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The water balance of Lake Victoria

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ABSTRACT The sharp rise in the level of Lake Victoria between 1961 and 1964 has been found difficult to explain in terms of the components of the water balance. After reviewing lake inflows and the method of calculating lake rainfall from lakeside gauges, the historic lake water balance has been reproduced. The rise in lake level can be explained through rainfall and resulting tributary inflows, which would allow projections of possible future levels to be made by analysis of rainfall series.

Bilan hydrologique du Lac Victoria
RESUME L'élévation sensible du niveau du Lac Victoria enregistrée entre 1961 et 1964 était restée difficile à expliquer en terme de bilan hydrologique. Après révision des débits arrivant dans le lac et de la méthode de calcul des précipitations sur l'étendue du lac, un modèle historique a pu être reproduit. L'élévation du niveau du lac peut alors être expliquée par la combinaison des précipitations et de l'effet résultant des débits des tributaires. Les évolutions futures du niveau du lac pourraient être prévues par l'analyse des séries de précipitations.

INTRODUCTION

The hydrology of Lake Victoria has received a lot of attention because of its interest and importance, and a number of hypotheses have been put forward to explain apparent anomalies in its behaviour. Average lake rainfall almost balances annual evaporation so that rainfall variations are exaggerated in their effect. However, the lake storage provides considerable attenuation so that variations in outflow persist for some years. These outflows, further attenuated and reduced in passing through the Sudd, provided much of the low flow of the Nile in Egypt before reservoir storage was available. Their variations received attention from early times; high and low Nile levels are available from 622 AD to the present (Toussoun, 1925).

Until recently, information on inflows from the tributaries of Lake Victoria and on lake rainfall was lacking, and it has been difficult to explain the variations in lake outflow. During a recent review of the hydrology of the lake, the authors used the comprehensive records collected over the past few years. This paper

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explains the water balance, and in particular the rise in lake level of 1961-1964, in terms of lake and catchment rainfalls. It is hoped that this may encourage meteorologists to search for the cause of the underlying rainfall fluctuations.

The lake and its basin

Lake Victoria is a large body of water, with an average area of 67 000 km^2. The total catchment area of the lake tributaries is some 194 000 km^2, so the lake itself forms a major portion of the basin (Fig.1). The tributaries drain a variety of areas: the forested slopes of the escarpment to the northeast; the drier plains of the Serengeti to the southeast; the Kagera draining the mountains of Rwanda and Burundi to the west; and the swamps of Uganda to the northwest. Although the tributary inflow is small compared with direct rainfall on the lake, its greater variability is important in the fluctuations of the basin supply.

The outflow from the lake at Ripon Falls was directly related to lake level, and this relationship has been broadly maintained in the operation of the Owen Falls dam according to a curve agreed between the interested parties after model calibration. Thus recent outflows can be deduced from lake levels, and historic lake levels can be inferred from flows downstream and *vice versa*.

History of level changes

The water balance of a lake and its basin is summarized by changes in water level where the relationship between level and outflow is fixed. Thus the balance can either be approached by estimating each individual component separately, or the net basin supply can be inferred by studying the variations in level.

The study of lake hydrology is usually made easier by the fact that lake levels often precede measurements of the balance components. In the case of Lake Victoria, regular lake levels are available from 1896; these have been converted to a single level series at Jinja from 1900 in Fig.2. A feature of this series is the rapid rise in lake level (2.5 m in three years) which occurred in 1961-1964, and it is this rise which has stimulated recent interest in the lake.

The recent record may be supplemented by information collected by early travellers and investigators. This is succinctly summarized by Lyons (1906), and in his appendix on lake levels to Garstin (1904). He concludes (Lyons, 1906, p.37) that the lake was very high in August and September 1878, that it fell between 1878 and 1892, and, that after rises in 1892 and 1895, it fell continuously to the end of 1902. These high lake levels from about 1875 to 1895 are also supported by evidence from the Sudan and even from river levels in Egypt.

Historical evidence on a longer time scale is presented by Nicholson (1980), who summarizes evidence from lake levels in East Africa, Nile flows and rainfall information. Evidence is presented of a number of climatically anomalous periods, including the return to wetter conditions in the late nineteenth century. It is clear that the 1961-1964 rise is not unique and that similar fluctuations

Fig. 1 Location map.

have occurred in the past.

In 1964 the lake rose close to a cave near Entebbe (Brachi, 1960) where beach sands dated by charcoal fragments to 3720 ± 120 years old had been deposited when the Jinja outfall was at a higher level. Bishop (1969) pointed out that Lake Victoria could not have risen more than 60 cm above the 1964 peak during this period.

Previous studies

Earlier studies of the hydrology of Lake Victoria include those of Hurst & Phillips (1933), de Baulny & Baker (1970) and the WMO Hydrometeorological Survey (Kite, 1981, 1982). While early measure-

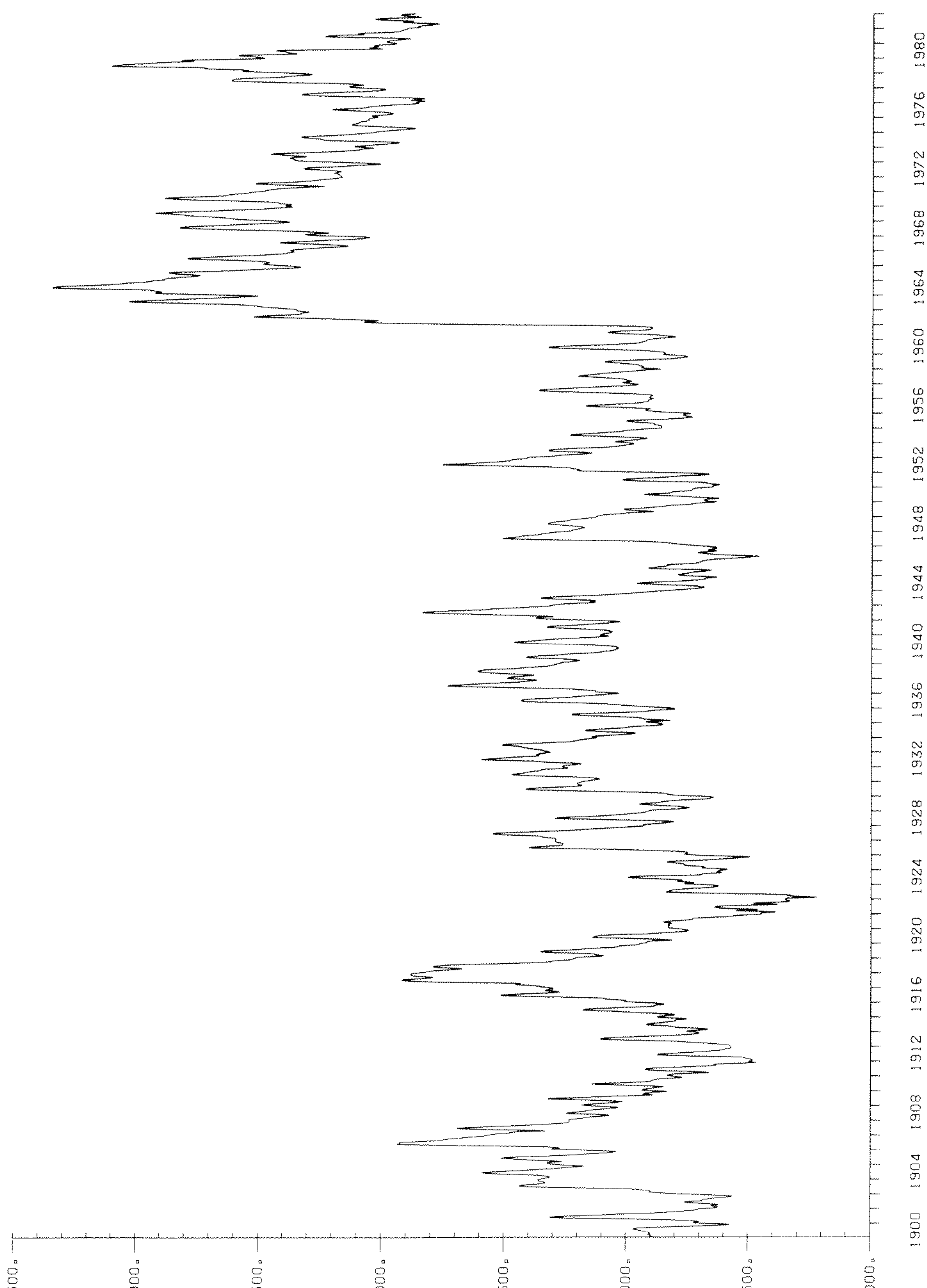

Fig. 2 Lake levels (1900–1982).

ments were carried out by the Egyptian government, Hurst & Phillips had to base their account of current knowledge on scanty data, including lake levels and some rainfall records around the lake. Their estimate of tributary inflows, based on "the character of the country" was remarkably accurate at 276 mm, but they underestimated the lake rainfall at 1151 mm.

After the 1961-1964 lake rise, Morth (1967) was able to relate rainfall around the lake with lake level changes, but used a growing network of raingauges that increased from 150 in 1938 to 300 in 1963. De Baulny & Baker (1970) dealt with each item of the balance in turn. They compiled monthly lake isohyetal maps and deduced a mean rainfall of 1650 mm. They used eight station records around the lake to compile a monthly rainfall series for the period 1925-1969, using monthly weighting coefficients. They present annual inflow series for the period 1959-1967 for 17 rivers (UNESCO, 1984), but as most of the rivers were not measured until 1969, these must have been inferred from rainfall. Outflows were calculated from Jinja levels and a rating based on model studies, while evaporation was estimated from the water balance on an annual basis.

A comprehensive programme of measurement and analysis was started by the WMO Survey in 1967, and this included gauging stations on all the major tributaries to supplement the stations on the Kagera from 1940 and on four Kenya tributaries from 1956. Rainfall stations were established around the lake and on islands; index basins were selected to study catchment hydrology and mathematical models were developed to study tributary inflows and the lake water balance. The water balance studies described by Kite (1981) were unable to reproduce the sharp jump in lake levels observed in the early 1960's; it was also deduced that an increase in rainfall of 25-30% over that recorded was necessary to explain the later rise of the lake between 1977 and 1980.

COMPONENTS OF THE WATER BALANCE

The components of the lake water balance are rainfall over the lake, tributary inflows, evaporation from the lake surface, and outflows. Changes in lake storage are implicit in lake levels. In the absence of any relevant information and in line with previous studies, it has been assumed that groundwater flow into or out of the lake is negligible. The data available for each of these components is discussed separately below.

Rainfall

In any one year the most reliable estimate of lake rainfall would be based on all the available records from gauges around the lake shore or on its islands. In recent years spatial coverage of gauges has been improved, particularly following the installation of new gauges as part of the WMO Hydrometeorological Survey. Thus this approach would mean that records for many more gauges would be available in later years and there would be doubts about the homogeneity of the time series of lake rainfall obtained.

Another approach to the calculation of lake rainfall was adopted by de Baulny & Baker (1970) who argue that on average rainfall should be constant over most of the lake with sharp gradients near the shore. Monthly lake rainfall was calculated from the records of eight long-term gauges distributed around the lake shore - Jinja, Entebbe, Kalangala, Bukoba, Kagondo, Mwanza, Musoma and Kisumu (see Fig.1). From a comparison of the monthly isohyetal maps with monthly averages for the eight gauges, coefficients adding up to 1.0 were drawn up for each month which gave a weighted mean of the eight records to represent monthly lake rainfall.

A more recent analysis that also included lake rainfall was conducted by the WMO Hydrometeorological Survey (WMO, 1974, 1981; Kite, 1981, 1982). Their estimate of lake rainfall takes account of all the records available in each year, so that the number and distribution of records used varies from year to year. The estimate also involves a model, proposed by Datta (1981), based largely on observations of the timing of rainfall on the east and west lake shores.

For this paper the approach used by de Baulny & Baker, using the eight gauges around the lake with continuous records from 1925, has been retained. The rainfall statistics for the eight gauges given in Table 1 show that the average seasonal pattern of rainfall is uniform around the lake, although the actual rainfall averages and annual standard deviations vary considerably between gauges. However, a different method of combining the individual rainfalls has been used here as explained later in this paper.

Tributary inflows

In order to analyse the historic lake water balance the total tributary inflows had to be estimated for as long a period as possible. Consequently gaps in the available records had to be filled and the contribution of the ungauged perimeter to the total inflow estimated. Gaps within the tributary inflow records were estimated from the ratio to the other gauged tributaries over the whole common period. Whereas flows for the ungauged perimeter were estimated by WMO (1974) for 1969 and 1970 from conservative runoff coefficients, these coefficients were reviewed for each shore by

Table 1 Monthly and annual rainfall statistics (1956–1978) (mm)

Station		J	F	M	A	M	J	J	A	S	O	N	D	Total
Jinja	Mean	64	85	141	195	140	69	70	83	100	141	161	87	1336
	SD	42	65	62	37	64	51	38	34	43	73	90	57	213
Entebbe	Mean	88	101	179	260	235	121	69	79	72	126	179	111	1620
	SD	49	54	83	89	103	61	59	56	47	63	85	58	176
Kalangala	Mean	135	137	239	340	322	162	96	94	114	159	210	208	2216
	SD	62	89	68	112	112	57	60	59	56	81	103	92	289
Bukoba	Mean	150	180	254	398	316	89	51	66	102	153	195	193	2147
	SD	51	82	49	104	93	53	47	32	56	70	94	78	307
Kagondo	Mean	119	152	219	362	234	47	26	40	94	115	201	161	1770
	SD	64	79	79	108	109	39	30	36	60	60	107	74	378
Mwanza	Mean	102	114	156	177	71	16	15	21	25	99	158	146	1100
	SD	51	64	93	83	52	20	29	29	25	70	99	67	246
Musoma	Mean	59	84	123	182	101	24	21	22	31	53	117	78	895
	SD	48	57	72	64	54	19	30	34	27	38	99	56	190
Kisumu	Mean	71	98	155	234	175	79	63	90	84	87	139	102	1377
	SD	56	70	68	73	79	45	34	40	39	45	96	63	224

comparison with gauged tributaries, and estimated ungauged inflows were revised; flows in other years were estimated from the ratio to the total tributary inflows.

Although the Kagera record starts in 1940, records of four Kenyan tributaries are available only from 1956 for comparison with the total tributary inflow from 1969. It was decided to extend the total tributary inflow record back to 1956 by comparison. For each year with complete data, the runoff totals in calendar months were compared between the four tributaries (Nzoia, Yala, Sondu and Awach Kaboun) and the total excluding the Kagera and Ngono. For each month a straight-line relationship passing through the origin was inferred, and used to extend the tributary runoff data back to 1956.

In order to extend the lake water balance back before 1956, it was necessary to estimate the tributary inflows. A simple net rainfall-soil moisture model, which uses monthly rainfall and evaporation as input, was chosen. Parameters for the four tributaries mentioned above and the Kagera were estimated independently. Using monthly catchment rainfalls on these catchments for the period 1925-1978, a sequence of flows was simulated, and then used to estimate the total inflow to the lake using the procedures described above. A comparison of the observed and simulated inflows for 1956-1978 is given in Table 2. While there is a seasonal pattern to the errors of

Table 2 Statistics of observed and predicted lake inflows (1956–1978) (million m^3)

	J	F	M	A	M	J	J	A	S	O	N	D	Total
Observed													
Mean	1330	1059	1542	2714	3217	2107	1981	2098	1948	1571	1678	1738	22983
Standard dev.	716	388	1182	1459	1663	744	642	636	522	429	926	1090	7064
Predicted													
Mean	1784	1529	1661	2796	2489	1779	1694	1802	1661	1561	1811	1996	22563
Standard dev.	951	727	819	1302	997	721	652	525	508	457	829	1096	7170
Observed–predicted													
Mean	−454	−470	−119	−82	728	328	287	296	287	10	−133	−258	420

% Explained variance of annual inflows: 80
Root mean square error: 3100

simulation, which is difficult to eradicate, the main interest is in the annual and longer term lake balance which is much less affected by these errors.

Evaporation

In their Phase II study, WMO adopted a variety of approaches to the estimation of evaporation from the lake surface. These included pan evaporation methods, a water balance for the period 1970-1974, a heat budget method and models using global solar radiation. Although there was good agreement in total, comparisons between the monthly figures were poor.

The study of evaporation of such a large lake is complicated by heat storage and the difficulty of estimating evaporation accurately from small changes in level. Moreover, it is not possible to distinguish easily between underestimates of rainfall and over-estimates of evaporation. Variations in evaporation from year to year are likely to be relatively small, so the estimates of monthly open water evaporation are based on monthly averages derived by the Penman method for stations around the lake. The average monthly distribution was scaled so that the annual total is approximately equal to the WMO estimates; the resulting values are given in Table 3.

Table 3 Estimates of lake evaporation (mm)

J	F	M	A	M	J	J	A	S	O	N	D	Total
135	135	145	130	125	120	125	135	140	145	130	130	1595

Lake levels and outflows

A comprehensive account of the early history of the lake gauges is given in Hurst & Phillips (1933). A consistent series of end-of-month lake levels was compiled by WMO from the records for various gauges (WMO, 1981) and was used in this work.

Before the construction of the Owen Falls dam in 1954, lake outflows were controlled by the Ripon Falls on the Victoria Nile at Jinja, and were therefore related to lake levels. Flow measurements are available before 1954 and the relationship was extended to higher lake levels by calibrating a model of the natural falls (HRS, 1966). This relationship is known as the agreed curve, and the operation of the dam is constrained to release the natural outflows corresponding to lake levels on this curve. Historic monthly outflows for the period 1900-1978 have been computed from lake levels using the agreed curve.

REPRODUCTION OF THE HISTORIC WATER BALANCE

The purpose of studying the water balance in detail over the period 1956-1978 is to determine whether the inputs (rainfall on the lake and tributary inflows) balance the outputs (evaporation from the lake, outflows and changes in storage). Of particular interest is whether the dramatic rise in levels of 1961-1964 can be explained in terms of the individual components of the water balance.

Initial trials using de Baulny & Baker's rainfall series showed that a reasonable balance could be achieved only by increasing the inputs by an amount equal to about 25% of outflow. Over the 23 year period the accumulated error implied a decrease in lake level of nearly 2.9 m.

Such large errors are unlikely in estimates of tributary inflows or the outflows at Owen Falls, but in terms of rainfall or evaporation the errors are relatively small. Both variables were estimated indirectly from records at lakeside stations and therefore do not necessarily represent conditions over the lake itself. Present evidence cannot distinguish between overestimation of evaporation or underestimation of rainfall. Without a network of gauges on the lake itself, the problem is analogous to estimating rainfall over an area half the size of England from eight gauges around the periphery.

In order to test the de Baulny & Baker series, an implied lake rainfall sequence was deduced by using the lake as a raingauge for the period when all the other variables in the lake balance were known. This test compared the monthly values of the implied rainfall sequence with the records of the eight lakeside gauges used by de Baulny & Baker, after normalizing these according to their monthly means and standard deviations. While de Baulny & Baker gave more weight to the western gauges, the comparison showed that there was no group of gauges clearly dominant.

Consequently it was decided that, rather than use different weighting factors for each gauge, it would be simpler to estimate normalized lake rainfall as the arithmetic average of the normalized station values. This procedure implies that the variability of rainfall at each station is given equal weight irrespective of the absolute average rainfall at the station. Absolute values of lake rainfall were obtained by rescaling the values of the normalized sequence using the appropriate monthly mean and standard deviation of the implied rainfall sequence. Inevitably, this combination procedure led to a lower standard deviation than the implied sequence; a multiplying factor of 1.3 was applied to the standard deviations.

Using the calculated lake rainfall for 1956-1978 the water balance of the lake has been simulated: Fig.3 shows the water balance components expressed in mm over the lake, and Fig.4 compares observed and predicted lake levels.

Using the tributary inflow model to simulate inflows over the period 1925-1978, an implied rainfall sequence was derived for the

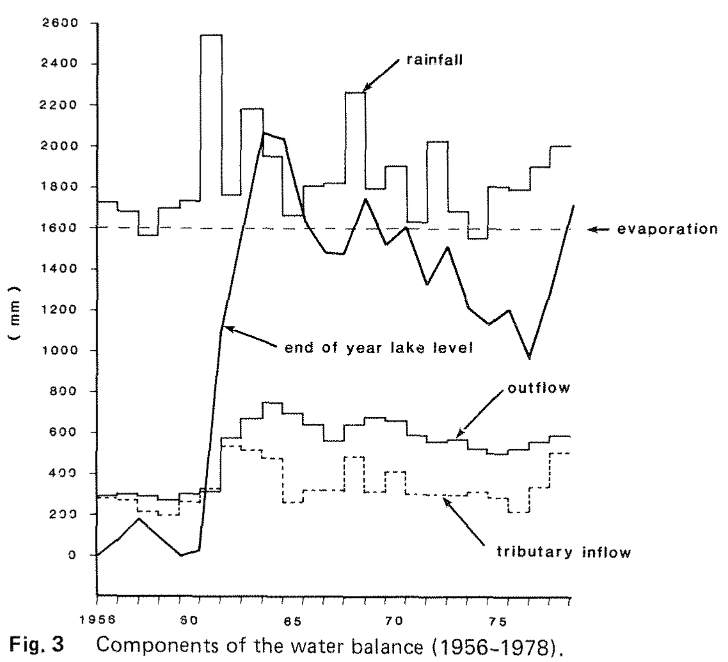

Fig. 3 Components of the water balance (1956-1978).

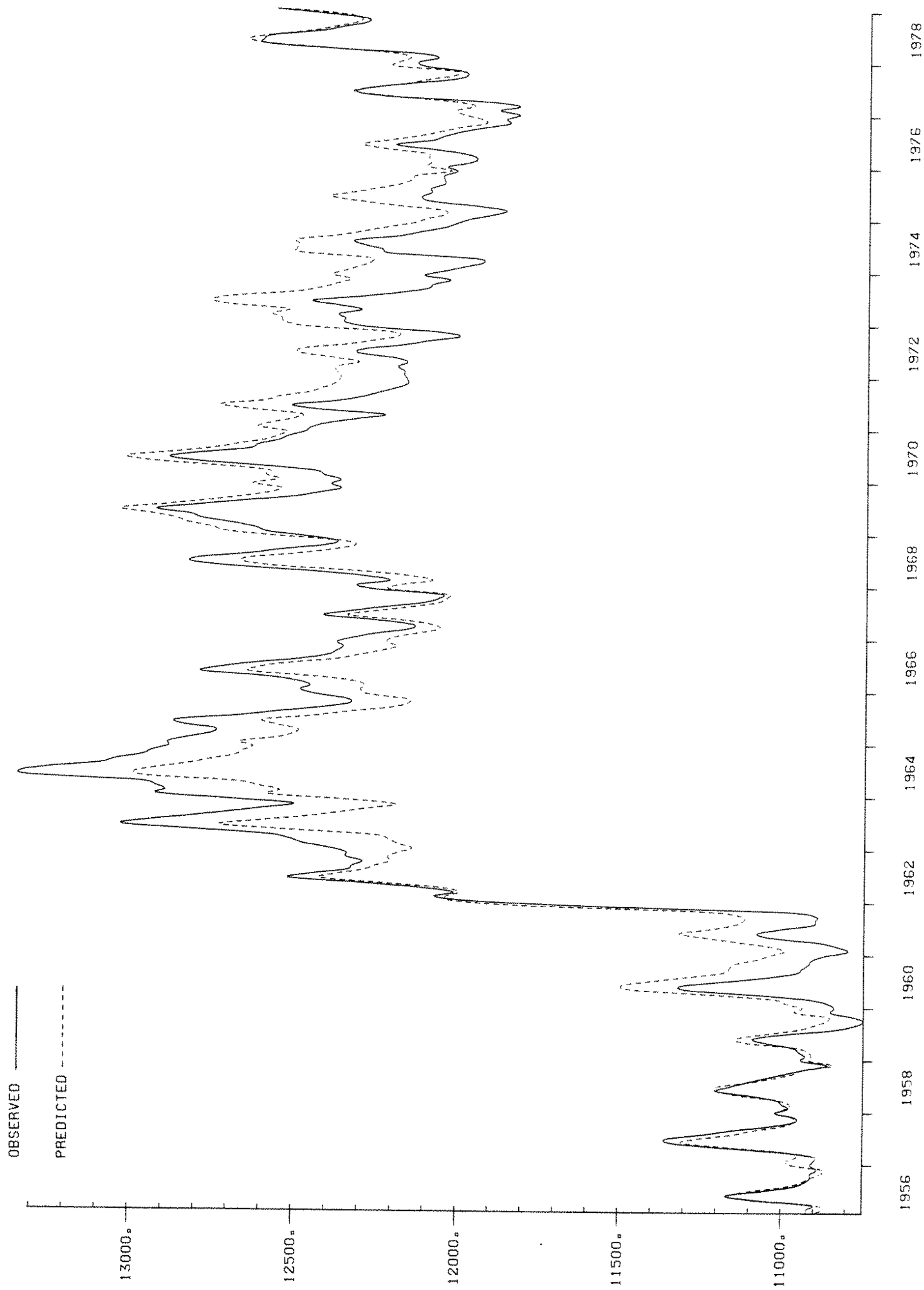

Fig. 4 Observed and predicted lake levels (1956–1978).

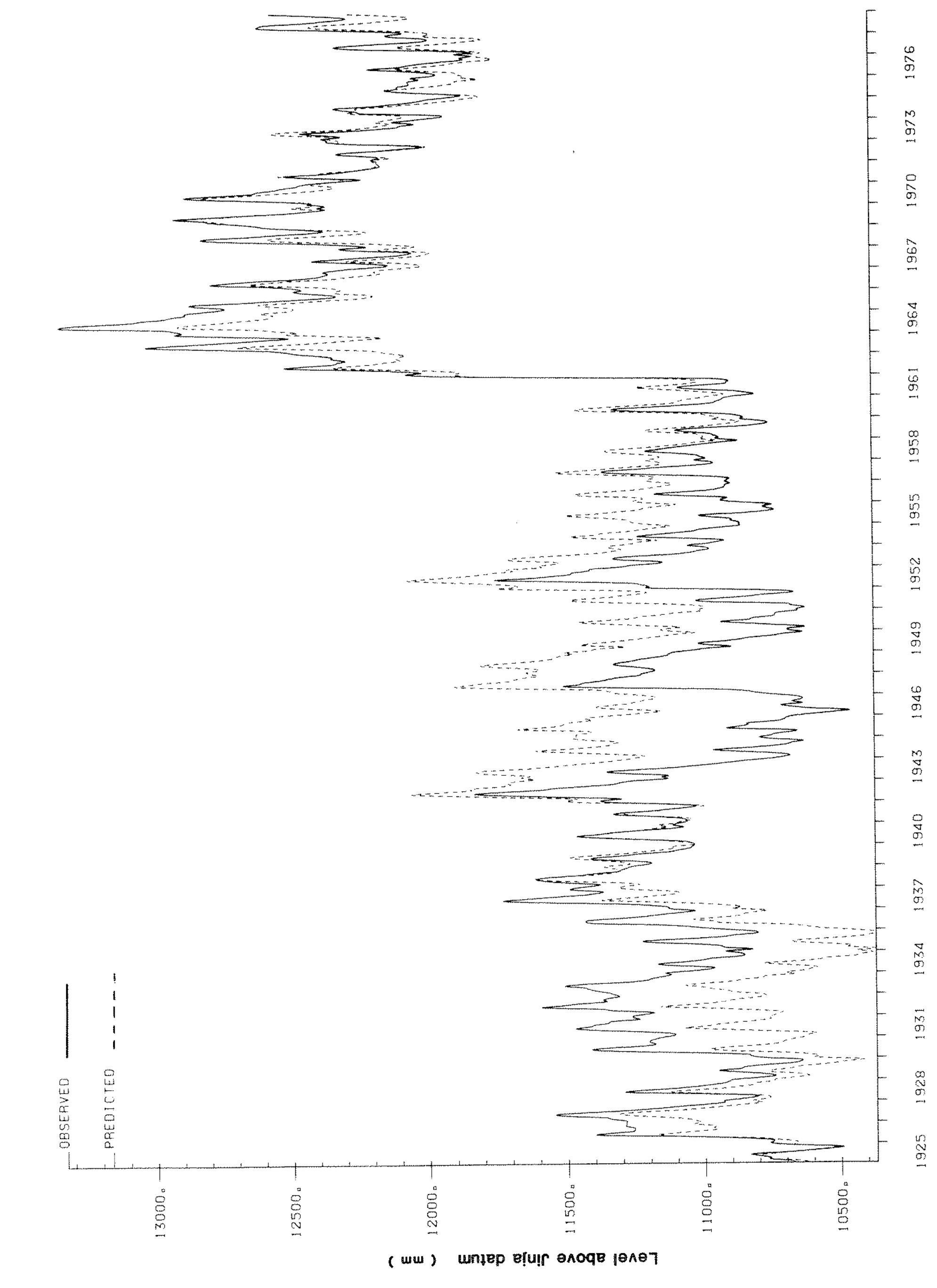

Fig. 5 Observed and predicted lake levels (1925–1978).

longer time scale. A new lake rainfall series, rescaled according to the mean and standard deviation of the longer implied rainfall sequence, was derived using the procedure outlined above. A new lake water balance was carried out; in this case outflows were based on predicted lake levels. The observed and predicted lake level series are shown in Fig.5.

CONCLUSIONS

The main finding described in this paper is that the historic sequence of lake levels can be reproduced using relatively simple combinations of the lakeside rainfall records, without the need for adjustment of the rainfall component during periods of lake rise. This rainfall series can be used either with measured tributary inflows over the period 1956-1978, or with tributary inflows simulated from catchment rainfall over the longer period 1925-1978.

The rainfall and tributary inflows, in combination with a reasonable estimate of evaporation, can reproduce the measured lake levels and lake outflows through the water balance in terms of seasonal and long-term variations. This success can be attributed to the fact that a constant set of raingauges was used, with no scaling constraint on the weighting factors, so that the important rainfall in the northeast was properly represented, whereas de Baulny & Baker's method gave undue weight to the western gauges. This has shown that a sequence of three years with rainfall above the average, together with the tributary flows responding to this rainfall but amplifying its variation from the mean, was sufficient to explain what appears to have been an exceptional event when the lake level series is studied in isolation.

The fact that this rise can be explained through rainfall alone means that the statistical properties of the lake balance may be studied and projections into possible future levels made by analysis of rainfall series. By linking the lake rise firmly to the immediate meteorological cause, impetus may be given to the search for a physical understanding of the apparently sudden change in Nile flows.

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