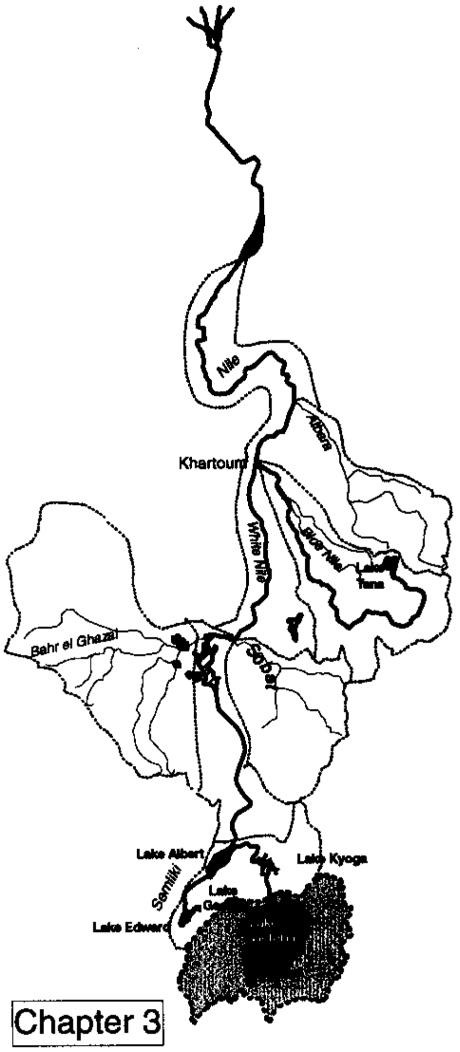
CHAPTER 3

THE LAKE VICTORIA BASIN

INTRODUCTION

It has been pointed out strikingly (Flohn & Burkhardt, 1985) that the true source of the Nile is not the Ripon Falls, where the river leaves Lake Victoria on its long course to the sea, nor the headwaters of the Kagera tributary draining the highlands of Rwanda and Burundi (Fig. 3.1), but rather the nocturnal cloud above the lake itself which provides most of the water supply to the lake. Therefore in the search for the source of the White Nile the successive studies of the lake water balance have been as important as the early explorations of the course of the river. This account of the Lake Victoria basin includes the historical studies of the water balance, which have depended as much on the accumulation of reliable measurements as on scientific insight.



EARLY STUDIES OF THE WATER BALANCE

The first study by Hurst & Phillips (1938) of the water balance of Lake Victoria was based largely on lake levels and some rainfall observations. The average lake rainfall was estimated as 1151 mm, the tributary inflow as 276 mm over the lake area, the mean outflow as 311 mm, and the evaporation therefore as 1116 mm. The flow of the Kagera was estimated from some 15 measurements, but the runoff estimates for the rest of the basin were "rough guesses based on a knowledge of the character of the country and the streams". The inflow estimates were nevertheless remarkably accurate, and although the rainfall was underestimated they established that lake rainfall and evaporation were roughly in balance. They showed that all the components of the water balance were important and thus laid the framework for future study.

There was a dramatic change in the lake regime with the sudden rise which occurred in 1961–1964 (Fig. 3.2). The lake level had fluctuated between relatively narrow limits since measurements began in 1896. Then a rise of 2.5 m after a period of heavy rainfall in 1961/62 led to general levels well above previous measured limits and raised the question of the cause of the rise. The fact that the rise followed the construction of the Owen Falls dam in 1951–1953 suggested to some that the two events were connected.

This event eventually led to the establishment, in 1967, of the WMO/UNDP Hydrometeorological Survey of the lakes (WMO, 1974, 1982) which has provided much of

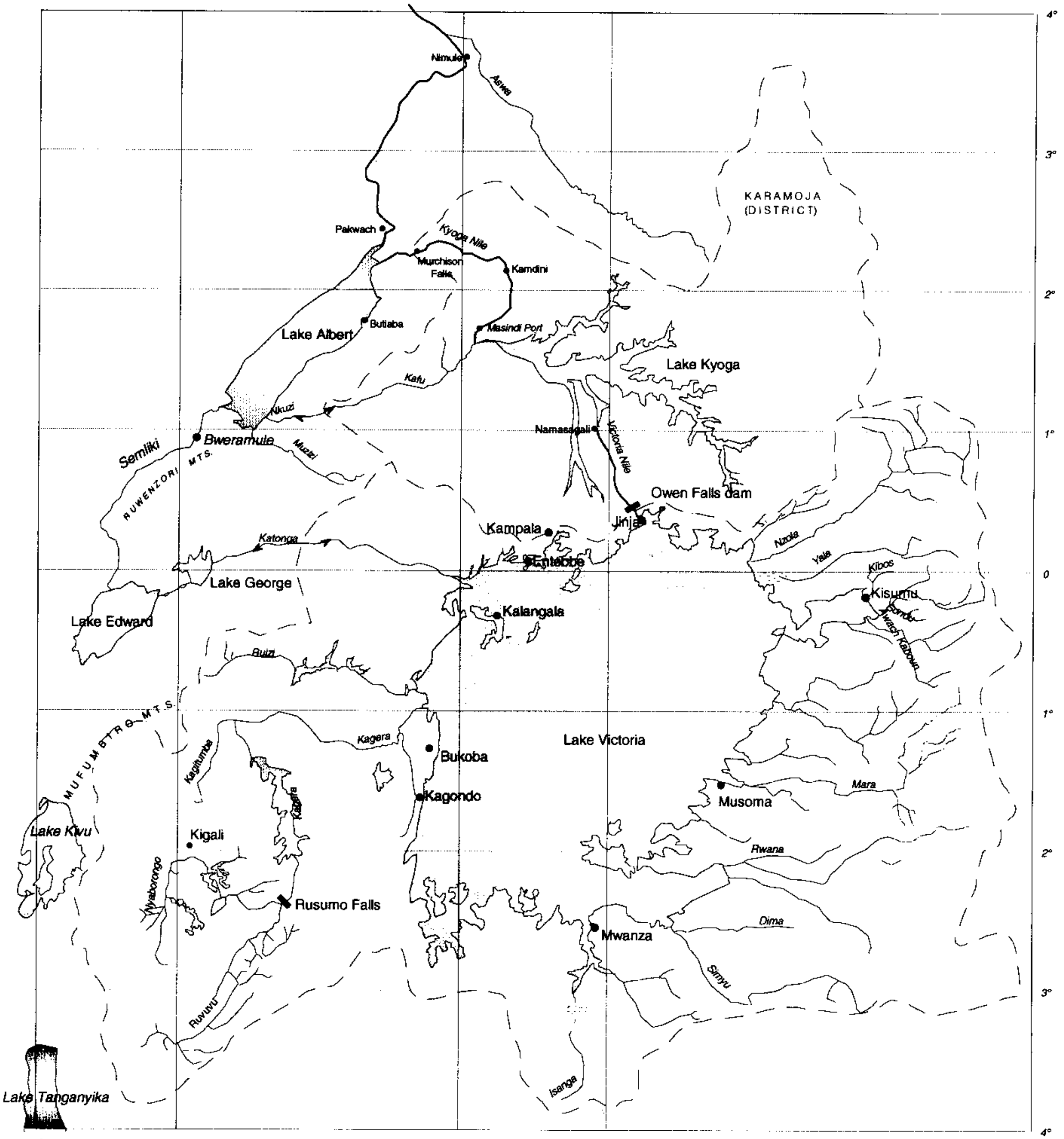


Fig. 3.1 Map of the lake region.

the data for later studies. Following early estimates of the lake balance, systematic measurements of tributary inflows have been carried out, and the components of the water balance are now reasonably well established. The key to the understanding of the hydrology of the lake is an application of the water balance principle that the rainfall and inflow to any area must equal the sum of the evaporation, outflow and increase of water storage.

In this chapter the main tributaries are discussed before looking at the components of the water balance of the whole basin. Although studies have been carried out over various averaging periods, particular attention is paid to the period 1956–1978, which has the most complete set of measurements.

THE KAGERA BASIN

The principal river flowing into Lake Victoria is the Kagera, with a basin of 60 000 km^2. With its main tributaries the Ruvuvu and Nyabarongo it drains most of Rwanda, about half of Burundi and parts of northwest Tanzania and southeast Uganda.

The basin has a general elevation of 1200–1600 m, but rises above 2500 m in the west, with peaks reaching 4500 m. The rainfall is less than 1000 mm over most of the eastern half of the basin but rises to over 1800 mm in the west, where most of the runoff is generated. Although the west is partly forested, much of the basin has become intensively cultivated, resulting in erosion and river sediment load from the high rainfall areas. The upper tributaries are generally steep but include flatter reaches where swamps have formed. The middle course of the river and its tributaries above Rusumo Falls is extremely convoluted; this reach reflects regional warping and drainage reversal, with some tributaries retaining the appearance of flowing towards the Congo. Several side valleys enter the river with their courses filled with either lakes or swamps. Between Kigali and Rusumo Falls (Plate 1) the slope diminishes from about 0.30 m km^{-1} to 0.05 m km^{-1}, and the valley is filled with papyrus swamp. Below the falls the Kagera flows north for 150 km flanked by a zone of lakes and swamps up to 15 km wide; it then turns east and flows across a plain in an incised channel before entering Lake Victoria through papyrus swamp.

There are two rainfall seasons, with the longer southeasterly monsoon bringing rain between about February and May, and the shorter northeasterly monsoon from about September to November. The runoff responds to the rainfall with a higher peak in May and a smaller peak in November. However, the river flows are attenuated by a number of lakes, and in particular by two sets of swamps and associated lakes above and below Rusumo Falls. The peak flow occurs in April in the upper tributaries, in May at Kigali and Rusumo Falls, but has been delayed to July at Kyaka Ferry on the lower Kagera. At this site the long-term mean runoff is relatively low at 136 mm compared with rainfall of 1170 mm. Near the western shore of Lake Victoria there is a belt with rainfall of over 2000 mm; the Ngono, draining this area of heavy rainfall, contributes a highly seasonal flow to the lower Kagera.

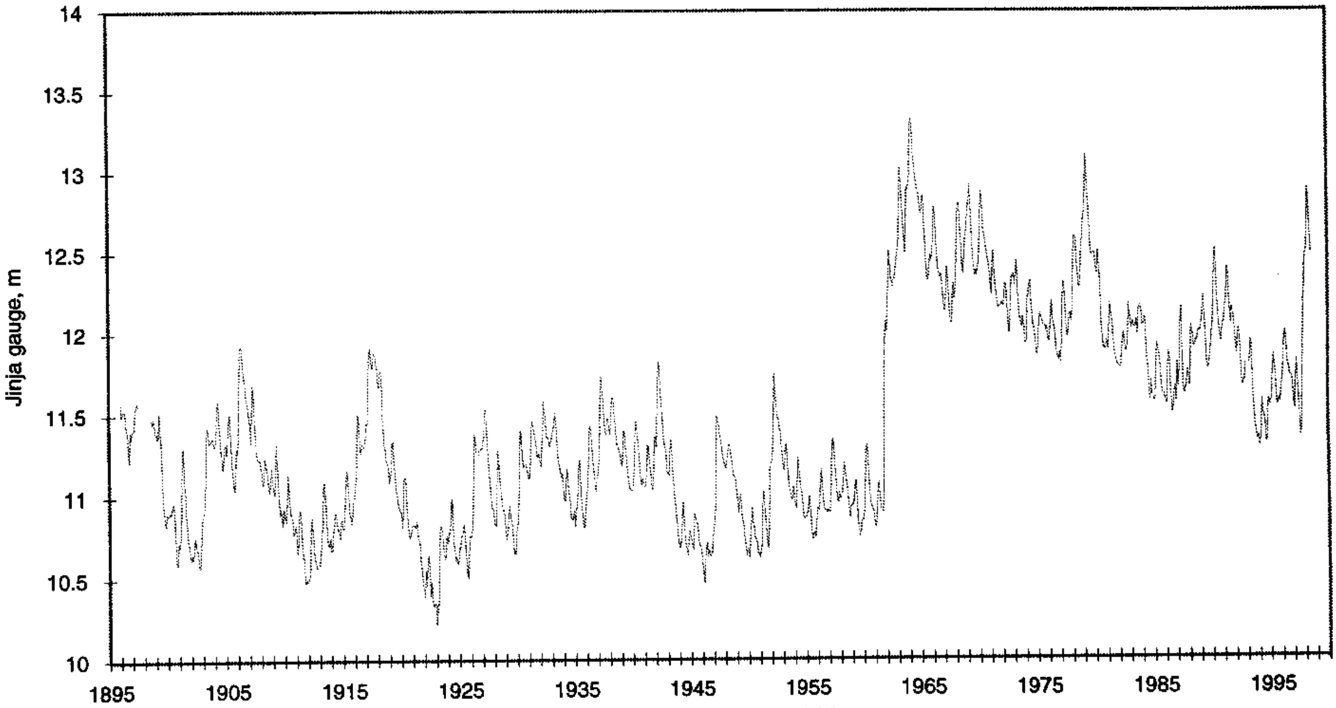


Fig. 3.2 Lake Victoria monthly levels, 1896–1998.

Plate 1 Kagera at Rusumo Falls.

The monthly flow series (Fig. 3.3) of the Kagera at Kyaka Ferry, or at Nyakanyasi some 80 km upstream, shows the high baseflow component of the Kagera flow, resulting from storage in lakes and swamps. This figure reveals that the seasonal rise, though pronounced, does not occur in all years. The most obvious feature of this series is the rise occurring after 1961, when the peak flows and also the baseflows increased markedly. The annual runoff doubled after 1961, although the basin rainfall only increased slightly; this illustrates the sensitivity of runoff in this regime to changes in rainfall amount and seasonal distribution. The timing of the Kagera flows is different from that of the other tributaries, mainly because of the wetland attenuation.

LAKES AND SWAMPS IN LOWER KAGERA

The river meanders through extensive areas of swamps and lakes both upstream and downstream of Rusumo Falls. Upstream of the falls papyrus swamps begin near Kigali where

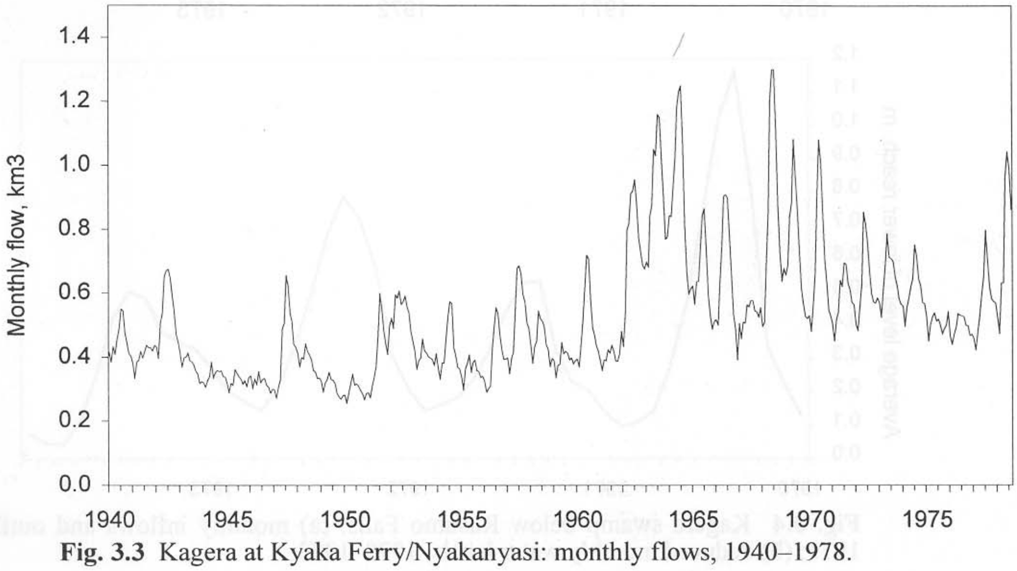


Fig. 3.3 Kagera at Kyaka Ferry/Nyakanyasi: monthly flows, 1940–1978.

the valley is some 0.5 km wide. The valley widens downstream of Kigali before narrowing again above the falls. The total area of swamps and lakes is about 1400 km^2. Below Rusumo Falls the Kagera flows north through about 1600 km^2 of swamps and lakes before turning east. The meandering channel is separated by dense papyrus from the lakes, some of which are near the river while others are comparatively isolated. However, there are usually hydraulic connections between the river and the lakes through channels or swamp.

It is possible to study the water balance of these two reaches by comparing inflows and outflows, rainfall and evaporation. For the lower reach, inflows are measured at Rusumo Falls and outflows at Kyaka Ferry, allowing for the Kagitumba inflows at the confluence. These flows (Fig. 3.4(a)) show the lag between the two sites. Rainfall and evaporation estimates have been included in a water balance expressed as water level changes over 1600 km^2. Figure 3.4(b) shows that the deduced levels for 1970–1973 exhibit an annual range of about 1 m and correspond with levels measured on Lake Ihema in 1970–1973. For the upper reach, similar comparisons (Sutcliffe, 1993) have shown that water level fluctuations are also about 1 m.

The vegetation distribution is consistent with these level ranges. In general, swamp and flood-plain vegetation require varying periods of flooding and are sensitive to range of

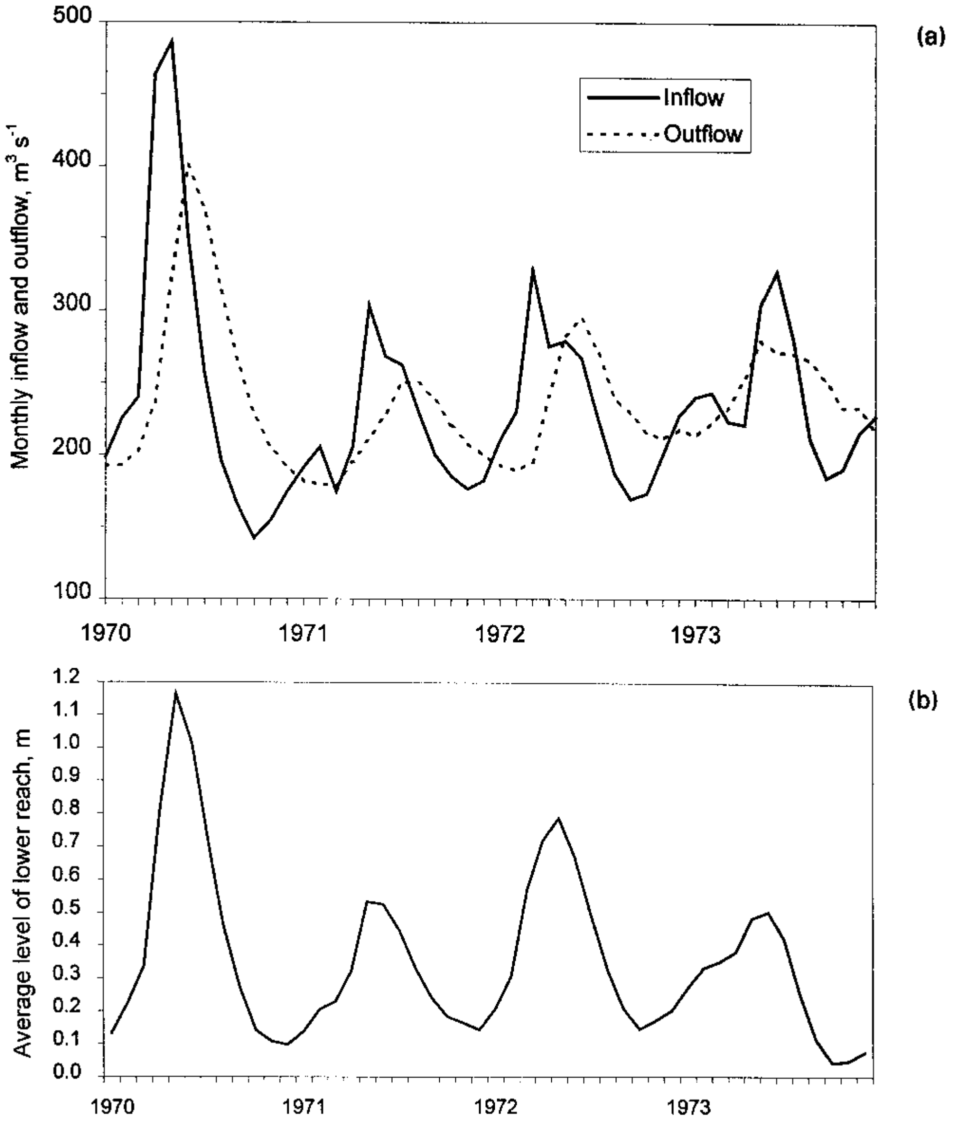


Fig. 3.4 Kagera swamp below Rusumo Falls: (a) monthly inflows and outflows, 1970–1973; (b) deduced monthly water levels, 1970–1973.

flooding level. Evidence from the Bahr el Jebel (Sutcliffe, 1974; Sutcliffe & Parks, 1996) showed that papyrus is limited by range of flooding, that *Vossia* can tolerate faster currents, and that *Echinochloa pyramidalis* is limited by depth of flooding. Above Rusumo Falls the river valleys are filled with papyrus swamps and lakes. Immediately below the falls the range of water level is probably higher and papyrus is absent except in off-stream basins, with *Vossia* along the river bank. Further down the lower reach, where the river floods a succession of papyrus swamps and lakes, there is a strip of *Vossia* near the river and *Echinochloa pyramidalis* along the shoreline away from the river, where the ground rises steeply from the lake or swamp. The growth of papyrus was less vigorous in the lower end of the reach, where the nutrient supply would be least. This distribution, observed in 1980 (Sutcliffe & Mhlanga, 1980), is consistent with findings from the Bahr el Jebel. The links between swamp vegetation and hydrology are discussed more fully in Chapter 5.

CONTRIBUTION OF OTHER TRIBUTARIES

Although the Kagera provides the largest component of the tributary inflow to Lake Victoria, a large number of other streams flow into the lake and together contribute twice that from the Kagera alone. Moreover, the annual variability of this input is exaggerated, because the runoff coefficient increases with basin rainfall. Thus the variability of the tributary inflow component of the lake balance is greater than that of direct rainfall on the lake. Indeed, earlier difficulties in explaining the historical lake level variations have partly stemmed from underestimation of the variability of this tributary inflow.

Rainfall records around the lake illustrate the rainfall regime in the contributing basins. Monthly averages at key stations (Table 3.1) show that the bimodal distribution is common to all, with the main rainfall season occurring from March to May and a secondary season from October to December. There are differences in the relative magnitude and the timing of these two seasons around the lake, and there is in particular evidence at Kisumu and Jinja of higher rainfall in July and August which is more marked in the northeastern tributary basins. There is also a contrast between the heavy rainfall in the west and northwest of the lake, at Bukoba and Kalangala, and the lower rainfall in the southeast, at Musoma, where the dry seasons in June–August and January–February are more marked.

Table 3.1 Mean rainfall at key stations, 1956–1978, mm (after Piper *et al.*, 1986).

Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Jinja												
64	85	141	195	140	69	70	83	100	141	161	87	1336
Entebbe												
88	101	179	260	235	121	69	79	72	126	179	111	1620
Kalangala												
135	137	239	340	322	162	96	94	114	159	210	208	2216
Bukoba												
150	180	254	398	316	89	51	66	102	153	195	193	2147
Kagondo												
119	152	219	362	234	47	26	40	94	115	201	161	1770
Mwanza												
102	114	156	177	71	16	15	21	25	99	158	146	1100
Musoma												
59	84	123	182	101	24	21	22	31	53	117	78	895
Kisumu												
71	98	155	234	175	79	63	90	84	87	139	102	1377

The tributary flows reflect this rainfall distribution; the runoff patterns are highly seasonal and accentuate the seasonal rainfall. The individual monthly totals for the whole period of record are included in a report by the UK Institute of Hydrology (1984, Fig. 2.7), but are not reproduced here. The flows of the Nzoia reflect more clearly than the other rivers the July–August rainfall to the northeast of the lake, superimposed on the effect of the other seasonal variations. The Yala and the Sondu reveal a greater proportion of baseflow; to the south, the Gucha shows much greater variability of flow and the dominant influence of the March–April rainfall season. Further south still the Mara, Rwana and Simyu show similar seasonal patterns but even less flow in the dry season. The other tributaries have an earlier peak and less baseflow than the Kagera, as they do not have the same extent of lakes and swamps. However, several tributaries, especially in Uganda, enter the lake through swamps, with estimated areas totalling 2600 km^2 (Brown *et al.*, 1979). In recent years many of the bays around the shore have been invaded by water hyacinth *(Eichhornia crassipes)*; the influence on the lake water balance will depend on its extent.

The average annual inflows of the different tributaries for the period of records, expressed as mm over the basin, are compared with basin rainfall deduced from isohyetal maps in

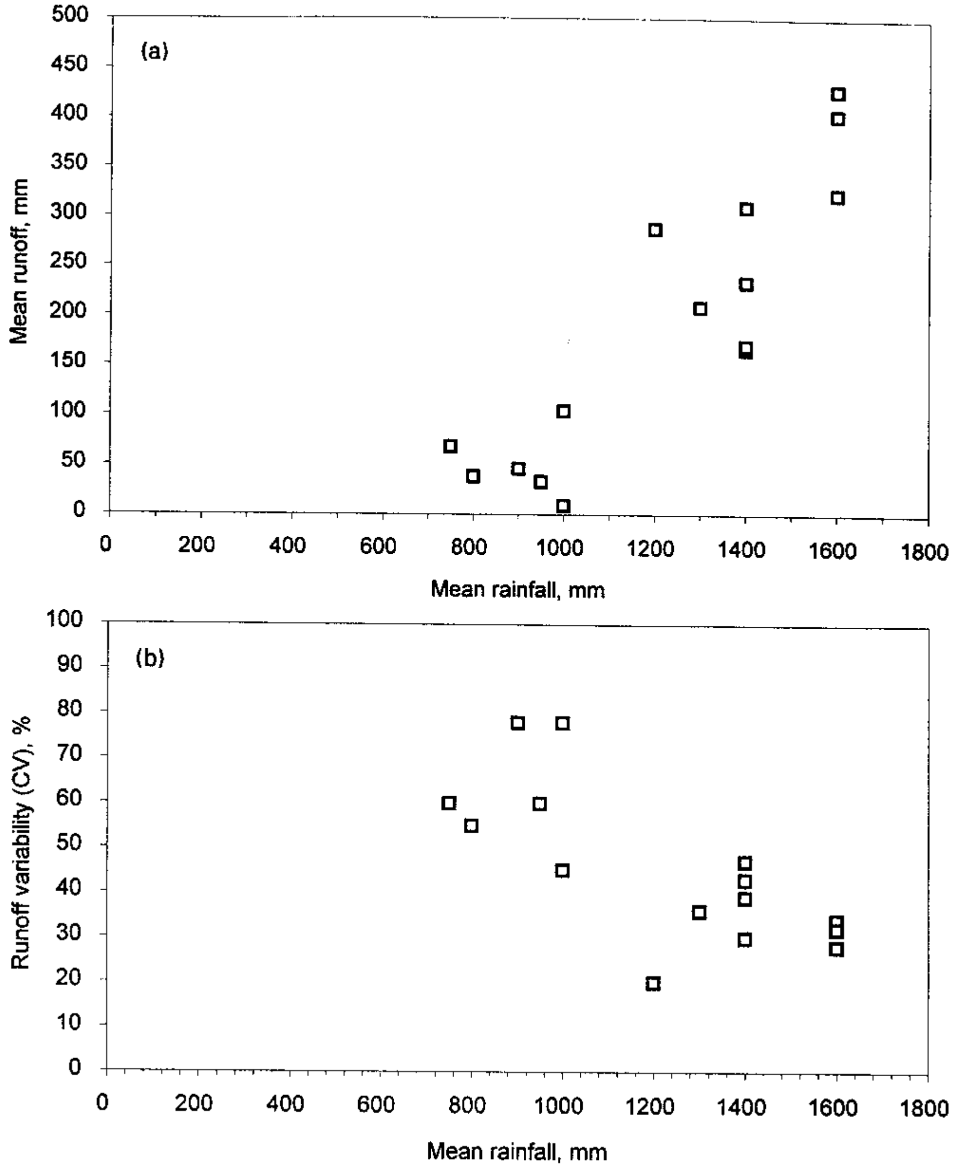


Fig. 3.5 Lake Victoria tributaries: (a) mean runoff and mean rainfall; (b) runoff variability and mean rainfall.

Fig. 3.5(a). It is clear that the average runoff from these tributaries is closely related to the average rainfall. On the other hand, the variability of annual runoff, expressed as the coefficient of variation, is inversely related (Fig. 3.5(b)) to mean rainfall. As expected, the drier tributaries have lower but more variable runoff than the wetter tributaries.

In order to estimate the total tributary inflow series it was possible to compare a short period with total flows against a longer period with some records. There are almost complete records of the tributaries measured by the WMO Hydrometeorological Survey for the period 1969–1978, and the runoff from the ungauged perimeter of the lake was estimated from the relation between mean rainfall and runoff. In addition, the flows of four major tributaries in the northeast of the lake—the Nzoia, Yala, Sondu and Awash Kaboun—are available for the period 1956–1978, with some short gaps filled by comparison. The total flows of the four tributaries were compared (Institute of Hydrology, 1985) with the total tributary runoff (excluding the Kagera and Ngono whose regime was different). The ratio between the flows of the four Kenyan tributaries and the total inflow was found to vary seasonally, and monthly multipliers were calculated to extend the total tributary runoff from the flows of the four tributaries. The mean seasonal distribution of the total tributary inflow for the period 1956–1978, including the Kagera, is expressed as volumes and as mm over the lake in Table 3.2. The average tributary inflow of 343 mm over the lake is only about 15% of the total supply to the lake, which is dominated by the rainfall component. However, because runoff coefficients increase with rainfall amount, runoff is more variable than the rainfall from which it is derived. The monthly flows for the years 1956–1978 are shown in Fig. 3.6 and the annual totals summarized in Table 3.3. Just as the Kagera flows increased after 1961, so the total tributary flows increased by about 50%. The variability of the tributary inflow is in percentage terms about three times higher than that of rainfall. Thus this component is important to the water balance of the lake.

RAINFALL OVER LAKE VICTORIA

The rainfall over the lake surface provides the greater part, on average about 85%, of the input to the lake water balance. However, it is not easy to estimate this rainfall as the only regular

Table 3.2 Monthly components of Lake Victoria balance, 1956–1978.

Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Lake rainfall (mm)												
138	153	228	309	208	71	52	68	104	157	201	170	1 858
Kagera inflow ($m^3 \times 10^6$)												
511	481	570	611	743	765	780	711	616	571	527	531	7 418
Total tributary inflow ($m^3 \times 10^6$)												
1330	1059	1542	2714	3217	2107	1981	2098	1948	1570	1678	1738	22 982
Total inflow (mm over lake of 67 000 km^2)												
19.9	15.8	23.0	40.5	48.0	31.4	29.6	31.3	29.1	23.4	25.0	25.9	343.0
Lake evaporation (mm)												
135	135	145	130	125	120	125	135	140	145	130	130	1 595
Lake outflow ($m^3 \times 10^6$)												
2902	2619	2884	2920	3182	3136	3093	2976	2859	2855	2736	2973	35 136
Lake outflow (mm over 67 000 km^2)												
43.3	39.1	43.0	43.6	47.5	46.8	46.2	44.4	42.7	42.6	40.8	44.4	524.4
Lake level (m on Jinja gauge)												
11.93	11.93	11.99	12.15	12.23	12.16	12.06	11.98	11.92	11.90	11.97	12.01	

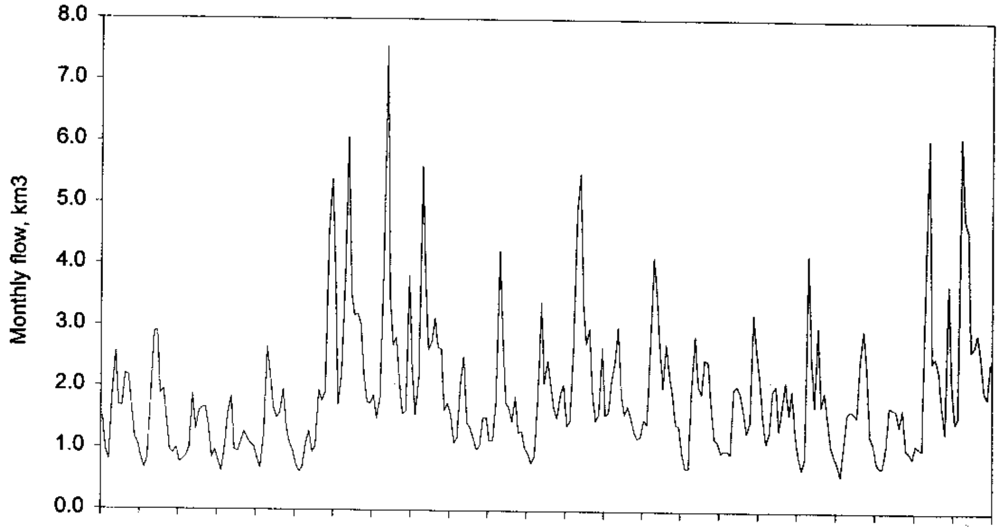


Fig. 3.6 Lake Victoria tributaries: monthly inflows, 1956–1978.

measurements have been around the lake perimeter. There are only eight stations with records since 1925 or earlier, and these have been used by various authors to estimate the rainfall over the lake. This approach has the advantage that a reasonably homogeneous set of records can be used to monitor rainfall variations from year to year.

Table 3.3 Annual water balance of Lake Victoria, 1956–1978.

Year	Lake rainfall (mm)	Kagera inflow ($m^3 \times 10^6$)	Total inflow: ($m^3 \times 10^6$)	(mm)	Outflow: ($m^3 \times 10^6$)	(mm)	Lake level (m)
1956	1787	4 918	19 326	288	19 636	293	10.91
1957	1727	6 299	18 121	270	20 112	300	11.02
1958	1622	5 412	14 629	218	19 671	294	10.94
1959	1702	4 730	13 310	199	18 434	275	10.84
1960	1827	6 160	17 526	262	20 348	304	10.87
1961	2370	4 895	21 856	326	20 577	307	11.94
1962	1919	9 114	36 136	539	38 716	578	12.39
1963	2121	10 941	34 664	517	44 788	668	12.91
1964	2011	11 045	32 332	483	50 476	753	12.88
1965	1663	7 760	17 428	260	46 878	700	12.48
1966	1889	7 951	21 435	320	42 950	641	12.32
1967	1752	6 421	21 448	320	37 832	565	12.31
1968	2114	10 375	32 600	487	43 305	646	12.58
1969	1770	8 923	21 083	315	46 006	687	12.36
1970	1865	8 477	27 572	412	44 282	661	12.45
1971	1639	7 030	20 139	301	39510	590	12.17
1972	1975	7 587	19 950	298	37 540	560	12.35
1973	1749	7 717	19 982	298	38 467	574	12.05
1974	1657	7 331	20 946	313	35 046	523	11.97
1975	1826	6 082	18 968	283	33 326	497	12.04
1976	1781	5 932	14 409	215	34 835	520	11.82
1977	1938	6 980	29 147	435	35 999	537	12.13
1978	2041	8 525	35 575	531	39 383	588	12.56
Mean	1858	7 418	22 982	343	35 136	524	
SD	180	1799	6908	103	9976	149	
CV (%)	9.7	24.2	30.1	30.1	28.4	28.4	

Sources: Lake rainfall and outflow from Institute of Hydrology (1993): Kagera inflow from *The Nile Basin* and WMO (1982); total inflow from Institute of Hydrology (1985).

The problem of estimation is complicated because evidence from the timing of rainfall on different shores, supported by rainfall observations from island stations, suggests that rainfall over the lake itself is higher than at the lakeside stations. The incidence of rainfall is linked with the seasonal migration of the InterTropical Convergence Zone (ITCZ) which gives rise to two rainy seasons in about March–May and October–December. The atmospheric circulation over Lake Victoria is approximately from east to west but is strongly influenced by onshore and offshore breezes generated by the lake itself. This local circulation frequently results in the formation of cumulonimbus clouds over the southwestern portion of the lake and in a narrow strip of land some 30 km wide around the shore (Channon, 1968).

The impact of the lake has been illustrated by measurements of rainfall near its centre, which indicated rainfall some 30% higher than observed at any lakeshore station. This is consistent with a model (Datta, 1981) in which the maximum rainfall on the west coast and the western centre of the lake is caused by convergence and lifting of westerly land breezes and prevailing easterlies. This interaction gives rise to convection storms in the morning on the western shore and in the evening on the eastern shore. This effect has been estimated to double the rainfall which would have occurred if the lake were not present (Flohn & Burkhardt, 1985).

In an early attempt to take account of this increase over the lake, de Baulny & Baker (1970) assumed that rainfall over the lake was fairly uniform with gradients around the shore. They used the eight long-term rainfall stations with monthly weighting coefficients to reconstruct a rainfall record for the period 1925–1969. However, when this technique was used by the Institute of Hydrology (1984) to extend the series to 1979, it was found that the coefficients gave particular weight to the higher rainfall stations and gave a series which did not reflect the increased rainfall of the later years.

In a further review, the Institute of Hydrology (1985) argued that the set of eight long-term gauges, after quality control had corrected some inconsistencies, provided the best basic data for estimating the lake rainfall series. However, they used the lake itself to measure rainfall by a water balance approach. Comparison of individual rainfall records with the inferred lake rainfall suggested that a reasonable series could be derived after normalizing each record in terms of its mean and standard deviation. The estimated mean annual lake rainfall was multiplied by the mean of the normalized series with the deviations enhanced by a factor of 1.3, on the assumption that taking the mean of the normalized series reduced its variability. This provided a monthly rainfall series based on continuous records. It could be argued that this procedure was somewhat arbitrary and even circular, but this rainfall series provided a reasonable answer not only to the problem of average water balance, which followed from the procedure, but also to the variations over the record period.

In a later study (Institute of Hydrology, 1993; Sene & Plinston, 1994) direct comparison between the lakeside rainfall and net lake rainfall for calendar months deduced from water balance for 1969–1978 suggested that they were linearly related. Rainfall series were derived for 1925–1990 using constant evaporation estimates. This lake rainfall series for 1956–1978 (Table 3.3) shows that there has been a trend to higher rainfall. This is largely explained by an increase in rainfall in October and November, according to Farmer (1981), who suggested a shift in East African rainfall after the heavy rains of 1961/62, and noted that the mean rainfall since then has been significantly above the mean for the previous 30-year period. Longer-term trends in rainfall are discussed at the end of this chapter.

EVAPORATION

A number of approaches have been used to estimate evaporation from the lake surface. WMO (1982) compared pan evaporation estimates, a water balance for the period 1970–1974, a heat budget method and models using global solar radiation. These different methods gave results which agreed reasonably well in annual total but not in monthly distribution. The estimation of evaporation from a lake of this size is complicated by the seasonal effect of heat storage and the difficulties of measuring small changes in monthly lake level. Because it is not possible in practice to differentiate between underestimates of rainfall and overestimates of evaporation, the choice of estimate becomes somewhat arbitrary. It is believed that variations of evaporation from year to year are likely to be relatively small, so the estimates of monthly evaporation used by the Institute of Hydrology (1985) were based on monthly averages obtained by the Penman method for stations around the lake. The monthly values were adjusted slightly so that the annual total approximated to the WMO estimates. The resulting estimates are given in Table 3.2.

LAKE LEVELS

Lake Victoria levels have been measured regularly since 1896, with a gap in 1897–1898. Early records at Entebbe and other sites were converted to equivalent level series at Jinja, near the outfall from the lake. The resulting end-month levels (Fig. 3.2) fluctuated from 1896 to 1960 between 10.2 and 12.0 m on the Jinja gauge. There were rises in 1906 and 1917, but the lake was relatively stable before 1961. The rise of almost 2.5 m between October 1961 and May 1964 is the most prominent feature of the whole series. Since 1964 the lake level trend has been generally downwards, with an interruption in 1979 when a peak of 13.0 m was reached. By 1995 the lake had fallen to 11.5 m, near the long-term mean of the series, but nearly reached 13.0 m in early 1998.

As mentioned earlier, the rise in 1961–1964 focussed attention on the cause, and led to the WMO Hydrometeorological Survey of the lake regime which provided most of the available measurements. After this event the evidence of earlier lake levels was examined to investigate whether any precedents for the rise existed, and this evidence is discussed at the end of this chapter.

LAKE VICTORIA OUTFLOWS

The outflows from Lake Victoria were controlled naturally by the Ripon Falls until the construction, some 3 km downstream, of the Owen Falls dam, which was begun in 1951 with the construction of a coffer dam. Although there is evidence of erosion over long periods, it can be assumed that the relation between lake level and outflow has been stable over the historical period.

The relation was studied at the time of the construction of the Owen Falls dam, because its operation was the subject of negotiation between Uganda and Egypt. It was agreed that the dam would be operated on a run-of-river basis, so that the flows of the White Nile, which provided the so-called "timely flows" (see Preface) would not be affected by the project. It was necessary to establish a rating curve between lake level and outflow which could be used as an operating rule. After study of the gaugings which had been made at Namasagali some 80 km downstream of the lake, an "Agreed Curve" was established. This relation is illustrated by Fig. 3.7 comparing gaugings from 1923 to 1950 with simultaneous Jinja levels.

Although flows through the Owen Falls site were reduced temporarily during construction, this Agreed Curve has been followed over periods of 10 days to a month. However, after 1961–1964, the lake level rose above the limit of the gaugings on which the curve was based, and a linear extrapolation was used until 1967. A model investigation was carried out at the Hydraulics Research Station, Wallingford (1966), based on surveys of the

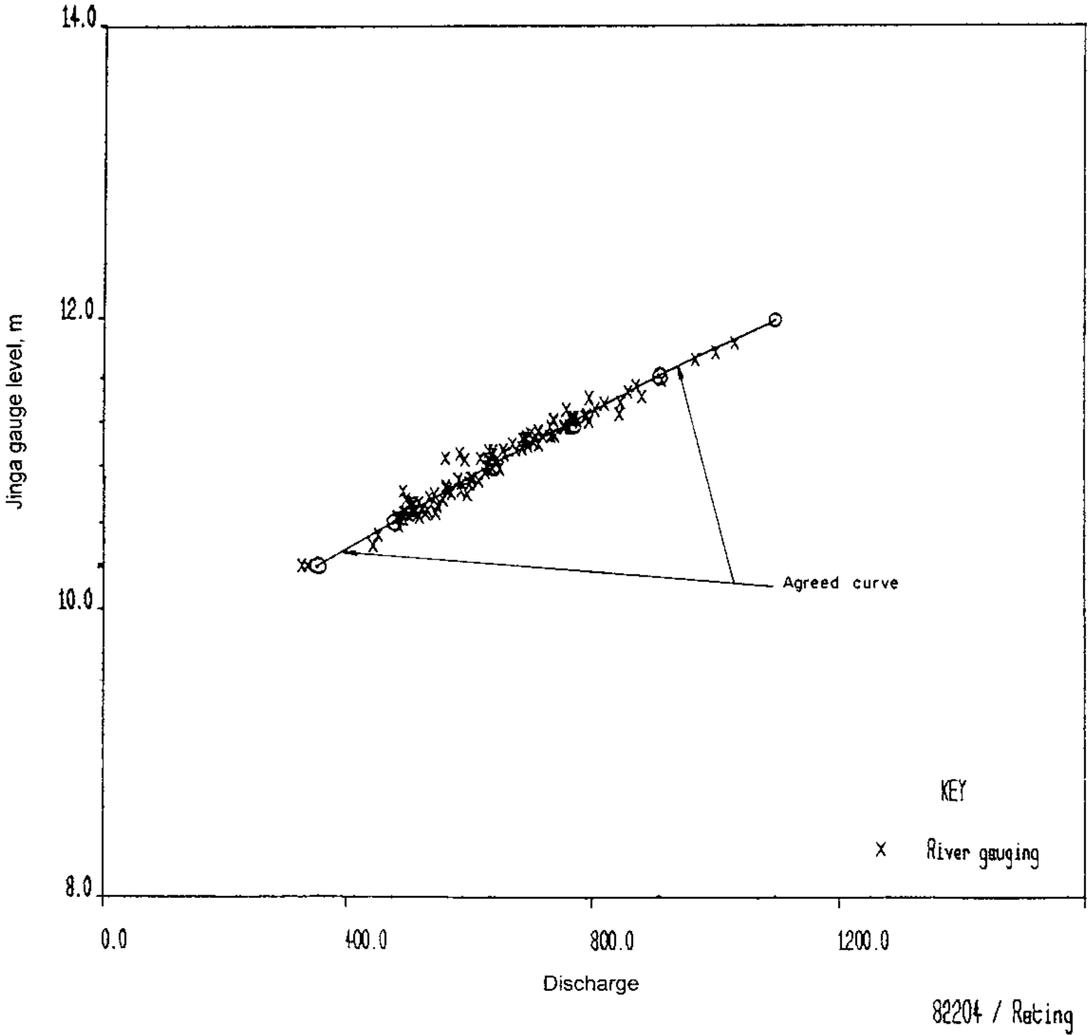


Fig. 3.7 Agreed Curve and gaugings (m^3 s^{-1}) at Namasagali, 1923–1950.

site. A curve was derived which fitted the Agreed Curve where it was supported by gaugings and was extrapolated in accordance with site conditions. Once this adjusted curve was accepted in 1968, the outflows were raised in accordance and the net cumulative effect of the dam has been shown to be small (Kite, 1981).

Recently, a detailed study was carried out by the Institute of Hydrology (Sene & Plinston, 1994). They compared three different estimates for the lake outflows after the completion of the Owen Falls dam. The first estimate is based on observed lake levels and the Agreed Curve; the second on the turbine flows and sluice releases for the period from 1957 to 1991; the third on interpolations between individual discharge measurements at Namasagali and Mbulamuti. These comparisons confirmed that there were shortfalls in the outflow in 1952–1954, during the construction of the dam, and in 1962–1967, when the linear extrapolation of the Agreed Curve was being used. Other differences occurred in the late 1970s and early 1980s, but the cumulative effect of these differences on lake levels was small.

Thus the best estimate of outflow from the lake was considered to be obtained from the lake levels and Agreed Curve for the period 1896–1939; from the Namasagali discharge measurements for the period 1940–1956; and from the turbine/sluice releases after 1956. These sources were used to compile a composite record (Sene & Plinston, 1994) and have been brought up to date in Fig. 3.8. Studies of the Namasagali discharge measurements and comparisons of the revised outflow records with independent flow records downstream led to the conclusion that the Agreed Curve is reasonable and provides a good estimate of the lake outflows for the whole early period of record.

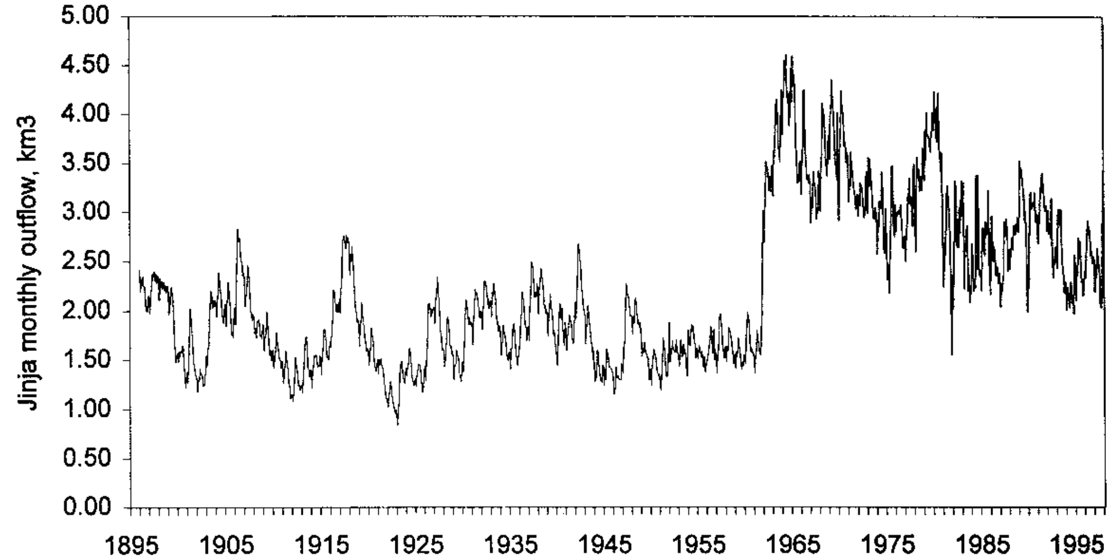


Fig. 3.8 Lake Victoria monthly outflows, 1896–1997.

This outflow record provides the longest flow series in the White Nile basin, and forms the basis for studies of the regime of the lakes and wetlands downstream of Lake Victoria. In order to understand the physical causes of the fluctuations of this important component of the river flows, it is desirable to compare the fluctuations of lake levels and lake outflows with the water balance of the lake basin. This has also been the subject of various investigations over the years, and some of these studies are described in the next section.

WATER BALANCE OF LAKE VICTORIA

The regime of Lake Victoria has been the subject of enquiry since the first quantitative study of Hurst & Phillips (1938), who set in train the measurements on which subsequent studies have been based.

The rise in the lake level in 1961–1964 led to several studies of the available data in attempts to explain the rise. Morth (1967) studied the relations between monthly rainfall and lake level changes. He used the average rainfall over all available stations, which grew from 150 in 1938 to 300 in 1963. He obtained reasonable relations for each calendar month, but the rainfall coverage used was uneven and not consistent over the whole period.

A more comprehensive study by de Baulny & Baker (1970) dealt with the components of the balance. They produced monthly isohyetal maps for the lake and deduced a mean rainfall of 1650 mm; they derived a monthly rainfall series from the records of eight long-term stations around the lake. Their series was brought up to date and reproduced by the Institute of Hydrology (1984); the annual totals ranged from 1281 mm in 1949 to 2201 mm in 1961. Tributary inflows were tabulated for the period 1959–1967, but the source of these flows is unclear. Changes of storage were deduced from gauge records and outflows were calculated from Jinja levels. A comparison between lake rainfall and deduced evaporation suggested that evaporation increased with rainfall until rainfall reached 1650 mm and then decreased. However, the evaporation term included all the uncertainties of measurement and it seems likely that high rainfall totals or inflows were underestimated.

The WMO/UNDP Hydrometeorological Survey

In these early studies the main sources of uncertainty had been the rainfall over the lake and the tributary inflow, and the first priority of the WMO Hydrometeorological Survey which started work in 1967 was to measure these. A network was established (WMO, 1974) which included 25 meteorological stations, 200 rainfall stations, and 45 streamgauging stations. A Data Centre was established and a series of yearbooks compiled. Seven index basins were chosen for study of rainfall–runoff relationships.

The report of Phase I of the survey used measured lake inflows for the years 1969 and 1970 to estimate the water balance. It was concluded that in a normal year lake rainfall is 50% higher than over the land basin, that lake rainfall exceeds evaporation by about 10%, and that direct rainfall is about six times the inflow and three times the outflow. Rainfall records showed that wet years are associated with heavy rainfall in the October–December season.

In Phase II the survey also developed mathematical models of the Nile system, and studied alternative patterns of regulation of the East African lakes. A monthly water balance of Lake Victoria for the years 1950–1980 used lake rainfall, evaporation and tributary inflow data to estimate lake levels and lake outflows (Kite, 1981, 1982; WMO, 1982). However, this balance did not reproduce the observed rise in lake level, and the basic data were re-examined. They used the de Baulny & Baker (1970) estimates for the years 1925–1969, isohyetal maps of shore and island stations for 1970–1977, and the mean of eight stations for 1978–1979. A detailed study of the years 1977–1980 showed that the observed rise of 1.5 m in lake level could have been caused by rainfall 25–30% higher than recorded. The tributary inflow data were also scarce in the early years and were estimated from Kagera flows. The only possible manmade cause was the Owen Falls dam, but it was found that this caused a rise of only 0.03 m over the period 1957–1980. Although the rise must therefore have been due to natural causes, neither a simple water balance nor the use of a mathematical model was able to reproduce it; this was attributed to inaccurate knowledge of lake rainfall and evaporation.

Retrospective analysis of the failure to explain the rise suggests that it was difficult to estimate accurately the increase in lake rainfall using the de Baulny & Baker method in the early years, and a different method for the later years; further, the de Baulny & Baker technique appears to underestimate rainfall in wet years. It also seems that the importance of the variability of tributary inflow was underestimated. It was claimed that the annual total inflows for the early years (1950–1958) were estimated by correlation with the Kagera flows. In fact the estimated inflows for these years apart from the Kagera varied only from 498 to 502 $m^3 s^{-1}$, and the variability was therefore greatly underestimated. In addition, the inflows for 1959–1967 were taken from de Baulny & Baker, and their derivation is unclear as measurements had not begun. In fact the tributary inflow should be more variable than the rainfall itself, because of the sensitivity of the rainfall/runoff process, and this damping of inflow variability must have been an obstacle to realistic modelling.

Reviews by the Institute of Hydrology

The Institute of Hydrology, in a series of reviews of the Lake Victoria water balance, was able to take advantage of the earlier measurements and analyses, in particular the evaporation estimates, the study of rainfall mechanism and the tributary measurements of the WMO Hydrometeorological Survey.

The way in which a consistent lake rainfall series was derived from the eight long-term stations was described earlier. The individual rainfall series were normalized and averaged to give an index which was multiplied by the average lake rainfall (Institute of Hydrology, 1985); the deviations from the mean were enhanced by 1.3 to overcome the effect of averaging on the overall variability. A later series (Institute of Hydrology, 1993) was derived by calendar month comparisons of lake-side rainfall and net rainfall deduced from lake balance. Lake evaporation was based on mean estimates for the period 1970–1974. The tributary inflows were based on actual measurements covering the period 1969–1978 for nearly all the tributaries, and measurements for four of the major Kenya tributaries for the longer period 1956–1978. The shorter series were extended to cover the period of the longer records using the monthly proportions of the long records to the total inflow during the joint period. The Kagera, with its different regime, was treated separately. Excellent results were obtained from a monthly water balance model (Institute of Hydrology, 1985; Piper *et al.*, 1986). The outflow records were originally based on the Jinja levels and the Agreed Curve, but in recent studies the actual turbine/sluice releases have been substituted.

When these components of the water balance are used to estimate the expected annual rise or fall in lake levels and are compared with the measured levels, the correspondence between model and measured levels is close. Reasonable results (Sene & Plinston, 1994) have been obtained for monthly water balances for the period 1956–1990, for the period 1925–1990 by extending inflows using a conceptual model, and also for an annual water balance for the longer period 1900–1990 with inflows estimated from lake rainfall. It may therefore be concluded that the problem of the regime of Lake Victoria, and in particular the rise of 1961–1964, has been satisfactorily explained as being largely due to an unusual variation in rainfall. Recently, Yin & Nicholson (1998) have suggested that variations in lake evaporation are sensitive to climate input, including cloud cover, and that these should be investigated.

The seasonal lake balance can be illustrated by Table 3.2, where the monthly components of the balance are compared with the lake level. The components of the annual lake balance, including their means and standard deviations, are listed in Table 3.3 for the most reliable period 1956–1978. The annual predicted and observed lake levels are compared in Fig. 3.9. It is clear that although the rainfall is the main component of the inflow, the tributary inflow is important in terms of its average, but even more because of its contribution to the variability of the inflow. The sensitivity of the lake balance can be explained by the similarity of average lake rainfall and evaporation, and the sensitivity of tributary inflow to high rainfall. Both the seasonal fluctuations and the longer-term variability of the Lake Victoria outflows are illustrated by the average flows for different periods summarized in Table 3.4. This shows the similarity of the periods 1901–1930 and 1931–1960, and the near doubling of outflows in the 1961–1990 period.

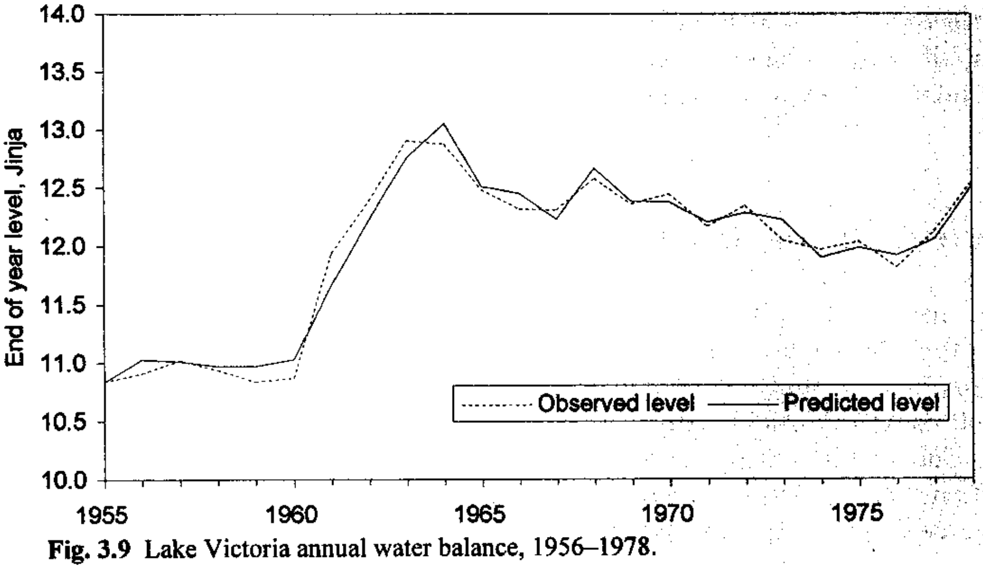


Fig. 3.9 Lake Victoria annual water balance, 1956–1978.

Table 3.4 Monthly mean Lake Victoria outflows for various periods ($m^3 \times 10^6$).

Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
1901–1930												
1640	1485	1659	1716	1926	1890	1854	1751	1634	1643	1577	1653	20 428
1931–1960												
1693	1536	1719	1755	1929	1908	1878	1792	1691	1699	1606	1684	20 888
1961–1990												
3056	2811	3146	3099	3331	3276	3314	3242	3073	3120	2955	3073	37 497
1901–1995												
2157	1968	2204	2214	2417	2376	2378	2282	2150	2170	2063	2160	26 539

LONG-TERM LAKE VICTORIA BALANCE

It is possible to take the study of Lake Victoria hydrology back before the start of historic lake levels by using indirect evidence. Lamb (1966) described the evidence for high Lake Victoria levels 10–20 years before the lake level gauges were installed in 1896. He noted that Catholic missionaries in Buganda reported that around 1876–1880 the average water level was about 8 feet (2.4 m) higher than in 1898, which would be as high or higher than the 1964 peak. The most thorough assembly of evidence was compiled by Lyons (1906) who took part in Garstin's (1904) expedition to the upper Nile and contributed an appendix to this report. He provided a number of travellers' observations of the very high level in August 1878 and a fall of 8–9 feet (2.5 m) by 1891, followed by a rise in 1892–1895 and a period of falling levels from 1896 to 1902. He was able to provide evidence of a rise about 1850 which inundated areas which were uncovered about 1890. The 1878 peak was supported by observations of flooding at Lado on the Bahr el Jebel, where levels were still high in December after a peak in August 1878, pointing to an unusually high level of Lake Albert and thus Lake Victoria (Lyons, 1906, p. 103).

There is indirect evidence from downstream to support these high levels. The flooding in the Sudd is known to have been more widespread at the end of the nineteenth century than in the early years of the twentieth century. Hurst & Phillips (1938), in discussing the outflows from Lake Albert, pointed out that the average discharge at Aswan from 1871 to 1898 was much greater than the average from 1899 to 1936, and they deduced that part of the cause would have been higher outflows from the lakes. They "infer that from 1870 to 1900 high floods seem to have been more common than in the period following 1900". The historic level records measured at Khartoum from 1869 to 1883 near the confluence of the White and Blue Niles show a very high level in May 1879, indicating high lake outflows in 1878. In the context of flood control, the Jonglei Investigation Team (1948) noted a "remarkable series of high floods" at the end of the nineteenth century, and pointed out that the 1878 flood was larger than that of 1917, quoting several early travellers and the history of Sudd blockages. There is evidence from the Sudd that these floods affected the Nuer of the Bahr el Zeraf; "the high flood of 1878 contributed to a major internal conflict among the Gaawar, and the continuous high levels of 1892–1896 encouraged the Bar Gaawar to occupy the northern half of the Duk ridge" (Howell *et al.*, 1988, p. 217). Johnson (1992) has presented a chronology of floods on the Bahr el Jebel based on oral and contemporary sources; the local impacts of the floods of 1878, 1895, 1917 and 1961–1964 are described in graphic detail.

Flohn & Burkhardt (1985) have attempted a tentative reconstruction of lake levels for the period 1870–1898 from observed Aswan low season flows. They deduce from statistical trials that the low season discharge at Aswan is controlled about half by the baseflow from the previous Blue Nile flood and half by the Lake Victoria level at the end of the previous year.

They provide lake series with peaks in 1878 and 1892–1895 which correspond fairly closely with those deduced from subjective evidence by Lyons. Thus there is strong evidence that the rise in Lake Victoria in 1961–1964 was not unique and has been equalled, in level if not in duration, less than a century before.

These variations are consistent with trends in East African rainfall over a longer time scale, which have been described by Nicholson (1980, 1989). Historical accounts and observations suggest a period of frequent but short dry episodes in the mid 1800s, a relatively wet period between the 1870s and 1890s and an abrupt continent-wide decrease starting in 1895 and lasting until the 1910s. Since then dry periods have occurred around 1920, in the 1940s and 1950s and the early 1970s, with wet periods in the 1960s and the late 1970s. A number of reasons have been put forward for these fluctuations, including sea surface temperatures and sunspot activity (Mason, 1993), but research is still required on this topic. The scale is such that they have important water resources implications and therefore research could help with global trends.

One question which arises from this evidence is whether an upper bound exists to the lake level fluctuations in the more distant past. The most direct evidence for such an upper limit is provided by evidence from an excavated cave (Plate 2) near Entebbe. Beach sands overlain by occupation debris in the mouth of Hippo Bay cave (near the southern end of the runway at Entebbe airport) were found to contain water-rolled fragments of charcoal distributed throughout the sands; a sample of charcoal was dated as 3720 ± 120 years BP (before present) (Bishop, 1969). The evidence of the excavation (Brachi, 1960) suggested that "the sand was deposited and the charcoal fragments incorporated at a time when Lake Victoria stood at least nine feet higher than at present". Unlike higher strand lines around Lake Victoria which show signs of tilting due to earth movement, the Hippo Bay level maintains a constant height above the lake. Therefore comparison of levels at the cave site with those at the lake outlet at Ripon Falls, are relevant though it should be remembered that downcutting will have occurred at Ripon Falls since the deposition of the sands in the Hippo Bay cave.

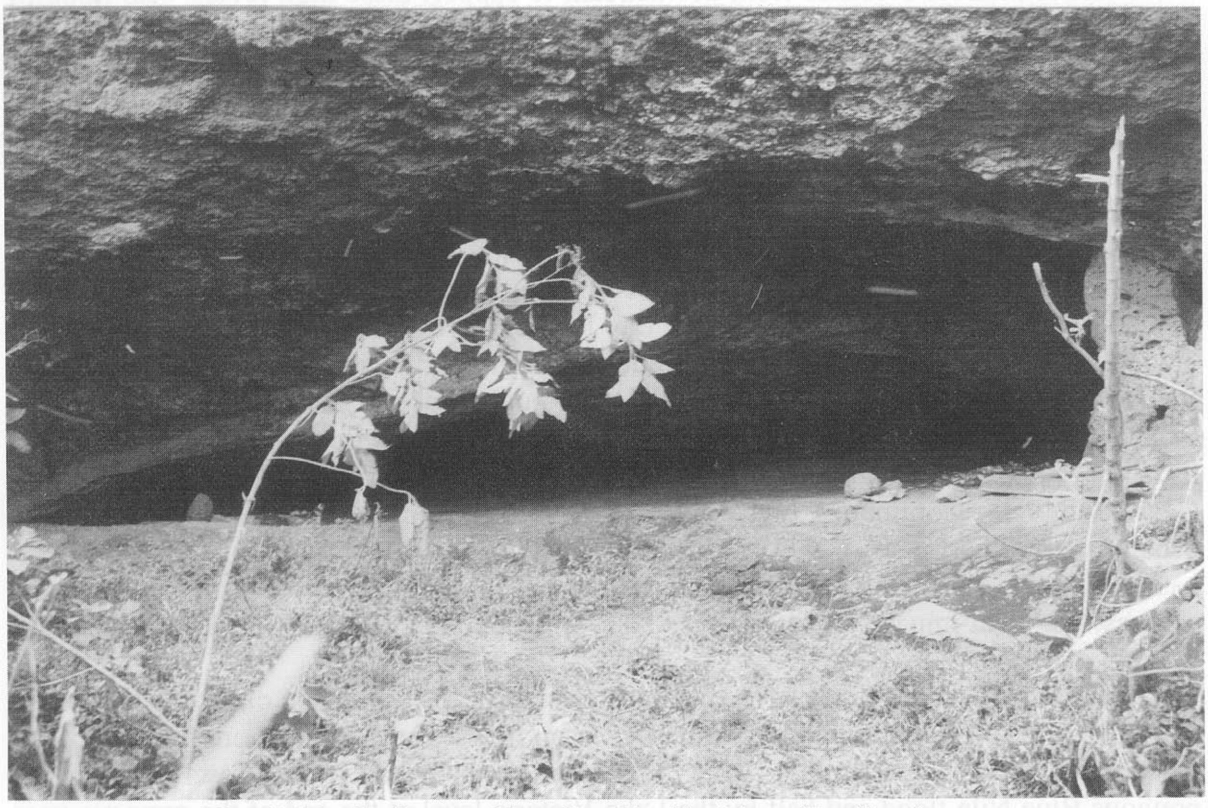


Plate 2 Mouth of cave at Hippo Bay, Entebbe (photo: Tim Sharp).

This excavation was of course undertaken and described before the rise in Lake Victoria levels. Bishop subsequently noted that "the recently recorded rise in the level of Lake Victoria between 1961 and 1964 is of interest as, at their maximum, the lake waters were within two feet of the dated beach gravel in Hippo Bay cave (Fig. 17). This cave fill is so unconsolidated that even a few weeks would suffice to remove the whole deposit. It is certain that at no time since 3720 ± years ago has Lake Victoria risen to re-occupy the 10- to 12-foot cliff notch". It certainly seems that such a rise in the lake would have disturbed the charcoal fragments which were found to have been distributed throughout the sand. Given that the mean Jinja gauge level for 21–31 August 1959 was 10.80 m, and the range of 10–12 feet (3.05–3.66 m) above this level is equivalent to 13.85–14.46 m on the Jinja gauge, this information provides a bound to the lake level fluctuations and an upper outflow limit of 3000 $m^3 s^{-1}$ (Sutcliffe, 1987) converted by the present rating curve.

It is possible to compare this evidence with the flood series derived from the historic lake level series. Annual levels are not independent over time scales up to about 10 years, due to storage effects. Therefore a series of the decade maximum levels for the years 1896–1905, etc., have been abstracted and the equivalent outflows deduced from the Agreed Curve. These have been plotted (Fig. 3.10) against their adjusted Gumbel reduced variates, according to the Gringorten plotting position (Cunnane, 1978), with the upper bound plotted as the highest of a 3720-year period. This graph provides a reasonable flood estimate of about 3000 $m^3 s^{-1}$ corresponding to a return period of over 4000 years.

DOWNSTREAM INFLUENCE

The whole of the Nile system may be regarded as a set of tributaries providing a slowly moving baseflow, with local contributions or influences causing seasonal fluctuations. The extent of these local fluctuations determines their downstream influence. The influence of the Lake Victoria basin on downstream flows is to provide such a baseflow, which after attenuation in the lower lakes, forms the relatively steady contribution of the inflows to the

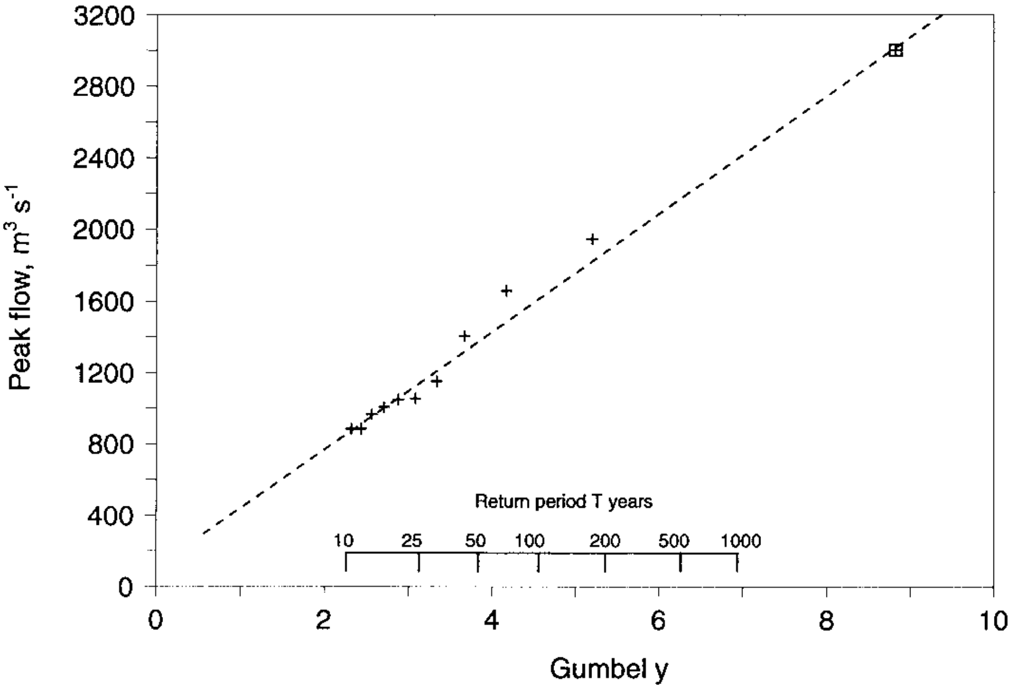


Fig. 3.10 Lake Victoria: decade peak outflows, 1896–1995.

Sudd. The extended seasons of rainfall, the storage in some of the tributaries, especially the Kagera, and the large storage available in Lake Victoria itself, ensure that the outflows vary little through the year. However, the balance of the lake system is not very stable, as average rainfall over the lake is almost in balance with open water evaporation. A period of high rainfall, such as occurred in 1961–1964, together with the effect on tributary inflow, can have a disproportionate effect on the lake balance. A large rise in the lake level may occur and persist for some years because of lake storage. The variations from year to year and the seasonal distribution of the outflows form the inflow to Lakes Kyoga and Albert downstream, and, after modification through the lake system, provide the major contribution to the flows of the Bahr el Jebel where it enters the Sudd. This has important implications for the regime of the Bahr el Jebel, which will become more evident in Chapter 5.