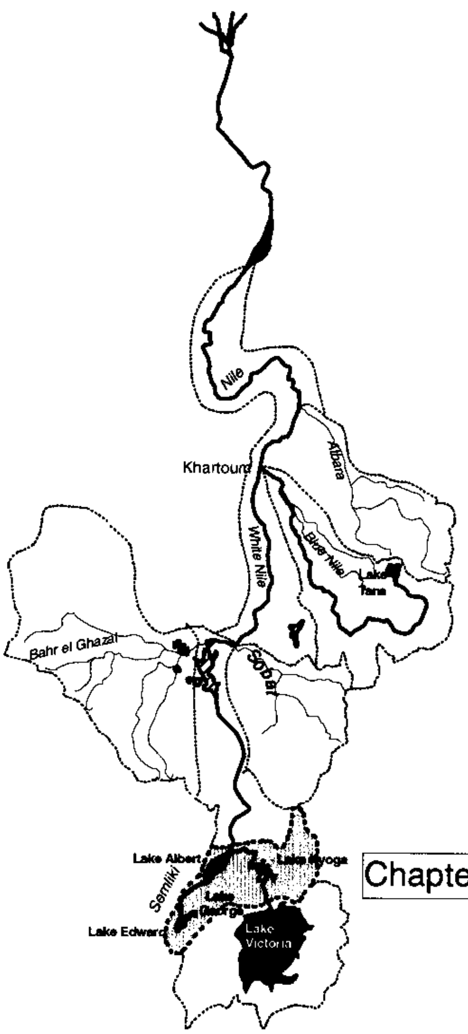
CHAPTER 4

THE EAST AFRICAN LAKES BELOW LAKE VICTORIA

INTRODUCTION

The outflows from Lake Victoria have a small seasonal variation, as the inflows and the direct rainfall on the lake are attenuated by the large lake storage. Table 3.4 shows that overall the highest monthly outflow in June is only 15% above the lowest in November, though the variation averages 20% in the earlier periods of low lake levels and 11% in the high lake period. Also, the lake storage corresponding to the rise in 1961–1964 was equivalent to five years' long-term outflow. An increase in inflows takes up to 10 years to reach a new equilibrium, so that major changes in the water balance take some years to work through the lake. In their turn the lake outflows form the major part of the White Nile flow. They are modified by their passage through Lakes Kyoga and Albert, and by the flows of various tributaries which enter the river network in most cases through these lakes. Thus the effects of the lake system between Jinja and Mongalla, the next reliable long-term gauging site, can be divided into net contributions in different reaches, and attenuation through lake storage. The aim of this chapter is to describe and quantify the effects of the individual lakes and their tributaries.



Chapter 4

GEOGRAPHY OF THE LAKE SYSTEM

The geography of the upper White Nile basin has been described briefly in Chapter 1; it may be useful to give more detail here. The pattern of lakes and tributaries, dominated by the geological evolution of the basin, is particularly complex (Fig. 3.1). Lake Victoria itself developed following the uplift of the earth's crust east of the western Rift Valley. This rise prevented the outflow of previously west-flowing rivers, like the Kagera and the Katonga, and Lake Victoria itself was formed in the basin between the two branches of the Rift Valley. The lake overflowed to the north at Jinja (Plate 3) and flowed down a tributary of the Kafu-Kyoga and thus into Lakes Kyoga and Albert. The course of the Kafu was also reversed so that the river flows both east and west from a point about 50 km east of the southern end of Lake Albert. This history explains not only the peculiar shape of the upper Kagera river system, but also the dendritic shape of Lake Kyoga, which is essentially a submerged river valley.

Plate 3 Victoria Nile at Bujagali Falls, below Owen Falls dam.

The course of the Nile between Lake Kyoga and Lake Albert is similarly influenced by the geological history of the area. The river flows up a former tributary of the Kafu after turning northeast at Masindi Port, and then swings west to enter the Rift Valley and Lake Albert through the Murchison Falls. The surroundings of Lake Kyoga are dominated by swamps along the various arms of the lake, and the topography is of moderate relief. In contrast Lake Albert is within the western Rift Valley, and the lake is flanked by the escarpment on the east and by steep mountains on the western or Congo side of the lake.

To the south of Lake Albert and the Ruwenzori mountains, Lakes George (300 km^2) and Edward (2200 km^2) are connected by the Kazinga channel. Although the Katonga tributary appears to drain a wide area, its course from a swamp is in fact relatively short. While Lake George is shallow at only 3 m and its basin is flat, Lake Edward is flanked by steep mountains to the west and is over 100 m deep in parts (Worthington & Worthington, 1933). The River Semliki drains Lakes Edward and George and thus both sides of the Ruwenzori mountains. Below Lake Edward its course is mainly across the Congo border, but the main channel forms the border with Uganda before entering the southwestern end of Lake Albert through the Semliki flats.

Below Lake Albert, the main river, here known as the Albert Nile or the Bahr el Jebel, flows along an extremely flat channel through a fringe of swamps as far as Nimule on the Sudan border. North of this point, the river turns again to the northwest on a continuation of the line of the River Aswa or Achwa, and passes through a series of rapids before entering the plains of the Sudd or Bahr el Jebel swamps. As well as the Aswa, there are a number of streams, known as the torrents, which flow into the Bahr el Jebel between Lake Albert and Mongalla. These streams, some of which rise within Uganda and others within the southern Sudan, are important because they provide the seasonal as opposed to the steady component of the inflows to the Sudd.

EARLY WATER BALANCE OBSERVATIONS

An early water balance of the lake basins was given by Hurst & Phillips (1938). They described the course of the Victoria Nile through Lake Kyoga, with an area of 1760 km^2 of open water and 4510 km^2 of swamps. They compared the 1913–1932 average inflow (20.5 km^3) with outflow at Masindi Port (18.0 km^3) and deduced an annual loss of about 2.5 km^3. They suggested a balance between direct rainfall (1295 mm or 8.1 km^3), local runoff at only 3% of rainfall over a flat and swampy area of 69 000 km^2 (2.7 km^3), and estimated evaporation of 1205 mm from the open water and 2230 mm from the swamps (12.2 km^3). This implied a net loss of 1.4 km^3. These figures are still quite reasonable.

Similar estimates were made for the Lake Albert basin. The runoff from the Semliki basin below Lake Edward was taken as 2.05 km^3 (16% of 1600 mm rainfall over 8000 km^2), added to the outflow of 3.69 km^3 from Lake Edward. The direct runoff to the lake was taken as 12% of 1256 mm over a relatively steep area of 17 000 km^2 or 2.56 km^3. The direct rainfall on the lake (5300 km^2) was estimated from the Butiaba records as 810 mm, and the evaporation as 1200 mm; the net evaporation is 2.07 km^3, and the net gain is thus 6.23 km^3. The Kyoga Nile inflows were estimated as 18.0 km^3, and an attempt was made to estimate the Bahr el Jebel outflow from Lake Albert.

The torrent flows between Lake Albert and Mongalla are significant during the rains but negligible in the dry season. Consequently Lake Albert levels at Butiaba gauge were related to monthly mean dry season flows at Mongalla, assuming an estimated 5% loss between the sites. This provided a rating curve to estimate outflows from Lake Albert throughout the year; the relation changed in 1922 after prolonged low levels. The monthly outflows from Lake Albert were published from 1904, and the average outflow for the period 1913–1932 was estimated as 24.0 km^3, compared with the Kyoga Nile inflow of 18.0 km^3. The balance between total inflows and outflows, including rainfall and evaporation, was thus close. The seasonal distribution of lake levels, calculated from the monthly water balance, corresponded closely with observed levels, whose seasonal fluctuations are largely due to rainfall and local runoff.

GENERAL CLIMATE OF LAKE KYOGA AND LAKE ALBERT BASINS

The rainfall of the two lake basins is intermediate between the bimodal regime of the Lake Victoria basin and the unimodal regime of the southern Sudan. Monthly rainfall averages for the different sub-basins of the Nile have been published in *The Nile Basin*, vol. VI and supplements, and Table 1.1 illustrates the seasonal distributions. The Lake Kyoga basin and the Lake Albert basin have two distinct rainfall seasons, with a maximum in April and a lesser peak around October. However, the area between Lake Albert and Mongalla has an extended single season, at least on average. The average annual rainfall is fairly constant over much of the plateau between Lake Victoria and Lake Albert, but decreases to the northeast of Lake Kyoga in the drier region of Karamoja, and is low over Lake Albert in the floor of the Rift Valley. Comparisons with Penman estimates of potential transpiration show that there is a surplus during the two rainy seasons in the south, and during the single rainy season in the north. Comparisons of rainfall averages for different periods show that while there was increased rainfall in parts of the Lake Kyoga basin since 1961, as in the Lake Victoria basin, there was little evidence of change in the few stations available in northern Uganda.

PUBLISHED FLOW RECORDS

Main Nile between Lake Kyoga and Lake Albert

The major components of the water balance of the Lake Kyoga and Albert basins are the inflows and outflows of the main Nile. The key hydrometric stations are those on the Kyoga Nile between the two lakes, and on the Bahr el Jebel between Lake Albert and Mongalla. Another is on the River Semliki at Bweramule above Lake Albert, together with the level gauges on the different lakes.

The main river gauges below Lake Kyoga were at Masindi Port just below the lake, at Kamdini about 80 km downstream, and at Fajao 1 km below the Murchison Falls and Paraa 5 km downstream. Levels have been measured at Masindi Port since 1912, at Fajao irregularly since 1932 and at Kamdini since 1940. The levels at Masindi Port and at Kamdini have been published as 10-day means in *The Nile Basin*, vol. III and supplements. Few records are available after 1980.

The discharge measurements made at various stations between Lake Victoria and Lake Albert have been published in *The Nile Basin*, vol. II and supplements, and the annual numbers of these gaugings are summarized in Table 2.1. Gaugings have been made regularly below Lake Victoria, either at Namasagali or more recently at Mbulamuti. Those at Masindi Port were concentrated in two periods, from 1935 to 1945, and in 1971 and 1976–1978; in the later period they were carried out by the Uganda Hydrological Department. At Kamdini, gaugings were carried out between 1940 and 1959, and at Fajao or Paraa downstream more or less continuously between 1922 and 1978.

Summaries of 10-day and monthly flows were calculated from levels, using in general annual ratings, and published in *The Nile Basin*, vol. IV and supplements. Flows at Masindi Port from 1912 were based on a rating curve for Masindi Port derived from gaugings made at Fajao downstream between 1907 and 1935. This curve was published in *The Nile Basin*, vol. V, and it was noted that the observations were fairly consistent over a long period. The flows for 1917–1918 were later revised. This record before 1940 was based on few gaugings but these include measurements in 1922–1923 when river levels were at their lowest. Later flows based on annual gaugings were published up to 1944. It was noted in *The Nile Basin*, vol. VII, p. 74 (Hurst *et al.*, 1946) that the rating was not stable and flows were discontinued. However, during 1988 (Gibb, 1989) the records at Masindi Port were examined in some detail and a flow record derived as discussed later.

Flows at Kamdini for 1940–1955 were published in *The Nile Basin*, vol. IV, based on annual gaugings. Gauge levels were published in vol. III from 1940 to 1977 as 10-day and monthly means, and further levels for 1978–1980 were kept by the Water Development Department, Entebbe. In order to obtain a record which should be more reliable than Masindi Port, gaugings at Fajao and Paraa downstream have been used to derive rating curves to cover this whole period, as discussed below.

A flow record for Fajao, derived by linear interpolation between monthly gaugings, was published for 1940–October 1961, with considerable gaps between 1944 and 1950. A similar record was derived for Paraa for 1963–1967. These flows have value for completion of other records.

Semliki at Bweramule

Discharges of the River Semliki have been measured regularly at Bweramule from 1940 to 1978, and the rating curve is reasonably stable. The early flows have been published in *The*

Nile Basin, vol. IV, based on annual rating curves, and are also available in the Uganda archive from 1950 to 1978. The two sources are compatible and a joint record can be compiled for the period 1940–1978.

Lake Albert outflows

Attempts have been made to measure Lake Albert outflows directly at Pakwach and elsewhere, but the rating curves at these sites were not stable. Estimates of Lake Albert outflows, as described earlier, have continued to be based on a relationship between monthly dry season flows at Mongalla, increased by 5% to allow for losses, and simultaneous Butiaba lake levels. This relation was assumed to apply throughout the year to give the lake outflows during periods when there would be inflows between the two sites. Although this relation changed in 1922, recent comparisons show that it changed back after the high flows of 1964.

It is doubtful whether the dry season losses between Lake Albert and Mongalla still amount to 5% after the doubling of outflows after 1961. The earlier assumption relied on simultaneous gaugings at both sites and on estimates of evaporation from swamps and open water. Its continued use implies that these areas also doubled. The later flows are therefore less precise.

An alternative is to treat the Lake Albert basin as extending down to Mongalla, where the inflow to the Sudd is confined to a single channel and gaugings have been carried out from 1905 and regularly from 1922. Flows have been computed regularly from continuous level observations and published in *The Nile Basin*, vol. IV and supplements. There have been changes in the rating over the years; for a given flow there was a continuous rise from 1905 to 1960 but a fall after 1962 to earlier levels. These flows are discussed in more detail in Chapter 5. It is sufficient to note that the flow records at Mongalla are reasonably reliable and that the estimated outflows from Lake Albert have been used to derive the flows of the seasonal torrents between Lake Albert and Mongalla.

REVIEW OF RIVER FLOWS AT KEY SITES

Lake Kyoga outflows at Masindi Port

A monthly flow record for 1912–1944 was published in *The Nile Basin* based on levels at Masindi Port and a rating based on gaugings at Fajao between 1907 and 1935, extended by later measurements. There are no other flow records for this reach before 1940, which includes the lowest outflows from Lake Victoria in 1922–1923. Because the rating is based on gaugings during this low flow episode, the flows may be accepted with caution.

During a recent study (Gibb, 1989) attention was paid to the later record at Masindi Port because of its potential length. The level record was considered reasonable, but gaugings were confined mainly to the two periods 1939–1945 and 1976–1978. The only rating which could be applied to the period 1945–1970 was that from 1942–1945. The level records were used to compile daily and monthly flows for the period February 1947–September 1978 (Gibb, 1989). At the time certain level records were not available in Uganda, but it has since been possible to complete these flows using 10-day levels published in *The Nile Basin*, vol. III. Thus the flow record, with its admitted limitations, has been completed for the period 1912–1978 and summarized as monthly flows in Fig. 4.1.

It would be possible to investigate further the ratings between 1945 and 1971 by comparing levels at Masindi Port with gaugings made downstream at Kamdini, Fajao and

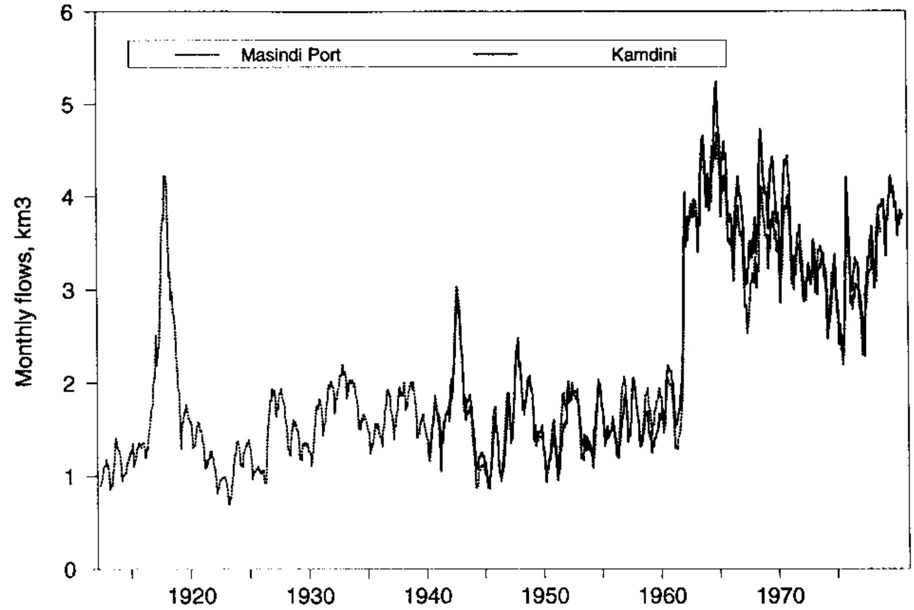


Fig. 4.1 Comparison of flows on Kyoga Nile, 1912–1980: Masindi Port and Kamdini.

Paraa. However, this would not add significant information to the flows derived in a similar manner downstream at Kamdini, where gaugings cover a longer period and analysis has been concentrated.

River flows at Kamdini

There is also a level record at Kamdini, where the rating should be more stable than at Masindi Port. Therefore records at or near Kamdini have been used (Gibb, 1996) to derive an independent flow record. Flows for the period 1940–1955 have been published in *The Nile Basin*, but these were deduced from gaugings made during each year. It is not easy to derive a reliable curve from individual years, because the range of levels and flows is limited during a

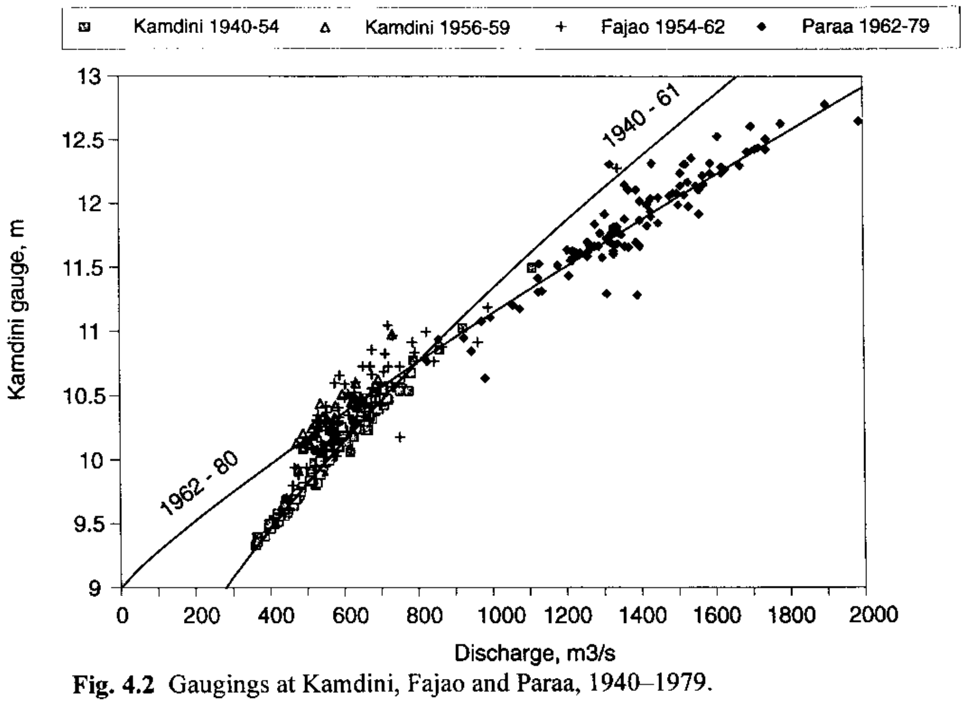


Fig. 4.2 Gaugings at Kamdini, Fajao and Paraa, 1940–1979.

single year on these lake-fed rivers. It is preferable to deduce a rating curve based on all available gaugings, and these have been used to derive two rating curves for the whole period. Gaugings at Kamdini itself were only made during the period 1940–1959; later gaugings from 1954 measured at Fajao and then Paraa downstream were included by comparison with the contemporary 10-day mean level at Kamdini. The inflows between Kamdini and the downstream sites are likely to be relatively small. Consequently it has been possible to monitor the rating at Kamdini over the whole period of level records (1940–mid 1980).

A total of over 330 discharge measurements were extracted from *The Nile Basin*, vol. II and supplements, and from gaugings available in the Uganda archive. The gaugings at different sites are distinguished in Fig. 4.2. There appeared to be a significant shift in the rating about 1955, according to the later gaugings at Kamdini as well as those at Fajao. There was a major change in 1962, when the lake and river levels rose following Lake Victoria. Using the HYDATA system (Institute of Hydrology, 1995) for deriving rating curves, a best fit equation was fitted to all gaugings in the period 1940–1961, and a second derived for the period 1962–1979. Because the annual range of levels is limited, it was preferred to derive a rating from the whole set of consistent gaugings and then monitor apparent annual changes in control. The program lists the deviations of individual gaugings from the derived rating curve, and these were averaged for each year or longer periods to obtain a rating in the form $Q = a(h - h_0 - dh)^b$ where dh is the vertical deviation from the rating curve. These adjusted rating curves have been used to derive 10-day and monthly flows, with some gaps filled from other sources (Sutcliffe, 1996). A monthly summary of this record is included in Fig. 4.1. This record is considered reasonable and preferable to other records on the Kyoga Nile, as it is based on contemporary gaugings either at the site or downstream.

Comparison of flows at Masindi Port and Kamdini

The independent flow records for Masindi Port and Kamdini may be compared in Fig. 4.1. The monthly flows for the common period suggest that both are reasonably reliable, although the Kamdini record is to be preferred where available. Both records exhibit increased flows after the rise in Lake Victoria levels after 1961 and are similar in form. Between about 1966 and 1970 the Kamdini record is the higher, but the overall difference over the common record is only about 3%. It should be noted that tributary inflow between the two sites is relatively small; the main tributary is the River Tochi, which contributes less than 1% to the flow of the main river. The two records are compared with the outflows from Lake Victoria in Fig. 4.3. The fact that the flows for Masindi Port and Kamdini both confirm the rise in outflows from Lake Victoria provides further proof that the Agreed Curve gave realistic estimates of the Lake Victoria outflows. The availability of reliable flows at Kamdini makes it possible to separate the net contributions of the Lake Kyoga basin between Jinja and Kamdini from those of the Lake Albert basin between Kamdini and Mongalla.

COMPARISONS OF INFLOWS AND OUTFLOWS FOR LAKE KYOGA

The net effect of Lake Kyoga on the Nile flows can be studied by comparing river flows below Lake Kyoga with Lake Victoria outflows. The most reliable record in this reach is at Kamdini, and analysis must be based on the period 1940–1977 when these flows are available; the gaugings during 1978–1979 were infrequent. Study is based on monthly flows, but when comparisons are made with lags of one or more months, the flows have to be

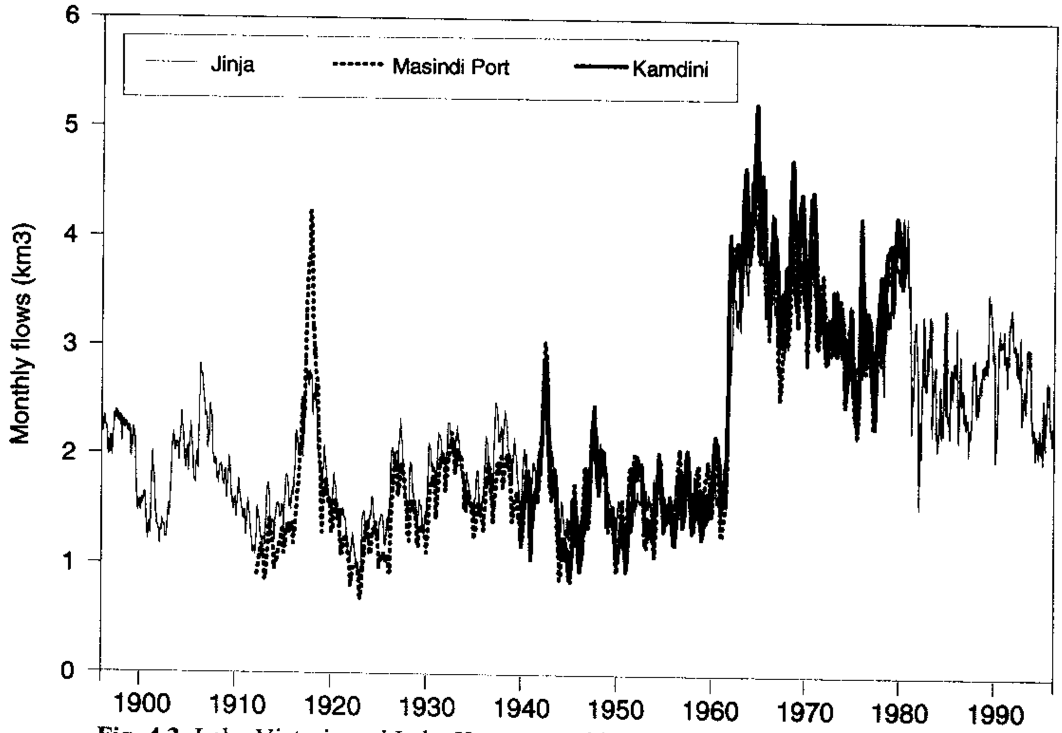


Fig. 4.3 Lake Victoria and Lake Kyoga monthly outflows, 1896–1995: Jinja, Masindi Port and Kamdini.

converted to $m^3 \times 10^6$ day^{-1} to take account of different month lengths. The results (Table 4.1) show that the regression is improved when lags of one month are taken into account, but not for greater lags.

The comparison based on annual Lake Kyoga inflows and outflows for 1940–1979 (Fig. 4.4) is similar to the monthly comparison, but the scatter has been much reduced; the line of equality has been superimposed. The comparison supports the hypothesis of Hurst & Phillips (1938) that the lake system is responsible for net losses in dry years and for net gains

Table 4.1 Regression of monthly outflows from Lake Kyoga on inflows (based on Kamdini flows, 1940–1977, and Lake Victoria outflows).

Lag (months)	Coeff.	seb	R	R^2	see	Constant
Monthly flows, $m^3 \times 10^6$ $month^{-1}$ (456 observations)						
0	1.1331	0.0150	0.9624	0.9263	300	−247
1	1.1331	0.0151	0.9619	0.9252	302	−242
2	1.1309	0.0154	0.9603	0.9221	308	−234
Monthly flows, $m^3 \times 10^6$ day^{-1}						
0	1.1319	0.0151	0.9620	0.9255	9.85	−8.03
1	1.1390	0.0139	0.9677	0.9365	9.09	−8.44
2	1.1336	0.0148	0.9633	0.9280	9.68	−7.92
3	1.1205	0.0169	0.9522	0.9067	11.02	−6.80

Coeff. is the regression coefficient b in an equation of the form $Q_o = a + bQ_i$.
seb is the standard error of b.
R, R^2 are the coefficients of correlation and determination.
see is the standard error of estimate.
Const. is the constant a in the equation.

The optimum equation linking inflow (Q_i) and outflow (Q_o) for Lake Kyoga is:

$$Q_o(t) = 1.1331\ Q_i(t-1) - 242 \text{ in terms of } m^3 \times 10^6 \text{ (ignoring length of month)}$$

or

$$q_o(t) = 1.139\,044\ q_i(t-1) - 8.441\,81 \text{ in terms of } m^3 \times 10^6 \text{ day}^{-1}.$$

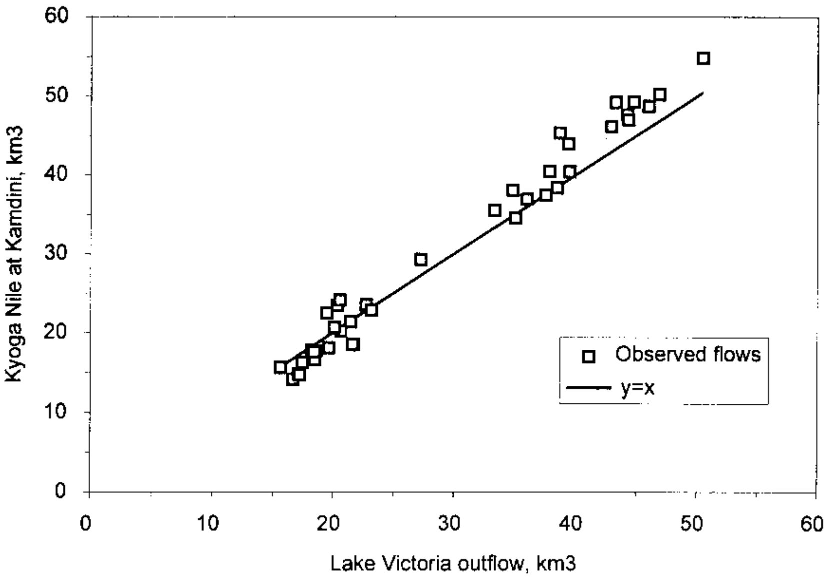


Fig. 4.4 Lake Kyoga annual inflows and outflows, 1940–1979.

in wetter years. This has been attributed (Institute of Hydrology, 1984) to the evaporation from Lake Kyoga exceeding direct rainfall and local runoff during relatively dry periods. In contrast the local runoff increases during wetter periods and together with lake rainfall exceeds lake evaporation, which should be relatively constant from year to year.

WATER BALANCE OF LAKE KYOGA

There are few records of the local inflow, mainly from east of Lake Kyoga, and it is not possible to make a complete study of the lake water balance. Differences between lake inflow and outflow are small by comparison with either river flow record and therefore affected by measurement errors at both sites. However, the hypothesis that net gain or loss is due to the balance between rainfall with its associated runoff and lake evaporation has been tested by analysis of the period 1940–1977.

A lake level record (Fig. 4.5) has been derived for Lake Kyoga from the 10-day mean levels at Masindi Port. This site is just below Lake Kyoga, but has the most complete record.

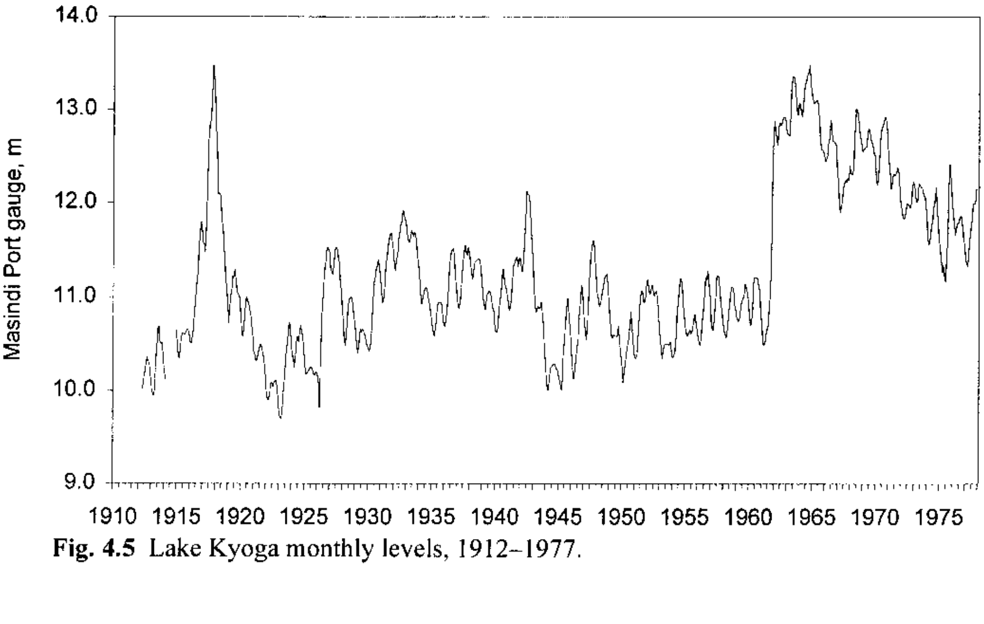


Fig. 4.5 Lake Kyoga monthly levels, 1912–1977.

The annual differences between Lake Kyoga inflow and outflow need to be adjusted for storage change within the lake by multiplying the level rise by the area of the lake and swamp. There is some uncertainty about the area of the lake and adjoining swamp, which must vary with elevation to some extent. A recent estimate by WMO (1982) of 4700 km^2 was adopted as fixed for this comparison. The net basin supply, which includes rainfall less evaporation on the lake, and local runoff into the lake, has been compared with the average annual rainfall at eight stations in the general area around the lake, as listed below:

Jinja	0°16'N, 33°06'E	Katakwi	2°00'N, 33°42'E
Kaberamaido	1°48'N, 33°18'E	Lira	2°18'N, 32°54'E
Masindi	1°42'N, 31°42'E	Mbale	1°06'N, 34°06'E
Namasagali	1°00'N, 32°54'E	Serere	1°30'N, 33°48'E

The annual net basin supply is plotted against this rainfall average in Fig. 4.6, which shows a fair degree of scatter indicated by the correlation coefficient (R^2 = 0.640). Nevertheless, the comparison suggests that the gains and losses through Lake Kyoga are real and are associated with local rainfall. The lack of local runoff records means that it is not possible to derive a precise water balance of the Lake Kyoga system. Assuming that the mean relation between Lake Kyoga net gain and regional rainfall is accepted, and the balance between rainfall and evaporation over the lake is taken as annual rainfall less 1600 mm for evaporation, the implied runoff into the lake system can be deduced. This infers that the runoff is insignificant when the annual rainfall is of the order of 1000 mm, but that it increases to 1% at 1200 mm and to 6% at a regional rainfall of 1500 mm. This is not unrealistic; an estimate of the local runoff into Lake Kyoga for a normal year was made by WMO (1974) of 2.91 km^3 or 50 mm over the effective basin of 59 000 km^2, which implies a runoff coefficient of 3.7% for an average rainfall of 1350 mm.

The delay of river flows as a result of lake storage may be deduced from comparison of monthly mean outflows with inflows over a common period. These have been compared in Table 4.2 for the periods 1951–1960 and 1966–1975, before and after the rise in Lake Victoria. In the earlier period the maximum inflow occurred in June, while the outflow reached its peak in September; in the later period the corresponding maxima were in June and October. The delay is about 2–3 months, but the timing of the peak appears to become later after 1961–1964.

In order to show that measured and inferred inputs are consistent with measured lake levels, monthly balances have been calculated (Table 4.2) for two periods. These illustrate the dramatic change in the lake regime after the rise in Lake Victoria. The balance includes inflows and outflows, rainfall in the area of the lake estimated from the mean of eight stations,

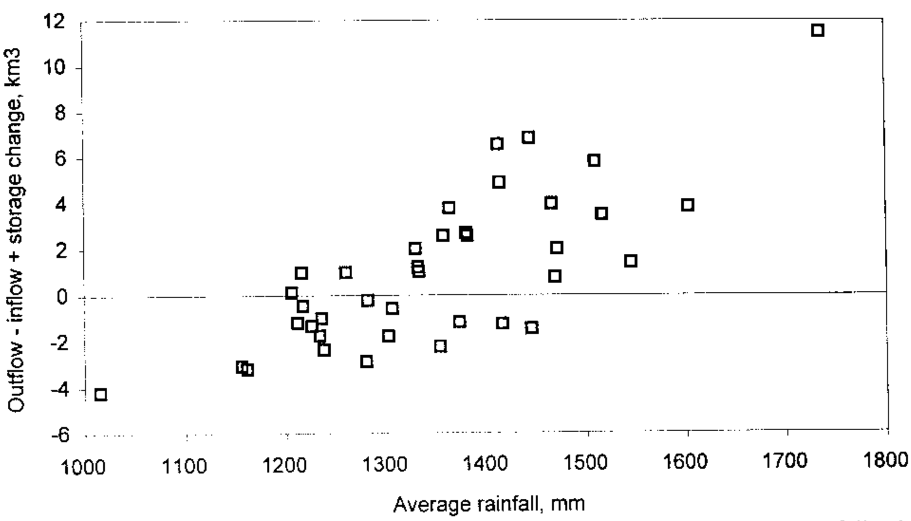


Fig. 4.6 Water balance of Lake Kyoga: net outflow + storage change *vs* rainfall, 1940–1977.

Table 4.2 Monthly water balance of Lake Kyoga (mm over 4700 km^2).

	Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Balance (1951–1960)													
Inflow	336	309	341	348	372	370	366	345	330	337	314	329	4098
Outflow	322	285	306	300	334	339	360	370	366	374	354	351	4061
Local inflow	14	15	32	57	50	28	27	44	40	41	28	20	394
Rainfall	44	47	101	181	158	90	88	140	126	132	89	64	1257
Evaporation	135	135	145	130	125	120	125	135	140	145	130	130	1595
Balance	–64	–50	23	155	120	29	–3	24	–10	–9	–54	–68	93
Level (m)	10.76	10.66	10.60	10.59	10.70	10.85	10.92	10.97	11.02	11.01	10.98	10.90	10.80
Balance (1966–1975)													
Inflow	702	632	706	701	768	755	740	723	696	687	657	704	8474
Outflow	740	648	699	678	736	742	781	782	768	803	765	762	8902
Local inflow	17	31	56	86	89	50	52	66	71	76	55	17	667
Rainfall	34	62	111	171	177	100	105	132	142	152	110	33	1328
Evaporation	135	135	145	130	125	120	125	135	140	145	130	130	1595
Balance	–122	–58	29	150	174	43	–8	4	1	–32	–72	–137	–28
Level (m)	12.28	12.16	12.08	12.03	12.12	12.24	12.31	12.33	12.35	12.39	12.39	12.33	12.23

evaporation taken from Lake Victoria, and local inflow deduced as a function of rainfall. In order to balance the two 10-year periods, the runoff coefficient for the first period can be calculated as 2.5% of areal rainfall, while the corresponding figure for the second period is 4%. Using these figures, the average predicted lake levels are compared with the measured levels in Fig. 4.7. Because the local inflows have been calculated to close the balance, and are about 10% of the main river inflows, their values should not be taken as more than approximate. However, the main features of the level regime have been reproduced with a range of about 400 mm, with a minimum level in March and a peak about September.

Lake Kyoga is relatively shallow, being 3–5 m deep at its western end and shallower in its upstream arms. The wider parts of the lake were previously open water fringed with papyrus and floating vegetation, while the narrower arms and inflow tributaries were overgrown with papyrus; this is related (Chapter 5) to the moderate range of lake levels. However, the southern fringes of the lake have recently been invaded with water hyacinth (*Eichhornia crassipes*) (Ntale, 1996).

The outflows from Lake Kyoga form the main component of the inflow to Lake Albert; they are closely related to the outflows from Lake Victoria, but there is evidently a net contribution in passage through Lake Kyoga in relatively wet periods and a net loss in drier periods.

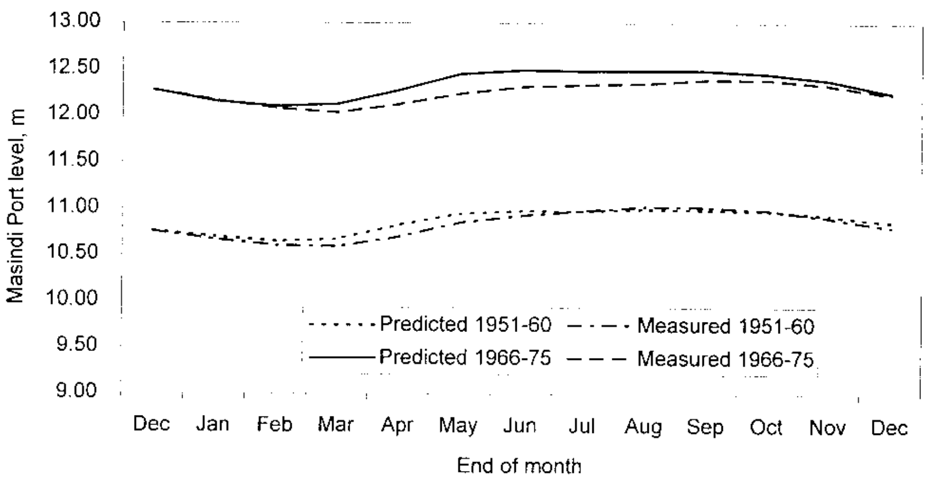


Fig. 4.7 Lake Kyoga monthly balance: measured and predicted levels, end of month, 1951–1960 and 1966–1975.

LAKES EDWARD AND GEORGE

The second largest inflow to Lake Albert is provided by the River Semliki. This river drains the basins of Lakes Edward and George, and a contributing area downstream which includes the western slopes of the Ruwenzori range. The western part of Lake Edward, and much of the lower Semliki, are within the Congo and hydrological data are not available. Records are not yet sufficient to deduce a precise water balance for the lake system. The main information consists of a series of lake levels extending from 1942 to 1978, and flow records for the Semliki at Bweramule, some 40 km above Lake Albert, from 1940 to 1978.

The monthly series of lake levels (Fig. 4.8) reveal a similar pattern to the other East African lakes, with a seasonal pattern superimposed on the longer-term fluctuations. The rise in 1961–1964 is similar to those of the other lakes, but the subsequent fall was more rapid than in those lakes which depend on the storage of Lake Victoria. They did however remain higher than before the rise. Long-term averages show that the level range is only about 0.2 m, with peaks in December and June and minima in March and April. The Semliki outflows are illustrated in Fig. 4.9. The seasonal distribution of flows is similar to the lake levels; the rise in Semliki flows since 1962 has been similar to the Kagera or the Victoria Nile.

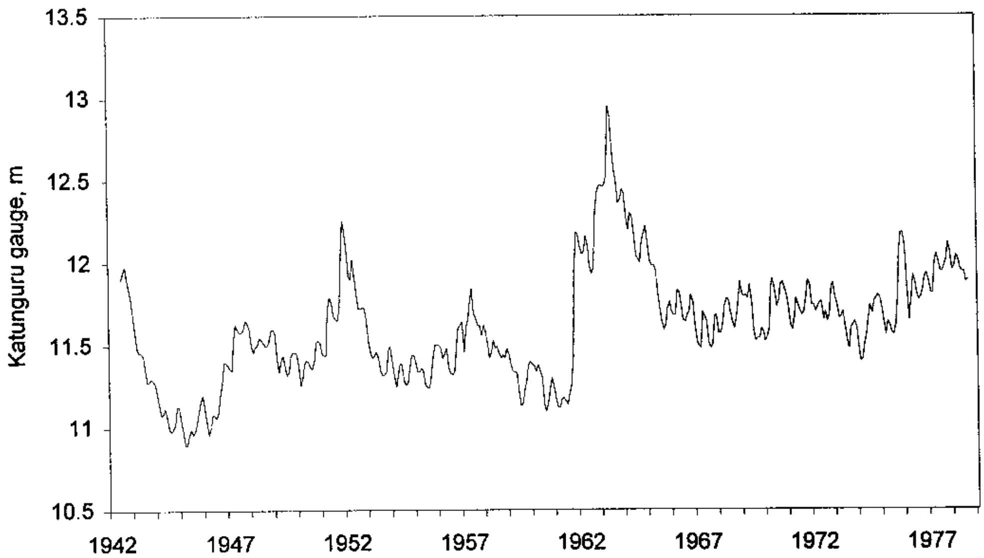


Fig. 4.8 Lake Edward monthly levels, 1942–1978.

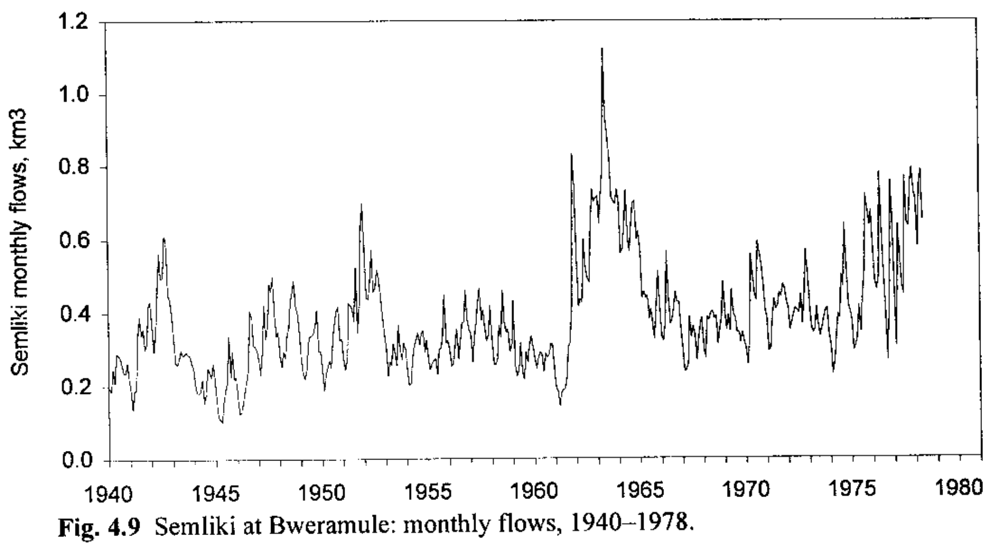


Fig. 4.9 Semliki at Bweramule: monthly flows, 1940–1978.

The vegetation of Lake George has been examined in some detail by Lock (1973). The lake is relatively shallow with a mean depth of 2.5 m. *Cyperus papyrus* forms a large area of swamp covering the northern half of the lake, through which most of the inflow, originating on Ruwenzori, enters the lake. Comparison of air photographs taken in 1954 and 1970 suggested that the northern shoreline with its papyrus fringe has been stable, in spite of the general rise in lake levels over the region. There are also fringes of *Vossia* and *Phragmites* in certain parts of the lake, with floating vegetation like *Pistia stratiotes* on sheltered shores around the lake. Papyrus, on the other hand, is limited to river mouths on Lake Edward.

LAKE ALBERT

The hydrology of Lake Albert is better known than that of Lakes Edward and George, because the main inflows have been measured for a reasonable period. However, the rainfall and evaporation over the lake are not known with any precision, while the lake outflow is not measured directly at its mouth. A major problem is that inflows and outflows are similar, so that measurement errors may disguise the main features of the balance. Before considering the balance of the basin as a whole, its various components are discussed in turn.

Kyoga Nile inflows

Without precise measurements of river flows on the Kyoga Nile, the water balances of the Lake Kyoga and Lake Albert basins cannot be established separately. Flows at Masindi Port are available from 1912, but records for the period 1912–1939 are not sufficiently precise for this purpose. Lake Victoria outflows date from 1896, but accurate flows at Kamdini are limited to the period 1940–1977.

Some tributaries flow into the Kyoga Nile between the lakes, such as the Tochi and Ayago. The annual flow of the Tochi, the largest of these rivers, averages 0.230 km^3, or less than 1% of the flows of the main river. The increase in flow from these tributaries can reasonably be neglected.

Semliki and local inflows

The net contribution of the Lake Edward and Lake George basins is combined in the outflows of the Semliki, and the flows measured at Bweramule (Fig. 4.9) give a reasonable estimate of this contribution. These flows are also available for the period 1940–1977.

There is also some direct inflow from local streams. The largest basins, the Muzizi and Nkuzi, drain into the southern corner of the lake from the east. Previous estimates (Hurst & Phillips, 1938) of this local runoff (2.56 km^3) were based on average rainfall (1256 mm) and a runoff coefficient of 12% over a relatively steep area of 17 000 km^2. Estimates of this local runoff were also made by WMO (1974) based on gauged flows of four tributaries and an isohyetal map; a relationship was found between the runoff coefficients for the four basins, ranging from 6 to 15%, and their channel slope. This led to an estimated average runoff of 2.7 km^3 from a rainfall of 1192 mm and a mean runoff coefficient of 12.4%. As the annual distribution of this runoff is required in this study, it seems reasonable to express it as a fixed ratio of the Semliki flows, corresponding to the basin areas, e.g. 17 000/30 500. This results in a mean runoff for 1940–1977 of 2.576 km^3, based on the Semliki flow at Bweramule of 4.622 km^3.

Albert Nile outflows

The most reliable gauging station below Lake Albert is at Mongalla on the Bahr el Jebel. River gauge levels have been recorded here since 1905, at a site where the river enters the Sudd in a single channel. Gaugings have been made since 1907, and have been frequent in some periods and regular in other periods. Although the rating curve has altered, the changes from year to year have been fairly regular, except immediately after the rise in Lake Victoria when the flows suddenly doubled. The changes in channel control are discussed in more detail in the next chapter, but it is sufficient to accept that reasonable flows at this site have been calculated and published in *The Nile Basin.*

Although the gains of flow between Lake Victoria and Mongalla can be deduced from flow series over the whole period 1905–1983, the balance of the Lake Albert basin can only be deduced for the period 1940–1977 between Kamdini and Mongalla. The outflows from Lake Albert itself have been estimated by relating Butiaba levels to Mongalla dry season flows. These have been published for the period 1904–1978, but there is a possibility that the losses between Lake Albert and Mongalla have been overestimated after 1964, and thus that the Lake Albert outflows have been overestimated. There is also direct evidence that the flows at Mongalla have been estimated incorrectly in 1963–1964, when gaugings were not possible, and this is in fact confirmed by the following analysis.

Other components of Lake Albert balance

The balance also requires rainfall on the lake, lake evaporation and changes of storage. The only long-term rainfall station near the lake is at Butiaba, and records have been somewhat sporadic in recent years. However, a record is available for the years 1904–1977, with an intermittent record in 1968–1970 and 1975–1977. It is not certain how lake rainfall compares with this record situated on a spit on the eastern shore of the lake. As a first approximation, the evaporation may be taken as the same as that derived for Lake Victoria, though the lower elevation and the drier climate are likely to result in a higher total for Lake Albert. The changes of lake storage may be assessed by using the end-month Butiaba gauge levels (Fig. 4.10) and an average area of 5300 km^2.

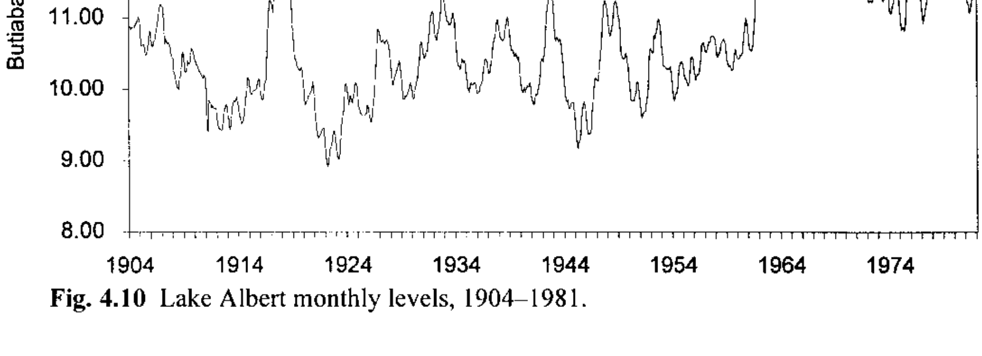


Fig. 4.10 Lake Albert monthly levels, 1904–1981.

Water balance

The results of this water balance analysis are presented in the form of a comparison between inflows, including rainfall, and outflows, including evaporation, and storage change. It should be stressed that two components of the balance, the inflow from the Kyoga Nile and the outflow down the Bahr el Jebel, are large by comparison with other components. Errors in their estimation will have a large effect on the estimated lake balance. The results of a provisional annual lake water balance are presented in Fig. 4.11. The annual outflows from Lake Albert, estimated but not directly measured, and increases in lake storage plus evaporation, are compared with the lake inflows. These inflows are measured for the Kyoga Nile at Kamdini and the Semliki at Bweramule, and estimated by analogy with the Semliki for the rest of the land catchment. They include rainfall at Butiaba. There is a fair degree of scatter; in particular, the years with the highest inflows, 1963 and 1964, are anomalous, as discussed in Chapter 5. An attempt to see how far lake rainfall is relevant is shown in Fig. 4.12, where Butiaba rainfall is compared with the difference between lake outflow and storage change, and inflows from the Kyoga Nile, Semliki and other basins. The scatter is considerable, even after omitting 1963 and 1964, when the outflows were underestimated.

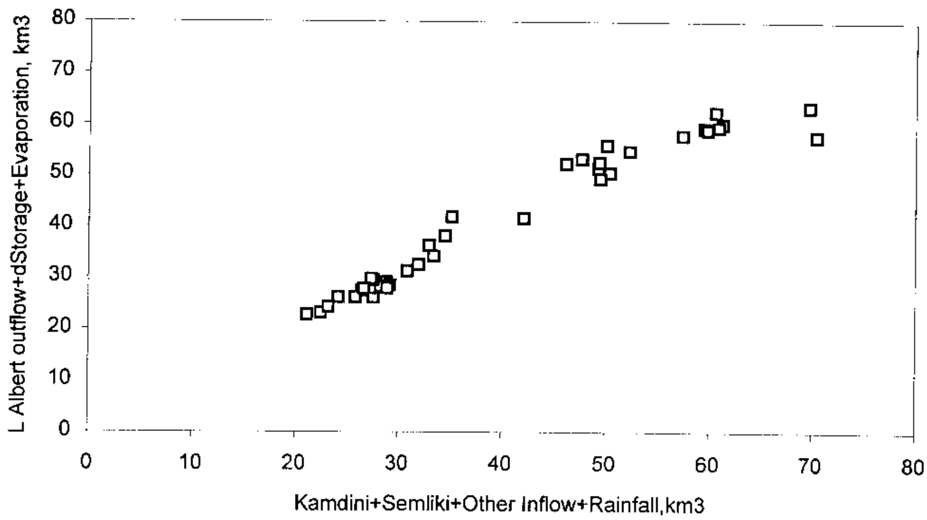


Fig. 4.11 Lake Albert annual balance: outflow + storage change + evaporation *vs* inflow + rainfall, 1940–1977.

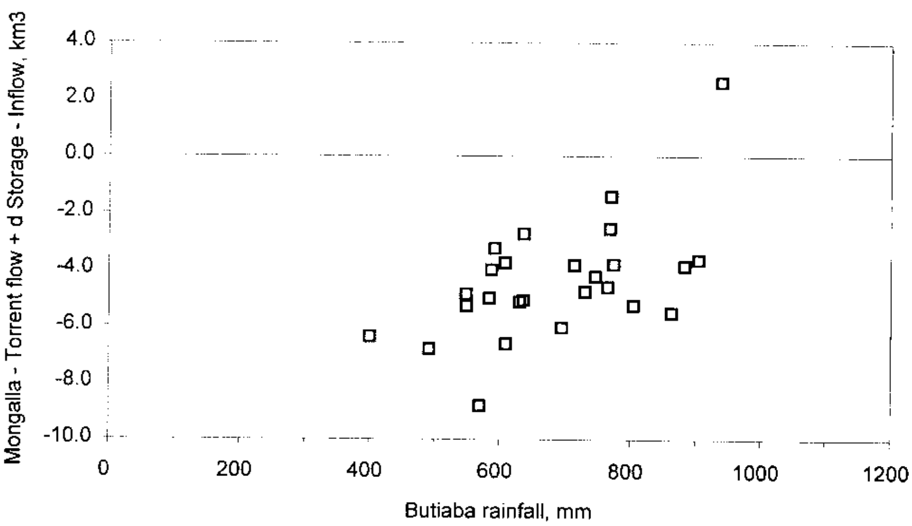


Fig. 4.12 Lake Albert annual balance: outflow + storage change – inflow *vs* rainfall, 1940–1967 excluding 1963–1964.

Table 4.3 Monthly water balance of Lake Albert (mm over 5300 km^2).

	Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Balance (1951–1960)													
Kamdini	286	253	271	266	297	300	319	328	324	332	314	311	3601
Semliki	63	50	53	60	69	62	64	71	65	70	68	68	762
Local inflow	35	28	29	34	38	34	36	39	36	39	38	38	425
Mongalla	320	277	296	312	379	367	392	480	473	468	397	358	4519
Torrents	0	0	0	19	69	63	81	162	154	127	55	7	738
Rainfall	19	22	55	107	50	31	59	63	62	85	58	31	643
Evaporation	135	135	145	130	125	120	125	135	140	145	130	130	1595
Balance	–52	–61	–33	45	19	4	42	48	28	41	6	–32	56
Level (m)	10.56	10.41	10.31	10.24	10.27	10.32	10.30	10.33	10.41	10.49	10.57	10.62	10.62
Balance (1966–1975)													
Kamdini	656	575	620	601	653	758	692	694	681	712	678	676	7895
Semliki	67	56	62	73	80	73	76	81	85	84	85	81	904
Local inflow	37	31	35	41	45	40	42	45	47	47	47	45	504
Mongalla	744	643	692	671	746	727	775	897	901	892	842	795	9326
Torrents	0	0	0	10	50	49	77	186	195	147	93	26	832
Rainfall	16	32	63	107	102	56	63	53	87	102	82	3	766
Evaporation	135	135	145	130	125	120	125	135	140	145	130	130	1595
Balance	–103	–84	–57	31	58	30	51	27	53	54	13	–94	–20
Level (m)	11.94	11.78	11.64	11.55	11.58	11.63	11.63	11.65	11.73	11.79	11.89	11.96	11.85

The rainfall on the lake is on average less than 10% of the total inflow, so that it is not surprising that its influence is not clear. The use of a single rainfall station and flow measurement problems must obscure any relationship.

In the hope that the effect of measurement errors might be reduced in the average conditions of a sample period, a study has been made of the monthly water balance of two periods: 1951–1960 and 1966–1975 to represent periods before and after the rise of Lake Victoria. Table 4.3 shows the balance for these periods, with rainfall taken as the average monthly Butiaba rainfall for each period, without attempting to fill gaps. More consistent results were obtained from estimating Lake Albert outflows from Mongalla flows less estimated torrent flows, though the overall balance must be fortuitous. The seasonal balance is illustrated by comparisons of predicted Butiaba levels in Fig. 4.13. This study also shows the effect of storage in delaying the lake outflow, and illustrates the effect of seasonal patterns of inflow and rainfall. Although the peak inflow occurs in September or October, the peak lake level and lake outflow occur in November.

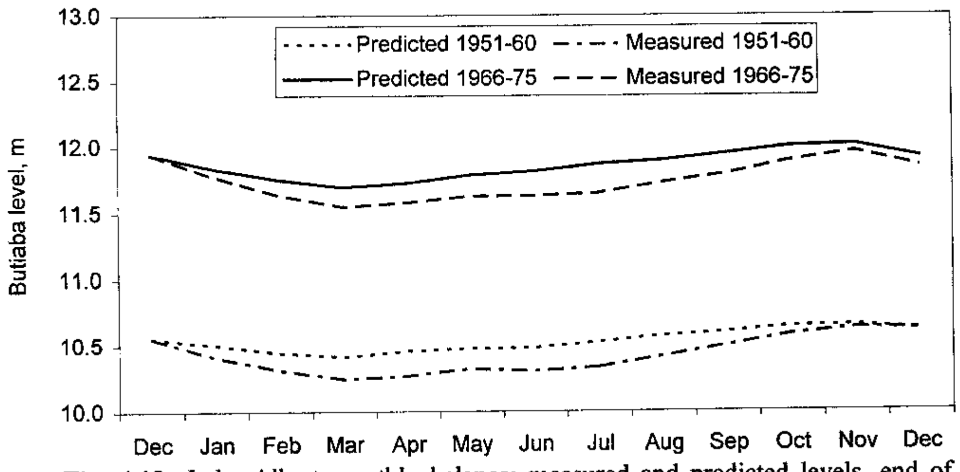


Fig. 4.13 Lake Albert monthly balance: measured and predicted levels, end of month, 1951–1960 and 1966–1975.

The surroundings of Lake Albert

The monthly lake levels show that, although the range of levels over the years has been relatively large, the seasonal range of levels has been comparatively small at about 0.4 m. The small range of levels is reflected in the vegetation. The main channel of the Kyoga Nile enters the lake below the Murchison Falls in a delta about 10 km in length; the mouth is surrounded by permanent papyrus swamp, with fringes of *Vossia* near the main channel. The shores of the lake are in general extremely steep, and there is no room for significant wetlands. To the southwest of the lake, the mouth of the Semliki lies adjacent to a wide sedimentary plain, and the river has been described as passing through wide papyrus swamps for the last 25–30 km of its course (Garstin, 1904, p. 58). The extent of the permanent swamp in about 1931 may be deduced from air survey maps of the period (Air Survey Company, Ltd, 1931/32, Sheets 100/3015 and 100/3030); these reveal a width of 5–10 km of swamp near the lake. All this vegetation would be vulnerable to changes in regime caused by regulating outflows from Lake Victoria.

Below Lake Albert the river is fringed by papyrus and other swamp between Pakwach and Nimule. The flood plain is shown on the Air Survey maps of 1931/32, and the extent is given by Hurst & Phillips (1938) as consisting of about 260 km^2 of open water and 120 km^2 of swamp. This swamp was noted by Sutcliffe in 1956 to consist mainly of papyrus and *Vossia* over this reach of about 200 km.

Potential of Lake Albert as a reservoir

The potential for Lake Albert as a reservoir has been considered over many years, on the basis that the relatively steep shores make it more suitable than Lake Victoria for overyear storage. The possibility of a reservoir on Lake Albert was discussed briefly by Hurst & Phillips (1938, p. 81) and it was noted that contours corresponding with a level of 20 m on the Butiaba gauge had been deduced by air survey. In the past it was considered as a possible site for "century storage" to control the supply of water to Egypt to arrive in the timely or irrigation season. It was proposed to store the flows of the torrents either by locating a dam at Nimule or by virtual storage based on forecasting. The Jonglei Investigation Team (1954) suggested that the dam could be used to provide the normal pattern of flow at Mongalla, and also for flood control, and this would have precluded its use for virtual storage (Hurst *et al.*, 1966).

The effect of flooding around Lake Albert was studied in 1956 to assist Uganda in possible negotiations (Sutcliffe *et al.*, 1957), but the construction of the Aswan High Dam reduced the immediate need for overyear storage. It was studied as one component of Nile control by WMO (1982). It may be useful as a way to reconcile the need for Uganda to optimize the hydroelectric potential of the Nile below Lake Victoria by storage, and the present requirement of those inhabitants of the southern Sudan dependent on the natural regime of the Bahr el Jebel to avoid disturbance of the pattern of seasonal flooding.

EFFECT ON FLOWS OF LAKE KYOGA AND LAKE ALBERT BASINS

The net effect on the flows of the White Nile of Lake Kyoga and Lake Albert and their tributaries may be illustrated (Sutcliffe, 1996) by monthly gains and losses between Jinja and Kamdini and between Kamdini and Mongalla (Fig. 4.14(a)–(b)) and by the annual equivalent

(Fig. 4.15(a)–(b)). The periods of net gain through Lake Kyoga after 1960 and the highly seasonal gains at Mongalla are clearly shown. This information is supplemented by mean flows for the common period of record of 1940–1977 at various sites between Jinja and Mongalla (Table 4.4). There is a difference of about 3% between Masindi Port and Kamdini, which is likely to be due to measurement problems; the Kamdini record is preferable. The effect of Lake Kyoga and its basin appears on average to be a small increase, with the peak flow at Jinja in June being delayed to September (allowing for length of month); however, the net effect has been a decrease in drier periods and an increase in wetter periods. The effect of the Lake Albert basin, with the Semliki contribution at its maximum in November, is a net increase in flow and a delay to November in the Lake Albert outflow. The average contribution of the torrents between Lake Albert and Mongalla is of similar magnitude to the Semliki, but its highly seasonal distribution with a peak in September leads to a peak flow at Mongalla in the same month. The overall effect of the lake basins is to delay the outflows from Lake Victoria and to increase the flows in magnitude and seasonal variability.

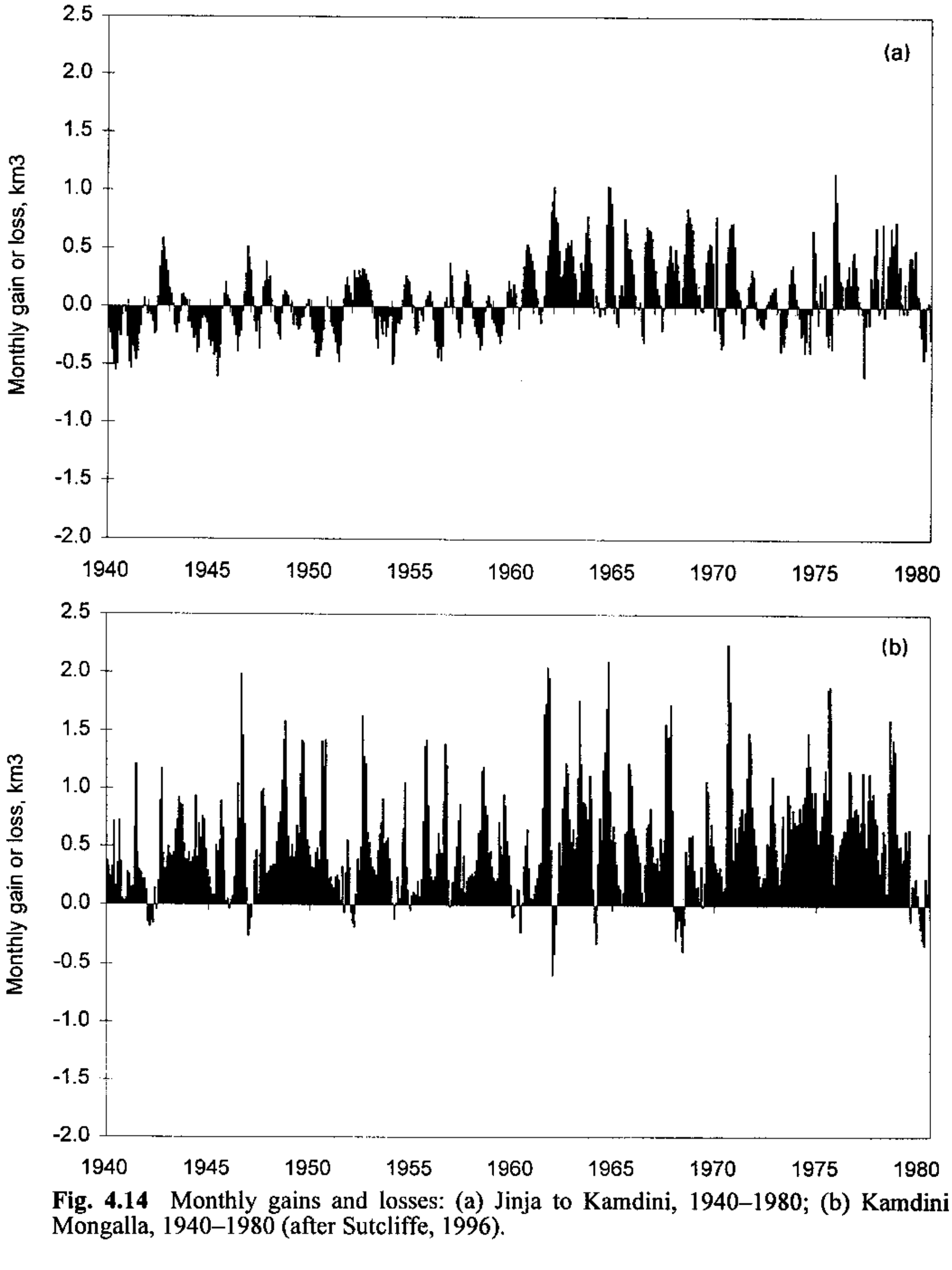


Fig. 4.14 Monthly gains and losses: (a) Jinja to Kamdini, 1940–1980; (b) Kamdini to Mongalla, 1940–1980 (after Sutcliffe, 1996).

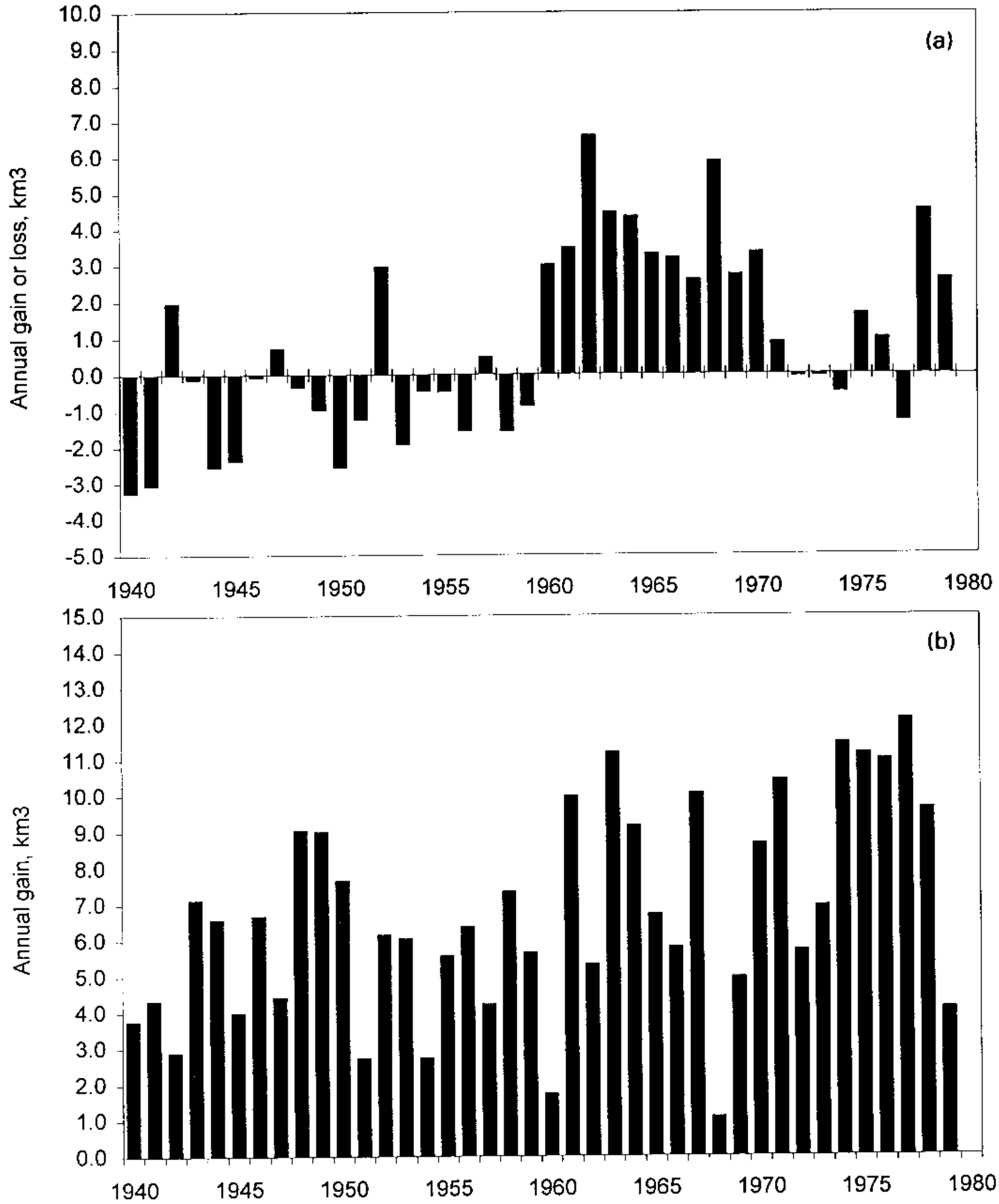


Fig. 4.15 Annual gains and losses: (a) Jinja to Kamdini, 1940–1979; (b) Kamdini to Mongalla, 1940–1979 (after Sutcliffe, 1996).

Table 4.4 Mean flows ($m^3 \times 10^6$) at sites between Jinja and Mongalla (1940–1977).

Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Victoria Nile at Jinja												
2352	2128	2366	2377	2594	2566	2524	2436	2327	2323	2216	2386	28 593
Kyoga Nile at Masindi Port												
2336	2047	2181	2122	2340	2372	2516	2567	2525	2598	2472	2489	28 564
Kyoga Nile at Kamdini												
2418	2111	2273	2205	2424	2447	2577	2624	2592	2665	2540	2563	29 438
Semliki at Bweramule												
350	285	316	352	409	371	392	417	409	423	435	419	4 577
Outflows from Lake Albert												
2829	2459	2615	2526	2684	2620	2712	2771	2768	2923	2906	2998	32 809
Torrent flows between Lake Albert and Mongalla												
0	0	3	119	406	386	538	973	967	765	404	130	4 691
Bahr el Jebel at Mongalla												
2714	2348	2519	2548	2965	2884	3121	3617	3601	3547	3184	3000	36 047

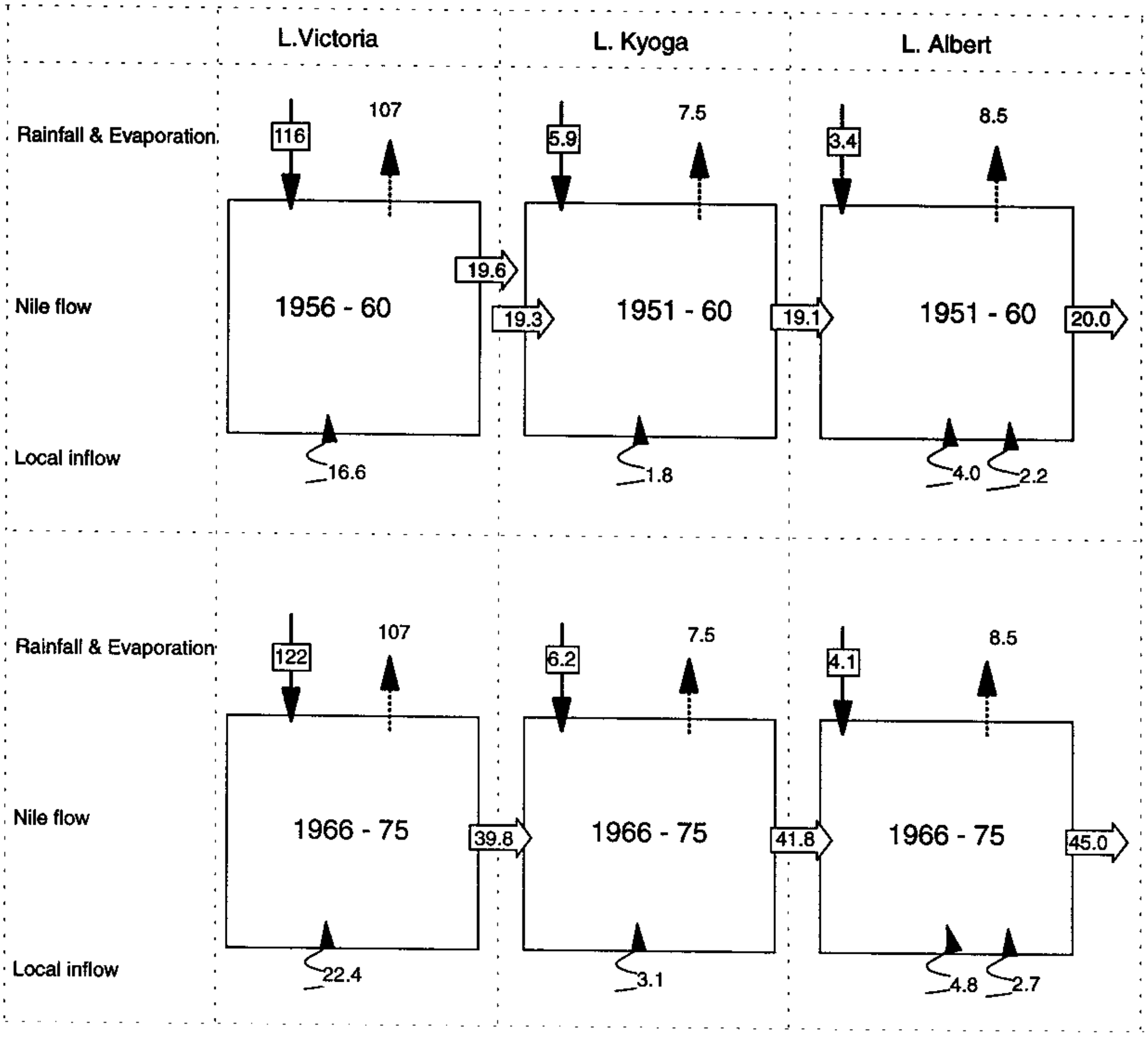


Fig. 4.16 Schematic balance of Lakes Victoria, Kyoga and Albert, km^3 $year^{-1}$.

The overall balance of Lakes Victoria, Kyoga and Albert is indicated in Fig. 4.16, where lake rainfall and local inflow are compared with lake evaporation and outflow for 1951–1960 (1956–1960 for Lake Victoria) and 1966–1975. Each component is estimated as described in the text and expressed as an annual volume (km^3). The balance is not precise and this is partly explained by storage change. However, the figures demonstrate the dominance of lake rainfall and evaporation on Lake Victoria, but also the importance of increased inflow in the later period. The dominance of Nile inflow and outflow for the lower lakes is apparent. The doubling of the overall outflow between the two periods is largely generated in the Lake Victoria basin, but the lower lake basins also contribute to the increase.