as:

$$r_c = 0.0002P_c - 0.1386 \quad (2)$$

The total inflow to Lake Victoria could then be estimated using tributary multipliers (Institute of Hydrology, 1985), calculated as the scaled-up sum of the annual runoff of Nzoia, Yala, Sondu and Awach Kaboun, plus the flow of the Kagera (increased by 10% to allow for the flow of the Ngono tributary that joins it downstream of the gauging station). The scaling factor used for the sum of the four tributaries was taken as 2.7 on an annual basis (Institute of Hydrology, 1985). The total inflow to Lake Victoria predicted by this technique could then be compared with the observed data for the period 1956–1978.

The net inflow to Lake Victoria was calculated from gross rainfall, plus the estimated inflow volume, minus evaporation (1595 mm year<sup>-1</sup>; Sutcliffe & Parks, 1999). Levels of Lake Victoria could then be estimated, assuming a starting level of 10.6 m (observed end-of-year lake level for 1924). The outflow was estimated using the Agreed Curve, on an annual basis, after which a lake level and revised outflow could be calculated (shown in Fig. 4).



**Fig. 4** Modelled vs observed Lake Victoria levels and outflows, 1925–2000.

## RESULTS OF THE WATER BALANCE MODELLING AND UPDATE

The errors in simulation of the water balance are generally quite low with a tendency to overestimate levels and outflows from 1941–1960, underestimate them from 1961–1992 and overestimate them from 1993–2000. Recent errors may be accentuated by departures from the Agreed Curve. Lake rainfall during the 1990s has remained higher than conditions before the 1960s. Lake levels rose sharply in 1997–1998 in response to extreme rainfall across the region but the rise was short-lived. Rainfall in 2000 was low, although this is based on only four available raingauges.

## THE SENSITIVITY OF LAKE VICTORIA WATER BALANCE TO CLIMATE CHANGE

After a reasonable model of the baseline period had been achieved (see Fig. 4), climate change data were considered. The climate scenarios used in this study are taken from recent experiments with the UK Hadley Centre's HadCM3 fully coupled global climate model. Details of the model and emissions scenarios and their use as the basis for future climate change scenarios for the UK are explained in Hulme *et al.* (2002). Here, results from a control run for a 30-year period (1961–1990) were first used to define a baseline climate, as well as results from two simulations of future climate for the 30-year periods 2021–2050 and 2070–2099 based on different greenhouse gas emissions scenarios, “medium low” and “medium high” (B2 and A2, respectively, based on IPCC SRES scenarios, IPCC, 2000). Results are compared with an alternative control period (1931–1960).

Results at the original climate model resolution ( $2.5^\circ$  latitude,  $3.75^\circ$  longitude) were regridded to  $0.5^\circ$  resolution. Temperature, wind speed, vapour pressure and cloud cover were used to derive values of potential evaporation (*PE*) with the Penman function. A standard approach was used to adjust climate inputs to the lake model, changes in annual rainfall and *PE* were calculated as per cent differences between the baseline and future periods and used to adjust the historical observations, maintaining their historical variability. Table 3 summarizes the seasonal and annual changes in rainfall and *PE* over the lake basin (average values for the area bounded by

**Table 3** Seasonal and annual rainfall and Penman *PE* for Lake Victoria region (2021–2050 and 2070–2099). Figures in italics show per cent change from 1961–1990 control period.

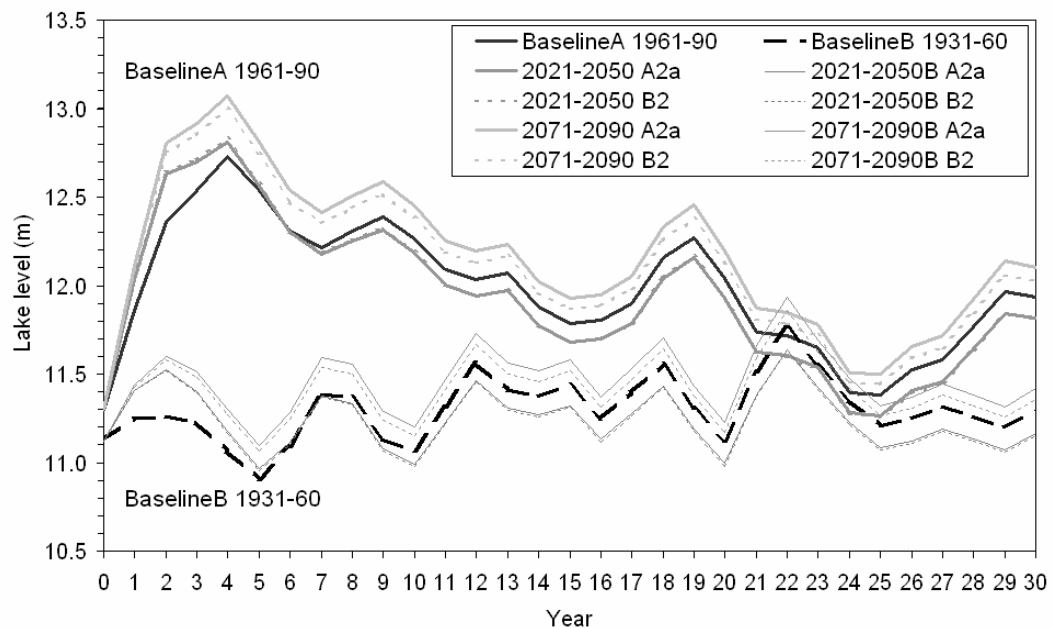
	Rainfall (mm day <sup>-1</sup> )					<i>PE</i> (mm day <sup>-1</sup> )				
	DJF	MAM	JJA	SON	ANN	DJF	MAM	JJA	SON	ANN
Control: 1961–1990	3.2	3.7	2.2	4.2	3.4	3.6	3.6	4.0	3.6	3.7
A2a: 2021–2050	3.4	3.9	2.1	4.0	3.3	3.6	3.6	4.3	3.9	3.9
	<i>6.3</i>	<i>5.4</i>	<i>-4.6</i>	<i>-4.8</i>	<i>-2.9</i>	<i>0.0</i>	<i>0.0</i>	<i>7.5</i>	<i>8.3</i>	<i>5.4</i>
B2: 2021–2050	3.6	3.8	2.1	4.0	3.4	3.5	3.7	4.3	3.9	3.9
	<i>12.5</i>	<i>2.7</i>	<i>-4.6</i>	<i>-4.8</i>	<i>0.0</i>	<i>-2.8</i>	<i>2.8</i>	<i>7.5</i>	<i>8.3</i>	<i>5.4</i>
A2a: 2070–2099	3.9	3.8	2.2	4.3	3.6	3.8	4.1	4.9	4.1	4.2
	<i>21.9</i>	<i>2.7</i>	<i>0.0</i>	<i>2.4</i>	<i>5.9</i>	<i>5.6</i>	<i>13.9</i>	<i>22.5</i>	<i>13.9</i>	<i>13.5</i>
B2: 2070–2099	3.8	3.9	2.1	4.2	3.5	3.6	3.8	4.6	4.0	4.0
	<i>18.8</i>	<i>5.4</i>	<i>-4.6</i>	<i>0.0</i>	<i>2.9</i>	<i>0.0</i>	<i>5.6</i>	<i>15.0</i>	<i>11.1</i>	<i>8.1</i>

DJF represents Dec-Jan-Feb, etc.

5.0°S–2.0°N and 25.0°E–45.0°E). Slight changes in annual rainfall mask large changes in monthly rainfall, with increases during January–April, August, and November–December. Marked differences in the magnitude and direction of rainfall change occur between successive months and seasons. The direction of change is generally similar between successive months and seasons. The direction of change is generally similar between both emission scenarios and is more positive for the 2070–2099 period than the 2021–2050s. The observed bi-modal seasonal regime (wet season “long rains” in March–May, and “short rains” in September–November) is reproduced in the climate model control. The short rains season is the wettest in the climate model under all simulations. Small increases in evaporation occur by the 2021–2050s and much larger increases occur by the 2070–2099 period.

### Applying climate change estimates

Changes in annual rainfall and evaporation (*PE*) derived from HadCM3 for the periods 2021–2050 and 2070–2099 were applied to two baseline Lake Victoria water balance models (Baseline A = 1961–1990; Baseline B = 1931–1960). The modelled levels of the lake are shown in Fig. 5, which presents both time horizons, both emissions scenarios, and both baselines.



**Fig. 5** Modelled 30-year lake levels and levels with changes in rainfall and *PE* applied.

Under both emissions scenarios and baselines, the 2021–2050 time horizon generally sees a fall in levels, whilst by 2070–2099, lake levels have increased. This is explained by a predicted fall in direct rainfall with a corresponding increase in lake *PE* by 2021–2050. The increase in *PE* by 2070–2099 is larger, but this is accompanied by roughly equivalent increases in rainfall, as shown in Table 4, and lake levels correspondingly rise slightly.

**Table 4** Summary of lake levels and outflow changes under HadCM3 climate change scenarios, using two different baselines.

Period	HadCM3 scenario	Mean level (m)	Level change* (m)	Total outflow (km <sup>3</sup> year <sup>-1</sup> )	Outflow change* (%)
<b>BaselineA</b>					
1961–1990	Observed	12.2		37.5	
1961–1990	Modelled	12.0		35.0	
2021–2050	A2a	11.9	–0.1	34.0	–2.9
2021–2050	B2	11.9	–0.1	34.1	–2.6
2070–2099	A2a	12.2	+0.2	38.4	+9.7
2070–2099	B2	12.1	+0.1	37.2	+6.3
<b>BaselineB</b>					
1931–1960	Observed	11.0		20.9	
1931–1960	Modelled	11.3		23.8	
2021–2050	A2a	11.3	0.0	22.9	–3.8
2021–2050	B2	11.2	–0.1	22.8	–4.2
2070–2099	A2a	11.5	+0.2	26.1	+9.7
2070–2099	B2	11.4	+0.1	25.3	+6.3

\* All changes with respect to modelled baselines.

## DISCUSSION AND CONCLUSIONS

The patterns of levels and outflows from Lake Victoria have been modelled directly from Lake Victoria rainfall series with reasonable accuracy, enabling the potential impacts of climate change on the lake water balance to be studied. Climate change estimates have been based on the standard WMO period of 1961–1990 (representing a period of higher observed lake levels) and an alternative baseline of 1931–1960 (representing a much drier time in the lake's history); the difference in the results emphasises the importance of selecting a representative baseline period for climate change studies.

The regression technique introduces inherent errors which contribute to the level of accuracy of the results. The regressions used here were derived from data for 1956–1990 and then applied outside that period (back to 1925). These regressions may not be entirely correct in other periods since the regime was different before the early 1960s. The technique of using regressions to derive related series reduces the amount of variability in the derived series. In the approach taken here, two successive regressions have been used, and thus the variability of the final derived catchment runoff series is undoubtedly lower than it would have been in its observed series; however, the use of nonlinear rainfall–runoff regressions reduces this effect.

### Sensitivity to climate change

There are well-known limitations to the use of climate change scenarios for climate impacts modelling. The example presented here serves to illustrate the complex hydrological response to climate change of a large lake system, one that has recorded major hydrological variability during the observed record. IPCC (2001) highlights the inter-model disparities in future rainfall changes produced by climate models and it is

important to note that only one has been used here. Indeed, IPCC (2001) shows that inter-model disparities are high over East Africa, including the Lake Victoria basin, and there is no clear direction for future rainfall change. The results presented here should therefore serve not as estimates of future Lake Victoria levels but more as an illustration of the sensitivity of lake levels and outflows to one possible future climate state.

In this case study, the change in lake regime pre- and post-1960, and the implications these have and continue to have for management of Lake Victoria releases at Owen Falls, is of interest and has relevance to planning for development of new hydropower facilities downstream of the lake.

The nonstationary behaviour of the lake system provides a fascinating case study of the implications of future climate change for management of water resources. Choice of a suitable baseline for Lake Victoria is difficult since the largest rainfall event in the observational record occurred in the early 1960s, at the beginning of the 1961–1990 baseline recommended by WMO (Sene *et al.*, 2001). However, given that many measurements started in 1956, a more representative 30-year period is not available. Given that there is no strong evidence to suggest that rainfall conditions will either continue as they are, return to pre-1960 conditions, or even increase again, then it would seem reasonable to base decision making and planning on the long-term (i.e. including pre- and post-1961) behaviour of the lake system.

**Acknowledgements** This paper was prepared with support from the UK Natural Environment Research Council (CEH Wallingford). The GCM data were supplied by the Climate Impacts LINK project (DEFRA Contract EPG 1/1/154) on behalf of the Hadley Centre and UK Met Office.

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**Received 4 November 2003; accepted 28 March 2004**