The Hydrology of the Nile Basin

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Abstract The hydrology of the Nile is discussed through a description of the various tributaries, ranging from Lake Victoria and its numerous tributaries, through the lower Lakes Kyoga and Albert which contribute inflows to the White Nile in different periods. A major feature of the Lake Plateau is the great increase in outflows between the periods before and after 1961–1964. The lake-fed inflow to the Bahr el Jebel where it enters the Sudd wetland is supplemented by the highly seasonal flow of the torrents, and half the inflow is lost by inundation of the wetlands and subsequent evaporation. The contributions of the Bahr el Ghazal and Sobat tributaries to the White Nile are discussed. The Blue Nile provides the greater part of the flow of the main Nile, but its contribution is more seasonal than that of the White Nile, being the residual of seasonal rainfall on the Ethiopian highlands. The regimes of the Atbara and the main Nile lead to a discussion of the Aswan High Dam and the variability of the tributary flows over the period of records.

1 Introduction

The main characteristic of the Nile basin is its variability; this is to a large extent a result of its size and its length. The topography varies from a region of lakes and moist and forested uplands, through an area of swamps filled with papyrus and seasonal grasslands to a single channel flowing through arid desert, joined by tributaries from a mountainous region. This topographic variety is matched with a variety of climate; its behaviour in time has been equally variable. Superimposed on seasonal variety, the climate has undergone periods of relatively wet and dry rainfall, which have persisted over a number of years. These changes have been

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magnified by the unusual regime of Lake Victoria into periods when the flow of the White Nile has doubled and persisted for some years. These changes have resulted in changes in vegetation downstream, which have impinged on the economy of large areas. Discussion of the hydrology of the Nile basin must deal with different tributaries in turn before the regime of the whole basin can be understood.

1.1 Geography of the Basin

The Nile, as the longest river in the world, extends over a very wide range of latitude, from 4°S to 32°N, and has a total catchment area of nearly 3 million km^2. However, (Said, 1993) the present river course is a recent development. The longitudinal profile (Fig. 1) includes a number of flat reaches linked by steep connecting channels. Rushdi Said describes how the Lake Plateau drained west towards the Congo before the formation of the African Rift led to the presence of Lake Victoria in the depression between the two arms of the Rift, and the reversal of west-flowing rivers like the Kagera, Kafu and Katonga. Both Lake Victoria and the Sudd basin of the southern Sudan were closed basins until they overflowed to the north through Jinja and the Sabaloka gorge north of Khartoum some 12500 years ago.

The furthest tributary of the Nile (Fig. 2) is the Kagera, which drains the mountains of Rwanda and Burundi, before flowing into Lake Victoria through a series of lakes and swamps alongside the channel. A number of other tributaries drain the forested escarpment to the northeast of the lake; these two sources contribute

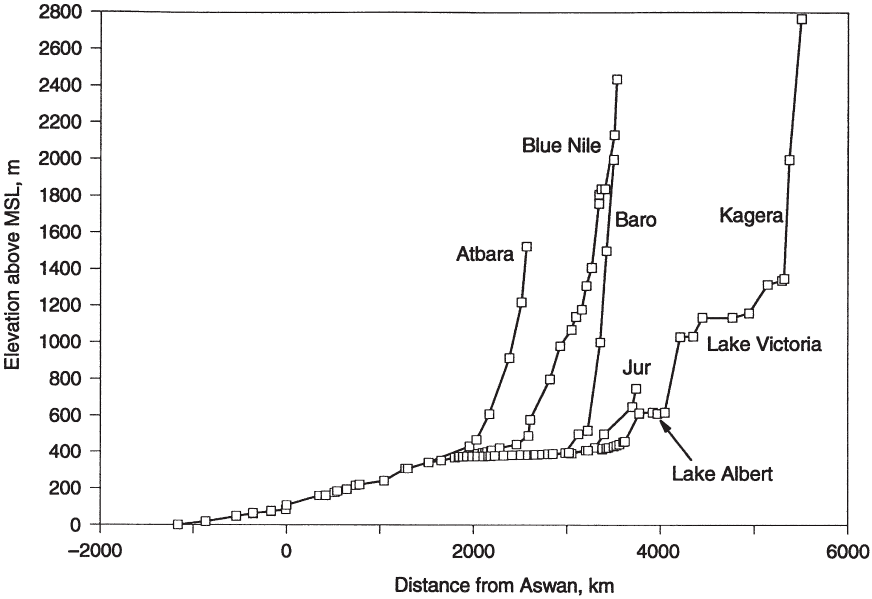

Fig. 1 Profile of the Nile and its tributaries (after Sutcliffe & Parks, 1999)

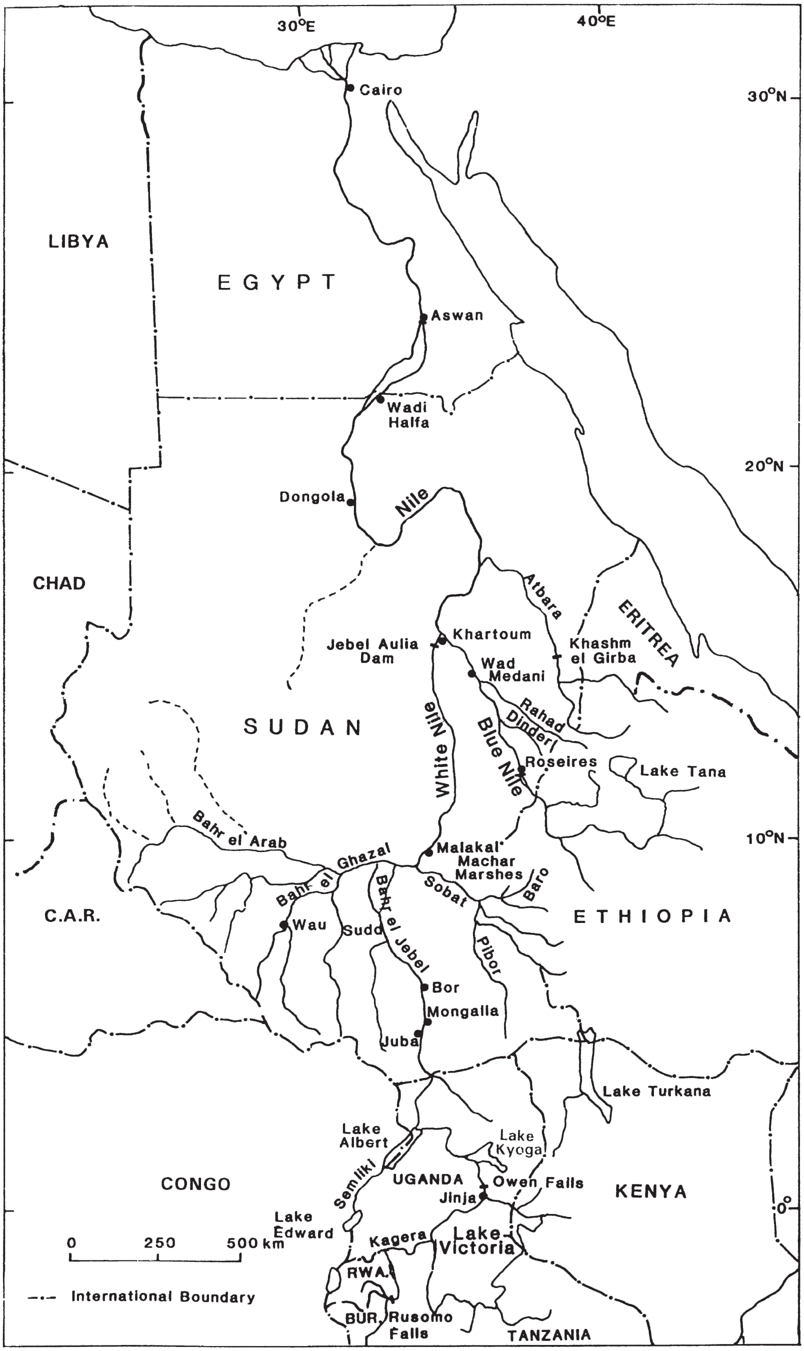

Fig. 2 Key sites of the Nile basin (after Sutcliffe & Parks, 1999)

most of the lake inflow, though other tributaries drain the Serengeti plains and the swamps of Uganda.

The Victoria Nile below the lake is confined to a single channel which leaves the lake at Jinja and reaches Lake Kyoga after about 100 km. This lake is relatively shallow and grass-filled; in some periods the lake causes a net loss of water and in other periods inflow to the lake provides a net gain.

The Kyoga Nile flows from the lake towards the western arm of the Rift Valley through a succession of level reaches and swamps, interrupted by rapids and falls, leading to the Murchison Falls and Lake Albert which it enters through a swamp near its northern end. This lake, unlike the lakes upstream, is located within the Rift Valley with steep sides. It also receives the inflow of the river Semliki which drains Lake Edward and the Ruwenzori mountains. The Albert Nile or Bahr el Jebel then flows towards Nimule in a flat reach through swamp vegetation.

At Nimule the river enters the Sudan, turns to the northwest and flows in a steeper channel towards Juba and Mongalla. Here the Bahr el Jebel enters a large swamp known as the Sudd or ‘blockage’. Between Lake Albert and Mongalla the river receives a number of tributaries known as the torrents, which provide seasonal and sediment-laden flows to supplement the less variable outflow from the East African lakes.

Below Mongalla the channel is inadequate to carry the high flows occurring during the flood season, and the alluvial channels are built up above the flood plain. The excess flows leave the river through small channels through the banks, or spill over the banks at higher flows; they then inundate large areas on either side of the main channel. In the southern part of the swamps the flood plain is limited by higher ground on either side, but further north there is no lateral limit to flooding. High river flows from the torrents coincide with rainfall within the swamps. The maximum extent of flooding occurs after the end of the rainfall season, when net evaporation is high, and water is lost by evaporation. The outflow from the swamp is only about half the inflow, and the seasonal variation of the inflow has been damped out. The large volumes evaporated within the swamps led to various proposals made from 1904 onwards to reduce these losses by various means, including a canal, so that hydrological attention has been focussed on this region. However, the complexity of the channel system and the problems of estimating evaporation from swamp vegetation have made the water balance of the region difficult to solve.

Below the Sudd the White Nile turns to the east at Lake No, where the Bahr el Ghazal enters from the west. Although this tributary drains a wide area with relatively high rainfall, the various tributaries spill into a succession of swamps, and the contribution to the main river is negligible.

The final tributary of the White Nile is the Sobat, whose tributaries the Baro and Akobo drain the southwestern Ethiopian highlands; the Pibor also receives occasional runoff from a wide area of the southeastern Sudan. These rivers spill into the Machar marshes and other wetlands, whose location along the Ethiopia–Sudan border has made detailed investigation difficult.

The course of the White Nile below the Sobat to its confluence with the Blue Nile near Khartoum is confined to a single channel with no inflow except in exceptional years. The steady outflow from the Sudd is supplemented by the seasonal contribution of the Sobat.

Two-thirds of the annual discharge of the main Nile at Khartoum is contributed by the Blue Nile and its tributaries the Dinder and Rahad. The Blue Nile drains a large area of the western Ethiopian highlands, where rainfall is concentrated in a single season and the river flows are highly seasonal. The upper river flows through Lake Tana, but only a small fraction of the inflow occurs above this site. As the rainfall depends on the seasonal migration of the ITCZ (InterTropical Convergence Zone), the length of the rainfall and runoff season decreases from south to north from the Sobat basin to the Blue Nile and the Dinder and Rahad.

The main Nile flows north from Khartoum through the Sabaloka gorge and is joined some 300 km north by the Atbara which drains the northern Ethiopian highlands and part of Eritrea; the runoff season is even shorter than the Dinder and Rahad, and the river is dry for much of the year. Below the Atbara mouth the river flows in a series of loops through an arid region of successive cataracts, where the river flows are reduced by evaporation before entering Egypt within the reservoir of the Aswan High Dam.

1.2 Climate

The climate of the Nile basin is extremely variable. Table 1 illustrates the average rainfall totals and seasonal distributions of various tributary basins of the system. It shows how the regime varies from the bimodal rainfall of the East African Lake Plateau, to a single rainfall season over the Sudd region. The rainfall season

Table 1 Average monthly rainfall over parts of the Nile basin (mm) (after Sutcliffe & Parks, 1999)

Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
Lake Victoria basin (excluding the lake)												
75	90	134	194	145	61	47	68	72	89	111	100	1,186
Lake Kyoga basin												
38	64	108	176	159	99	89	127	121	120	109	66	1,276
Lake Albert basin												
27	55	95	149	137	81	87	128	134	142	121	58	1,214
Lake Albert to Mongalla												
9	25	62	122	154	131	150	162	139	135	68	23	1,180
Mongalla to Lake No												
2	6	25	70	119	121	147	141	125	90	19	6	871
Bahr el Ghazal basin												
4	12	39	90	143	162	186	205	174	118	31	5	1,169
River Baro basin												
18	25	61	118	198	207	220	244	202	125	63	22	1,503
Pibor, Akobo, Veveno basin												
4	12	33	89	122	118	155	165	123	88	35	10	954
Ethiopia												
14	28	57	91	125	137	237	243	167	73	34	21	1,227
Lower Blue Nile basin												
0	0	0	2	8	24	84	109	44	8	0	0	279
Main Nile												
0	0	0	0	2	1	12	18	3	0	0	0	36

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continues to shorten to the north, to the relatively dry regime of the lower Blue Nile and the arid main Nile reach.

Compared to the size of the basin, the total flow of the Nile is comparatively low; the average annual runoff from the whole basin is only about 30 mm. This runoff is very variable across the basin; the areas which make significant contributions are quite small. They are largely confined to the East African lake region, where rainfall is high and spread between two rainfall seasons, and to the Ethiopian highlands where high rainfall within a short season and steep slopes result in relatively high and concentrated runoff. The climate and runoff regimes are discussed further under individual tributaries.

1.3 The Hydrometric Network

Although Nilometers had been used to measure flood levels on the Nile for thousands of years, the first modern staff gauges were installed at Aswan and Khartoum in the 1860s. Scientific river flow measurement began about 1900, when staff of the Survey of Egypt measured discharges of the Blue and White Niles using Price current meters. The Sudan branch of the Egyptian Irrigation Service was formed in 1905 to erect gauges on the different tributaries of the Nile. By 1912 gauges had been installed at most of the important sites within the Sudan. In 1915 Dr H. E. Hurst became head of the Physical Department, who established a comprehensive network of gauges throughout the basin, including the East African lake system, and published in '*The Nile Basin*' descriptions of all the different basins and summaries of all gauge levels, discharge measurements and 10-day flows (Hurst et al., 1933). By 1953 the number of river discharge stations had reached a maximum of over 150 stations, but gradually the number of records published has decreased as the responsibility for maintaining stations was taken over by upstream hydrological services or as conditions in the southern Sudan made access difficult. Nevertheless the sixty or so volumes and supplements of '*The Nile Basin*' present an unparalleled record of the behaviour of the river system over most of the 20th century. Since 1967 a number of international organisations have carried out investigations in the East African basin, and a series of conferences held in different basin countries have led to informal exchange of technical findings. These activities, along with support from multi-lateral agencies such as the World Bank, have helped contribute to the establishment of the Nile Basin Initiative in 1999.

2 East African Lake Plateau

2.1 Lake Victoria Basin

It has been pointed out (Flohn & Burkhardt, 1985) that the true source of the Nile is not the outfall of Lake Victoria at the Ripon Falls, nor the headwaters of the Kagera in the highlands of Rwanda and Burundi, but the nocturnal cloud above the lake which provides most of the inflow to the lake. Therefore improved estimates of the lake rainfall in addition to tributary inflows have provided an essential element to the understanding of the lake water balance.

The contributions of the various tributaries are discussed before dealing with rainfall and evaporation over the lake. The Kagera is the major tributary contributing to Lake Victoria, and its basin contains a large number of small lakes and swamps. With a basin area of 60,000 km^2, it drains, with its tributaries the Ruvuvu and Nyabarongo, much of Rwanda and Burundi as well as parts of Tanzania and Uganda. The basin rises above 2,500 m in the west, with peaks up to 4,500 m; the annual rainfall is less than 1,000 mm in the east but rises to 1,800 mm in the west. There are two rainfall seasons, in February–May and September–November, but the runoff, which reaches a peak in April in the upper reaches, is delayed by lakes and swamps formed by drainage reversal to May at Rusumo Falls, and by further lakes and swamps to July at Kyaka Ferry above the mouth of the river; at this point the mean runoff is only 136 mm compared with rainfall of 1,170 mm. The feature of the flow series, which has been measured since 1940, was a marked rise to higher flows after 1961; this increase is reflected in the lake levels and outflows.

Although the Kagera provides the largest tributary inflow to Lake Victoria, a large number of other rivers flow into the lake and together contribute twice the flow of the Kagera. The flows of these other tributaries are available from various dates; four of the major tributaries in the northeast of the lake have been measured since 1956, and nearly complete tributary flows for the period from 1969 to 1978 were obtained by the WMO Hydrometeorological Survey. This Survey was established to investigate the cause of the rise in the lake after 1961. The total flows of the four tributaries were compared with the total tributary runoff (excluding the Kagera) by the Institute of Hydrology in 1985 and monthly multipliers were calculated to complete the inflow series for the whole period 1956–1978.

The annual totals, including the Kagera, are shown in Table 2, where the totals are also expressed as mm over the lake surface of 67,000 km^2. Although the average tributary inflow of 343 mm is only about 15% of the total lake supply, which is dominated by the rainfall component, the runoff is much more variable than the rainfall itself, because runoff coefficients increase with rainfall amount. The variability of the tributary inflow is about three times that of the rainfall, and this component is important to the water balance of the lake.

The rainfall over the lake surface provides the largest component, 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 measurements have been taken around the lake peri-meter. Only eight stations have been measured regularly since 1925 or earlier, and these have been used in various studies of the lake water balance. The problem is complicated by evidence from the timing of rainfall on different shores, and by some rainfall measurements on islands, which together suggest that rainfall on the lake surface is higher than at lakeside stations. A model (Datta, 1981) has explained this by convergence and lifting of westerly land breezes and prevailing easterlies, which give rise to convection storms in the morning on the western shore and in the evening on the eastern shore. This has been estimated to double the rainfall which would have occurred if the lake were not present

Table 2 Annual water balance of Lake Victoria, 1956–1978 (after Sutcliffe & Parks, 1999)

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	1,787	4,918	19,326	288	19,636	293	10.91
1957	1,727	6,299	18,121	270	20,112	300	11.02
1958	1,622	5,412	14,629	218	19,671	294	10.94
1959	1,702	4,730	13,310	199	18,434	275	10.84
1960	1,827	6,160	17,526	262	20,348	304	10.87
1961	2,370	4,895	21,856	326	20,577	307	11.94
1962	1,919	9,114	36,136	539	38,716	578	12.39
1963	2,121	10,941	34,664	517	44,788	668	12.91
1964	2,011	11,045	32,332	483	50,476	753	12.88
1965	1,663	7,760	17,428	260	46,878	700	12.48
1966	1,889	7,951	21,435	320	42,950	641	12.32
1967	1,752	6,421	21,448	320	37,832	565	12.31
1968	2,114	10,375	32,600	487	43,305	646	12.58
1969	1,770	8,923	21,083	315	46,006	687	12.36
1970	1,865	8,477	27,572	412	44,282	661	12.45
1971	1,639	7,030	20,139	301	39,510	590	12.17
1972	1,975	7,587	19,950	298	37,540	560	12.35
1973	1,749	7,717	19,982	298	38,467	574	12.05
1974	1,657	7,331	20,946	313	35,046	523	11.97
1975	1,826	6,082	18,968	283	33,326	497	12.04
1976	1,781	5,932	14,409	215	34,835	520	11.82
1977	1,938	6,980	29,147	435	35,999	537	12.13
1978	2,041	8,525	35,575	531	39,383	588	12.56
Mean	1,858	7,418	22,982	343	35,136	524	
SD	180	1,799	6,908	103	9,976	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).

(Flohn & Burkhardt, 1985). In an early study by the Institute of Hydrology (Piper et al., 1986) this enhanced rainfall was estimated by enhancing the deviations from the mean, but in a later study (Sene & Plinston, 1994) the lake was treated as a giant raingauge and a linear relation derived between lakeside rainfall and net lake rainfall deduced from the water balance for 1969–1978. Lake rainfall series were then deduced using constant evaporation estimates. This lake rainfall series for 1956–1978 (Table 2) shows a trend to higher rainfall, which is largely explained by an increase in rainfall in October and November after 1961/62. Extreme October–November rainfall seasons are associated with El Nino Southern Oscillation and Indian Ocean Dipole events and have caused widespread socio-economic disruption (e.g. 1961 and 1997, Conway, 2002).

The water balance is completed with outflow totals which were measured at the Ripon Falls before 1954, and after construction of the Owen Falls hydroelectric dam were controlled by agreement to maintain the natural relation between lake level and outflow. The flows could be estimated from this ‘Agreed Curve’ or derived from the turbine/sluice releases. Lake evaporation estimates were based on Penman estimates for stations around the lake, and the lake levels and volumes measured at Jinja.

The water balance can be illustrated by the annual balance (Fig. 3) for the period 1956–1978, which is the period when measurements of the water balance constituents

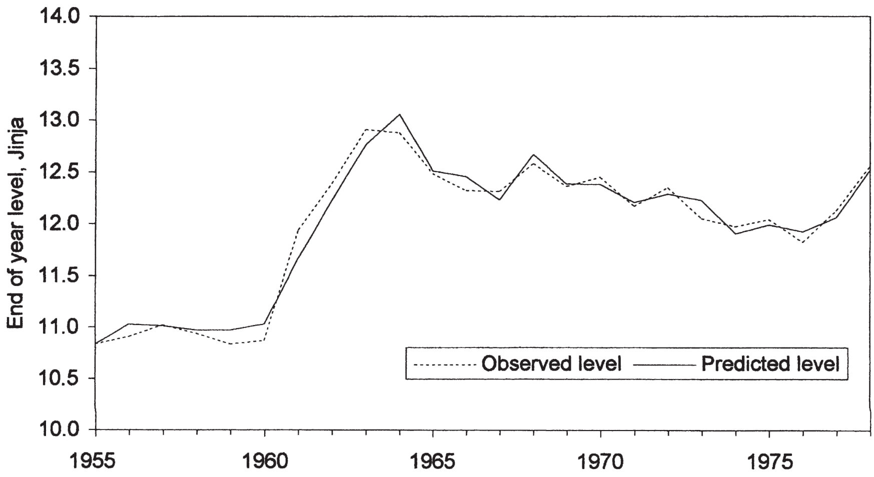

Fig. 3 Lake Victoria annual water balance, 1956–1978 (after Sutcliffe & Parks, 1999)

have been most complete. This covers the period of the lake level rise in 1961–1964, and shows that it is possible to explain the behaviour of the lake during this period. Reasonable results were also obtained by Sene & Plinston (1994) for the periods 1925–1990 and 1900–1990.

Because river flows have been measured at Aswan since 1870, and because low flows at this site are largely composed of outflows from the East African lakes conveyed by the White Nile, it has been possible to estimate lake levels by correlation with downstream flows for the period from 1870 until lake levels were measured in 1896. These modelled levels were found to correspond reasonably with levels deduced from early travellers' observations (Tate et al., 2001) and show that the rise in lake level which occurred in 1961–1964 was not unique, but that earlier rises had been followed by returns to lower levels more rapidly than after 1964 (Fig. 4).

There is also evidence from an archaeological investigation near Entebbe that the high lake level of 1964 has been near the limit of levels over a long period. Bishop (1969) has 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." He deduced that Lake Victoria had not risen to occupy the 10- to 12-foot cliff notch in the past 3,720± years; this corresponds with a Jinja gauge level of 13.85–14.45 m.

Although the Jinja levels from 1896 to 2000 reflect the water balance of Lake Victoria while the outflows corresponded to the Agreed Curve, the outflows have increased above the Agreed Curve in recent years. The natural level series can be estimated by adjusting the measured lake levels for over-abstraction on a continuous basis to those which would have occurred if the Agreed Curve had been followed. The measured levels after 2000 have been adjusted on a monthly basis to obtain the natural series illustrated in Fig. 5 (Sutcliffe & Petersen, 2007).

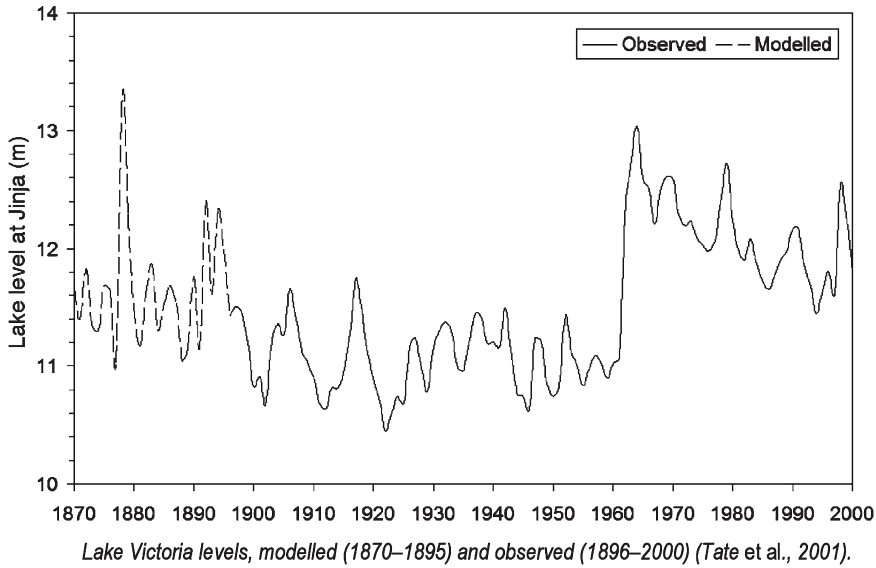

Fig. 4 Lake Victoria levels, modelled (1870–1895) and observed (1896–2000) (after Tate et al., 2001)

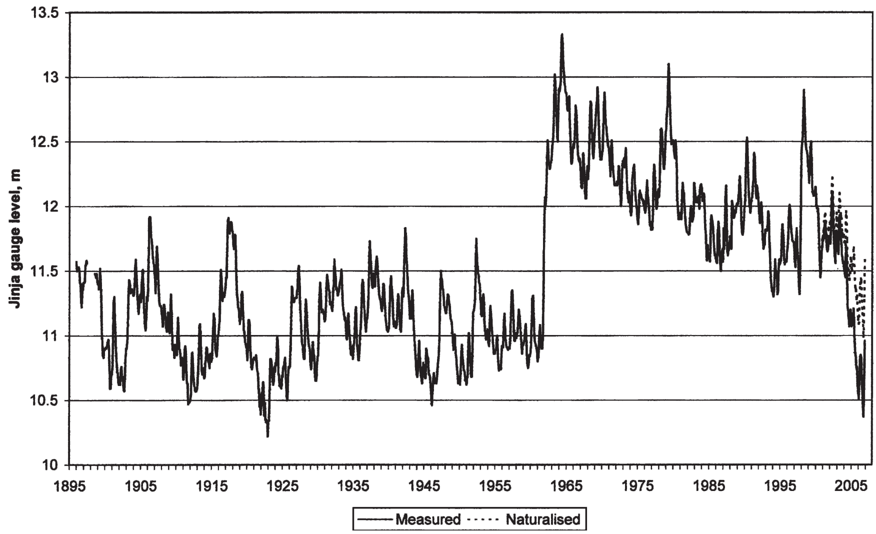

Fig. 5 Lake Victoria levels, 1896–2006 after Sutcliffe & Petersen, 2007

2.2 Lake Kyoga

The Victoria Nile flows north from the Owen Falls complex towards Lake Kyoga in a channel with a series of rapids and falls. Lake Kyoga is unique among East African lakes as it is essentially a dendritic river valley which formed the headwaters of the River Kafu flowing to the west. The formation of the Rift Valley reversed the direction of flow of the Kafu, and resulted in the Victoria Nile entering Lake Kyoga from the side and leaving to the north through Masindi Port. The lake is relatively shallow and its surface is fringed with papyrus and floating vegetation; the lake has recently been invaded with water hyacinth. The inflows to the lake correspond to the outflows from Lake Victoria, while the lake outflows have been measured at various sites; however, the most reliable estimates have been derived for the period 1940–1979 from water levels at Kamdini and discharge measurements at Kamdini, Fajao and Paraa downstream (Sutcliffe, 1996; Sutcliffe & Parks, 1999). These records show that during the period 1951–1960, before the rise in Lake Victoria levels and outflows, the outflows from Lake Kyoga are slightly lower than the inflows, whereas in 1966–1975, after the rise the outflows were 5% higher than the inflows. This is doubtless due to increased local inflow in a period of higher rainfall, but few measurements of this local inflow exist.

2.3 Lake Albert

The Kyoga Nile, in its course from Lake Kyoga to Lake Albert, first flows down the course of the River Kafu, but when it meets the reversed course of this river, turns north past Masindi Port. There are a number of rapids and falls, culminating in the Murchison Falls where the channel reaches the Rift Valley before entering Lake Albert. The topography of Lake Albert contrasts with the other lakes, as the lake lies along the course of the Rift Valley and the sides of the Rift form steep slopes rising from the lake.

Although the rainfall on the lake surface is relatively low and less than lake evaporation, Lake Albert receives the inflows of the River Semliki, which contributes some $4.5\,m^3 \times 10^9$ from the basins of Lakes Edward and George and the Ruwenzori mountains. The water balance of this lake is not easy to calculate, as precise estimates of rainfall and evaporation are not available. However, it is clear that, after the rise in Lake Victoria rainfall, lake levels and outflow in 1961–1964, the inflow from the Semliki and local runoff also increased, and Lake Albert has contributed significantly to the flow of the Bahr el Jebel or White Nile after 1964. A summary of the water balances of Lake Kyoga and Lake Albert is given in Fig. 6.

The Albert Nile flows in a very flat channel confined within swamp vegetation as far as Nimule, where it turns to the northwest and flows into the Sudan; here it is known as the Bahr el Jebel.

3 White Nile Basin

3.1 Bahr el Jebel and the Sudd

The river course as far as Juba is steep and passes through several rapids. It also receives between Lake Albert and Mongalla a number of seasonal streams known as the torrents, which have steep basins and contribute spates and heavy sediment

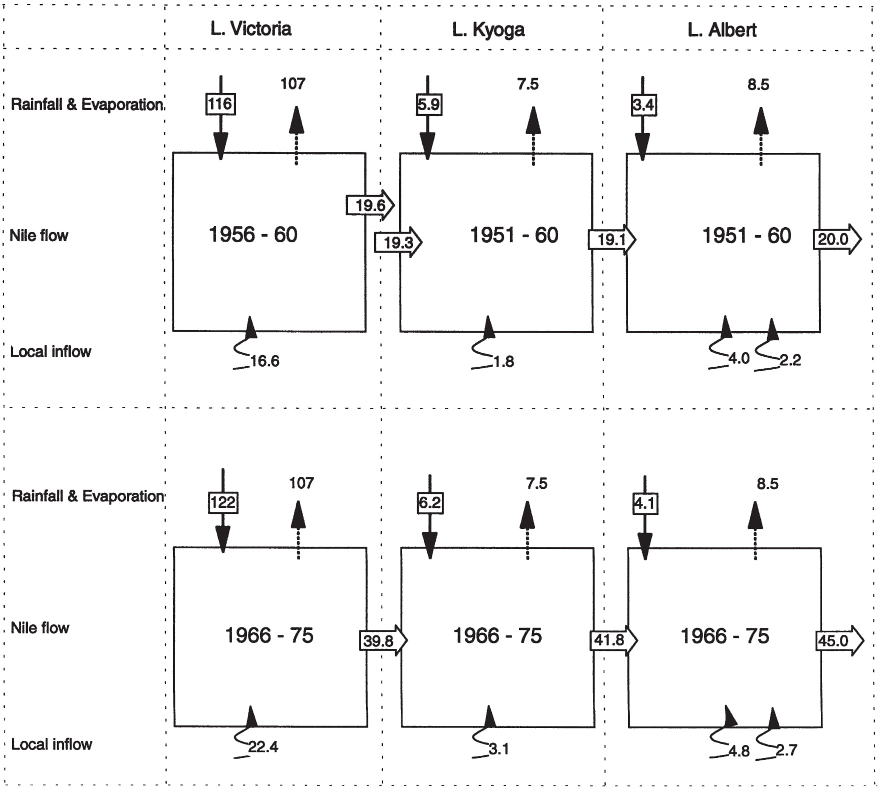

Fig. 6 Schematic balance of Lakes Victoria, Kyoga and Albert, km^3 per year (after Sutcliffe & Parks, 1999)

as a result of local rainfall between April and October. At Mongalla, where the river enters the swamps and seasonal grasslands of the Sudd, the flow is made up of the outflow from the East African lakes, which is seasonally fairly constant but has in the past been liable to severe fluctuations on a longer time scale, together with the torrents providing the seasonal high flows.

The inflows to the Sudd have been measured at Mongalla from 1905 to 1983, while the outflows have been measured as the difference between flows at Malakal on the White Nile and the inflows from the Sobat tributary just upstream from Malakal. The inflows from the Bahr el Ghazal are negligible by comparison. The outflows from the Sudd are on average only about half the inflows, so that half the inflow is lost by spill and evaporation. For this reason the hydrology of the Sudd has been a major focus of the investigations of the Egyptian Irrigation Service, since a canal to bypass the Sudd was first suggested in 1904.

Some description of the topography is necessary to understand the hydrology of the Sudd. Between Juba and Mongalla the river is incised within an even plain sloping gently north or east of north, turning west of north below Gemmeiza; this plain is flanked by scarps of a few metres marking the limit of woodland on either side; these scarps decrease in height from south to north, fading out north of Bor on the east bank and south of Shambe on the west. From Juba to Bor the river meanders in one or more channels from one side of the restraining trough to the other, dividing the flood plain into a series of isolated basins or islands. These basins are below the levels of the alluvial river banks, which are pierced by many spill channels; at the downstream limit of each basin, a large channel carries spill back into the river. Further north, there is no lateral limit to the flood plain, and spillage to the east leads to large areas of seasonally flooded grassland and permanent swamp. It is important to note that the doubling after 1964 of the base flow from the East African lakes has led to a large increase in the area of permanent swamps.

The complex flooding process is best illustrated by the study of sample basins. In 1951–1952, when river flows were very low, a number of sample reaches between Juba and Bor were surveyed (Sutcliffe, 1957, 1974). The way in which spill leaves the river can be deduced from cross-sections of the flood-plain and sections of the river bank. At moderate flows and levels, spill passes through the alluvial banks of the river through a succession of spill channels. A survey along the east bank of the river from Mongalla to Gemmeiza revealed 170 spill channels over 57 km. When river levels are high widespread spilling occurs over the banks of the main river, starting in the north of the basin where banks are relatively low and spreading upstream. When the flood-plain is inundated, the stored water flows north parallel to the river either through channels or through the swamps. A cross-section of the floodplain east of Tombe (Fig. 7) illustrates the process at this stage.

Where the river touches the high ground, a channel invariably carries upstream spill back into the river. Thus the basins of the floodplain, especially above Bor, act as a series of reservoirs which receive flood water and return water to the river downstream. The volume of water in temporary storage increases as the river rises and decreases as it falls. For example, the return channel at Gemmeiza was stagnant in March 1952 when the Mongalla basin was relatively dry, but was flowing strongly in February 1982 when the higher lake outflows caused large scale spilling into the basin. Between Juba and Bor the flooding is confined by higher ground but below Bor and Shambe these limits disappear and flooding extends further during high flows.

However, a detailed study of the basin between Mongalla and Gemmeiza enabled the volumes and levels of flooding to be deduced from inflow records at Mongalla and outflow records at Gemmeiza and Gigging on the west bank. The volumes of flooding were related directly to Mongalla inflows and thus to frequency and duration of flooding. Comparison of flooding levels and vegetation species recorded on the flood-plain cross-sections revealed how hydrological factors control the wetland vegetation. This procedure was extended to develop a simple hydrological model to describe the behaviour of the whole Sudd over the period of flow records.

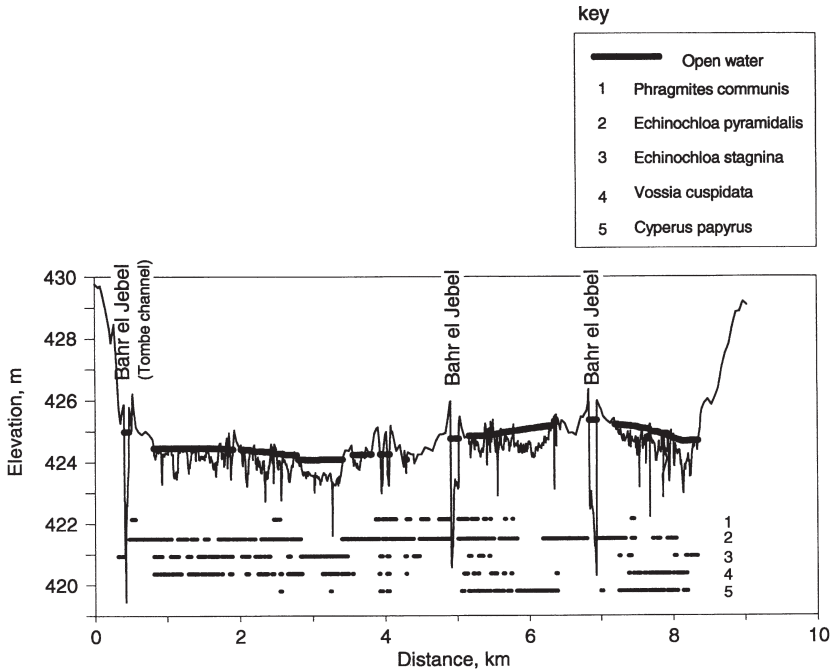

Fig. 7 Bahr el Jebel valley cross-section east from Tombe (after Sutcliffe & Parks, 1999)

3.2 Hydrological Model of the Sudd

After construction of the Jonglei Canal had begun, interest in the local effects of the canal was renewed and as a part of an environmental study a hydrological analysis of the Sudd was carried out by the Institute of Hydrology (Sutcliffe & Parks, 1987; Howell et al., 1988). The whole area of the Sudd was modelled, as flow records within the Sudd were not available after the rise in Lake Victoria and Bahr el Jebel flows after 1964. The inflows at Mongalla and outflows from the swamps were available from 1905 to 1980. Monthly rainfall records at eight stations around the Sudd were used to derive a swamp rainfall series for the same period. A reasonable estimate of swamp evaporation is vital for realistic modelling of the Sudd. Early measurements of evaporation from tanks filled with water and papyrus gave results which were too low to explain the water balance, but improved experiments by Migahid using tanks with healthy vegetation gave results which Penman (1963) suggested as showing that swamp transpiration and open water evaporation were nearly equal. Open water evaporation, estimated by the Penman method from temperature, humidity, sunshine and wind speed at Bor, corresponds to 2,150 mm/year and average values were used in the model. The model is based on the equation of continuity and treats the swamp as a reservoir receiving inflow from the river and rainfall on the flooded area. The losses include outflow, evaporation from the flooded area, and infiltration into newly flooded ground, estimated as 200 mm at the start of the wet season. A relation between volume V and area A of flooding is required, and field evidence suggested that a simple linear relation was reasonable. Thus A = kV was used which implies a constant mean depth of 1/k as the area increases; 1/k was estimated as 1 m.

The equation of continuity for a time interval dt is:

$$dV = [Q - q + A(R - E)]dy - rdA \quad (1)$$

where V is volume of flooding, Q is inflow, q is outflow, R is rainfall, E is evaporation, A is flooded area and r is soil moisture storage, which is positive but set to zero when dA is negative. The analysis for month t, allowing for rainfall and evaporation over the mean of the initial and final values of area A, and substituting kV for A, becomes:

$$V_{i+1} = V_i + Q_i - q_i - k/2(V_i + V_{i+1})(E_i - R_i) - kr_i(V_{i+1} - V_i) \quad (2)$$

and hence

$$V_{i+1} = V_i\,[1 + k\{r_i - (E_i - R_i)/2\}] + Q_i - q_i/[1 + k\{r_i + (E_i - R_i)/2\}]. \quad (3)$$

Storage volumes and flooded areas were estimated at monthly intervals starting from initial estimates of 8,000 $m^3 \times 10^6$ and 8,000 km^2. These model estimates (Fig. 8) corresponded reasonably well with estimates of flooded areas derived over the years from survey maps, vegetation maps and satellite imagery. The series of

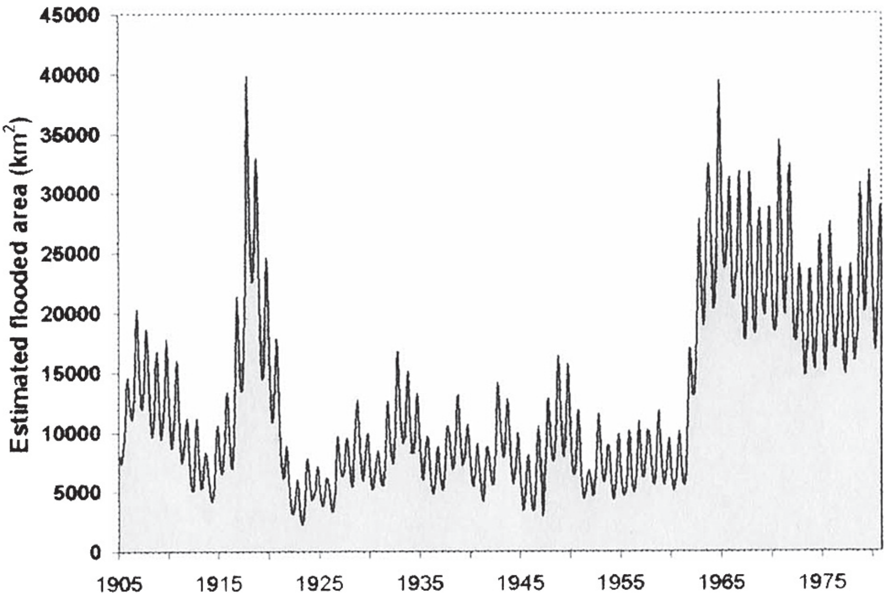

Fig. 8 Bahr el Jebel swamps: monthly estimates of flooded areas, 1905–1980 (after Sutcliffe & Parks, 1987)

monthly flooded areas show the influence of the seasonal torrents in providing areas of annual flooding and recession, which provide the important areas of dry season grazing, while the lake-fed flows of the Bahr el Jebel below Lake Albert are responsible for the more permanent swamp. The important effect of the rise in Lake Victoria after 1961–1964, when the areas of permanent swamp more than doubled, is also shown.

By substituting measured outflows from the Sudd by outflows derived from inflows over the period of records, the model could be run without measured outflows. Then the inflows were reduced by abstractions into the Jonglei Canal and the model was rerun and the flooded areas derived. This suggested that, with the Jonglei Canal operating with a constant discharge of $20\,m^3 \times 10^6\ day^{-1}$, the seasonally flooded areas would be reduced by some 26% in the lower flow period of 1905–1961, and by 17% in 1961–1980; the permanent swamp would be decreased by 46% and 21% respectively. The hydrological modelling also suggested that the adverse impact could be reduced by varying the canal flows seasonally; altering the canal flow to $25\,m^3 \times 10^6\ day^{-1}$ from November to April and $15\,m^3 \times 10^6\ day^{-1}$ from May to October would lead to a decrease in seasonal flooding of only 12% in the early period and 10% in the later period.

3.3 Vegetation Distribution

A similar water balance of the Mongalla basin, on the right bank between Mongalla and Gemmeiza (Sutcliffe, 1957, 1974), showed that the volume of water in transit through the basin could be related to the inflow, and therefore the volume of seasonal flooding could be deduced from the records at Mongalla. A survey of this basin carried out in 1951–1952 included 12 cross-sections of the basin, as well as a longitudinal survey of the alluvial bank of the river, transects of the vegetation and soils along the cross-sections, and studies of the use of the valley for grazing. From the recorded vegetation along each cross-section (Fig. 9), the distribution of species could be deduced along each cross-section and down the flood-plain. This revealed a distinct elevation boundary between the deep-flooded species (*Echinochloa stagnina, Vossia* and *Cyperus papyrus*) and the shallow-flooded species (*Echinochloa pyramidalis*, *Oryza* and *Phragmites*). The vegetation boundary was traced along the river profile and shown to be parallel to the high river level; it was deduced that the boundary was controlled by the maximum depth of flooding, and it was estimated from the statistics of flooding volume that this maximum depth was 1.3 m. Because papyrus was limited to the lower end of each basin, and the range of flooding increases from the lower to the upper end of each basin, it was deduced that the presence of papyrus, anchored by fragile rhizomes, is controlled by the range of flooding; the limiting vertical range was 1.5 m. These conclusions on how the hydrological conditions control the vegetation (Sutcliffe, 1957, 1974; Sutcliffe & Parks, 1996) were supported by the areal distribution of species, by similar analysis of the Aliab valley opposite Bor and by observation elsewhere in the Sudd.

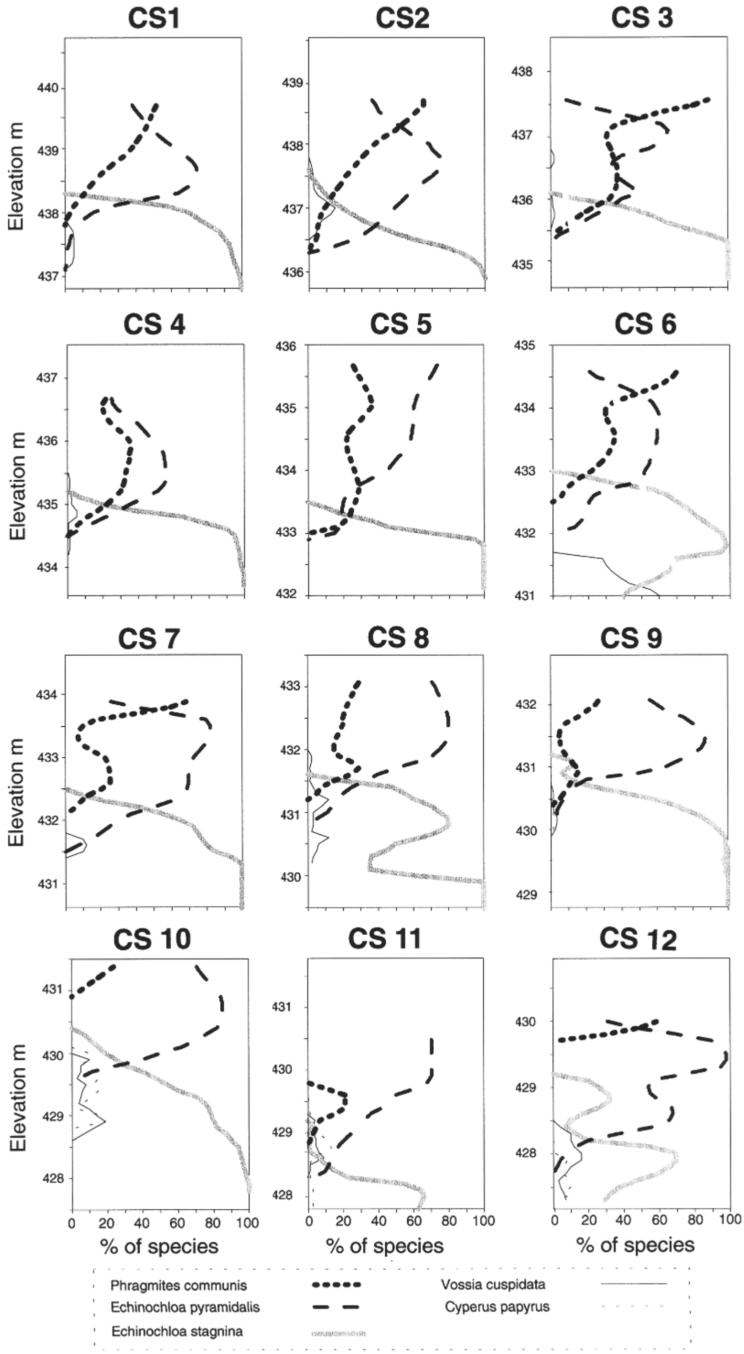

Fig. 9 Mongalla basin: vegetation and elevation on cross-sections (after Sutcliffe & Parks, 1999)

The observed changes in the Aliab valley after the rise in Lake Victoria and the doubled outflows and the resulting vegetation change support the deductions about the links between flooding and vegetation. During the 1982 hydrological study, the opportunity was taken to observe the Aliab valley from the air at low level along the survey cross-sections, armed with vegetation and topographic maps of the 1951 survey. *Vossia* and papyrus had spread over areas previously dominated by grazing grasses. The spread of key species between 1951 and 1982 is illustrated by Fig. 10. Because the seasonal torrent flow volumes had not increased after 1961, but the area of flooding had doubled, the range of flooding would have decreased to favour papyrus. In the drier Mongalla basin, by contrast, the increased flooding had resulted in the increase of grazing grasses, and cattle were observed grazing areas which had previously been dominated by *Phragmites*.

The distribution of these vegetation species on the floodplain was important because the pastoral economy relied on the dry season grazing from *Echinochloa* species and *Oryza*, while the papyrus swamp and *Phragmites* provide no grazing. The local economy was based on annual migration to the flood-plain during the dry season, and on rain-fed vegetation during the rest of the year. The maintenance of the seasonal inflow regime, with steady outflow from the East African lakes with a modest seasonal variation, and the seasonal contribution of the torrents leading to the annual inundation and uncovering of the flood-plain, were essential to the pastoral economy; alternative agriculture on the higher ground was difficult because of the frequency of either drought or excessive flooding.

The contribution of the White Nile flowing out of the Sudd has continued to be fairly constant in seasonal terms, but also reflects the increased contribution of the East African lakes; however, the losses in the Sudd, because of the greater areas of flooding, have increased disproportionately and the flows of the White Nile have not increased as much as the lake outflows.

3.4 Bahr el Ghazal

The Bahr el Ghazal tributary, which joins the Bahr el Jebel at Lake No to form the White Nile, is unusual because it has relatively high rainfall but its contribution to the flow of the main Nile is almost negligible. The annual rainfall of 1,200–1,400 mm is spread over a relatively long period between March and October, and feeds a number of individual tributaries which flow from the fairly impermeable upper plateau towards clay plains and Lake No. After soil moisture recharge, runoff occurs between June and November and averages about 60–100 mm over the gauged basins. Each of the rivers leaves the plateau in defined channels, but then meanders through flood plains in alluvial channels, with initial spill over limited areas during high flows. They converge downstream in complex swamps where spill occurs into widening flood-plains and unconstrained clay plains causing seasonally flooded grasslands and areas of permanent papyrus swamp.

River flows have been measured at a number of gauging stations sited along the main road from Juba to Rumbek, Wau and Aweil where the rivers leave the ironstone

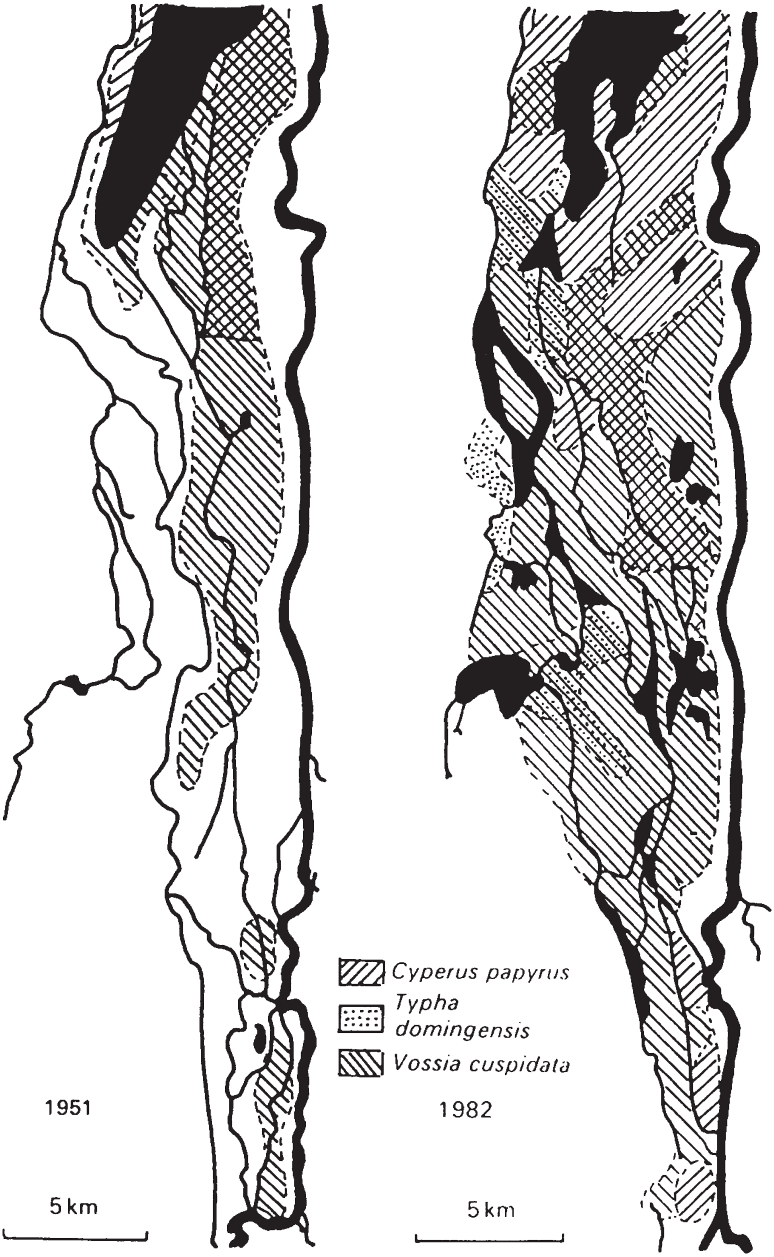

Fig. 10 Aliab valley: channels and vegetation in 1951 and 1982 (after Sutcliffe & Parks, 1999)

peneplain and enter the clay plains. These gauges were established by the Egyptian Irrigation Department and levels were read from 1932; regular discharge measurements began about 1942 and were maintained until 1961; the flows were published in '*The Nile Basin*'. After 1970 measurements at key sites were resumed by the Sudan authorities and published in yearbooks, but were discontinued about 1986. A number of estimates of the total flow of the Bahr el Ghazal tributaries have been made over the years. They vary from 12.3 $m^3 \times 10^9$ (Hurst et al., 1978) to 11.3 $m^3 \times 10^9$ (Sutcliffe & Parks, 1994), but other authors (e.g. Chan & Eagleson, 1980) have estimated considerable additional unmeasured flow by comparing measured runoff with the catchment yield simulated by a conceptual model. It is likely that measured flows have been underestimated by spill bypassing the gauging stations but the topography of the sites must limit this effect.

It is clear from these records that the increase in rainfall and river flows which occurred in the Lake Victoria basin after 1961, did not affect the Bahr el Ghazal basin. There has been a decrease in flows in the 1970s and 1980s which is more similar to the Blue Nile basin.

The wetlands of the Bahr el Ghazal system have not received the detailed attention as those of the Bahr el Jebel, but the species and the influence of the hydrological regime are likely to be similar. The seasonal distribution of the inflows and the inundation and uncovering of the floodplains are similar, but the extent of the flooding are not known so precisely. A satellite image of December 1986 (Sutcliffe & Parks, 1999) illustrates a number of isolated areas of flooding, totalling about 4,000–5,000 km^2, which is considerably smaller than the area of the Bahr el Jebel wetland of the same date. The importance of these wetlands to the local economy is underlined by the distribution of population (see Sutcliffe & Parks, 1999, Fig. 6.4). There are proposals for conservation works to reduce the evaporation losses in the Bahr el Ghazal, but these require more precise hydrological estimates than are available at present.

3.5 Sobat Basin

The Sobat flows into the White Nile from the east just above Malakal, and contributes about half the flow of the White Nile; its contribution is therefore about equal to the outflow from the Sudd. As the river derives most of its runoff from the mountains of southwest Ethiopia, its flow is seasonal and it provides the seasonal element to the flow of the White Nile. However, the river system loses a lot of spill in the region of the Sudan–Ethiopian border, where flow measurements are not complete, so its regime is known with less precision than other rivers.

There are two main tributaries of the Sobat: the Baro and the Pibor. The Baro drains an area of the Ethiopian mountains east of Gambeila, and the Pibor receives the flow of the Gila and Akobo from the mountains south of the Baro basin, but also drains a wide area of the plains east of the Bahr el Jebel which provides high runoff in some years. The upper Baro above Gambeila, where flows were measured by the Egyptian authorities from 1905 to 1959, receives runoff from a number of mountain streams which flow through deep gorges. Below Gambeila it flows towards the Pibor junction, but about 100 km above this junction it splits into the Adura and Baro which rejoin downstream; these rivers receive tributaries but also lose water through several spill channels leading towards the Machar marshes. In addition the river overtops its banks at high flows and inundates wide areas. The Machar marshes are a wetland to the north of the Baro, whose extent is little known except from satellite imagery. Outflow from these marshes sometimes reaches the White Nile.

The main contribution to the Pibor channel comes from the Gila and Akobo, which drain areas of the Ethiopian plateau rising to 2,500 m elevation. The Pibor above the Akobo junction forms the outfall for a number of ephemeral streams which drain a large area of the plain between the Bahr el Jebel and the mountains; the runoff from this area is likely to be small in most years as rainfall is low. These streams start as depressions in the southern part of the plain which are ill-defined but are filled with swamp vegetation towards the northern limit; there is evidence that in a few years there is significant inflow from these streams. This may well include the result of 'creeping flow', which has been observed on several occasions and consists of the slow movement of large bodies of water across a gently sloping and impermeable plain following heavy rain.

Although a large number of observations have been made and gauges established to study the interchange of river flows and swamps between Gambeila and Nasir, the complexity of the channel system and the intermittent nature of the flow records make it difficult to quantify the balance with any precision, but a number of estimates have been made over the years (Sutcliffe & Parks, 1999, Fig. 6.5). There have been proposals to reduce the amount of water evaporated in the Machar marshes either by regulating the river flows by means of upstream storage to reduce spill or by constructing a channel to convey water through the swamps. Satellite imagery is likely to be useful in further investigation.

Analysis of inflows and outflows in the Sobat channel and flood-plain adjacent to the Sobat channel between Nasir and the Sobat mouth has shown that losses and gains of water can best be explained by the flooding and drainage of a wide area of plain flanking the river channel. The outflows from the Sobat into the White Nile have averaged 13.5 $m^3 \times 10^9$ over the period 1905–1983. There has been no significant difference between the periods before and after 1961.

3.6 White Nile

The White Nile between the Sobat mouth and the junction with the Blue Nile at Khartoum is largely self-contained and only falls about 13 m over a distance of 840 km. The flood-plain storage results in some delay in the outflows and causes losses by evaporation. The natural backing up of the White Nile during the Blue Nile flood also results in delayed outflow and increased evaporation losses. The construction of the Jebel Aulia dam above the confluence, originally designed to store water for irrigation in Egypt during the low flow season, also raises river levels upstream and has facilitated the development of irrigation upstream along the White Nile.

The inflows to the White Nile above Malakal combine two very different components. The outflows from the Sudd reflect the outflows from the East African lakes and the seasonal torrents, reduced and highly damped by losses in their passage through the swamps; however, they also reflect the rise in levels and outflows of Lake Victoria and the other lakes, so they include a muted rise after 1961–1964. They also reflect the seasonal outflows of the River Sobat, which derive from the extended rainfall season in the southern Ethiopian highlands, damped by spill of the higher flows along the river course.

Analysis of the water balance of the White Nile reach, taking account of flood-plain storage related to river levels, showed that the apparent losses and gains could be explained by inundation of the flood-plain, with associated soil moisture recharge and evaporation, and subsequent return of stored water; in some years, however, the water balance suggested that there were significant inflows during certain years when high floods occurred on the Baro, when there had been eye-witness accounts of inflow from the Machar marshes to the White Nile. There is evidence of increasing losses within the reach, which is attributed to the construction of Jebel Aulia dam and to increasing irrigation abstraction.

The flood-plain vegetation along this reach is similar to that of the Sudd, and detailed investigation near Gelhak (11°N) aided by air photography showed that the flooding process and the vegetation distribution were similar to those observed on the Bahr el Jebel.

4 Blue Nile Basin

4.1 Blue Nile

The Blue Nile (Abbay in Ethiopia), provides about 60% of the flow of the main Nile, but published information about its hydrology within Ethiopia is limited. Although some observations for Lake Tana exist from the 1930s, it was not until the late 1950s that Ethiopian agencies began regular hydrological monitoring in the basin (Conway, 2000). The Blue Nile and its tributaries rise on the Ethiopian plateau, which lies generally at 2,000–3,000 m with peaks up to 4,000 m or more. The basin is very broken and cut by deep ravines or canyons in which the Blue Nile and other rivers flow. The plateau drops steeply to the plains of the Sudan.

Lake Tana, at an elevation of 1,800 m, is a feature of the upper basin and has been studied as a possible site for storage, but only some 7.7% of the main river flow passes through the lake. The Blue Nile leaves the lake through a series of cataracts, including Tississat Falls with a drop of 50 m, and enters the ravine while receiving a series of tributaries. The Didessa and Dabus, draining the relatively humid southwest of the basin, contribute over a third of the total flow, but other tributaries drain an area of high rainfall in the loop below Lake Tana. Below the Damazin rapids at Roseires, where a reservoir was built in 1961–1966, the profile changes and the river is little below the surrounding plain. Two tributaries, the Rahad and

Dinder, enter the river from the north between Sennar and Khartoum; both streams are highly seasonal and are dry for much of the year.

The average rainfall of the Blue Nile basin above Roseires is about 1,600 mm, but it increases from 1,000 mm near the Sudan border to 1,400–1,800 mm in the upper basin and above 1,800 mm in the south. The seasonal distribution is governed by the migration of the ITCZ from south to north and back, so that the duration of the rainfall season decreases from south to north. Conway (1997) has shown that it is possible to reproduce the 1951–1987 Blue Nile flow series near the Sudan border from distributed rainfall and potential transpiration estimates, using a simple water balance model. The mean annual runoff for this period was 47.37×10^9 m^3, or 269 mm over the basin of 176,000 km^2, compared with a mean annual rainfall of 1,590 mm; the runoff coefficient is 17%. Lake Tana levels were modelled using rainfall and estimates of runoff and evaporation and observed outflows during the period 1960 to 1992 (Kebede et al., 2006). Whilst lake levels were fairly stable, outflows showed quite high variability, primarily driven by rainfall fluctuations.

Within the Sudan Blue Nile flows have been measured regularly at Roseires/ el Deim from 1912, and at Khartoum from 1900. The Dinder and Rahad flows have been measured since 1907/8, with a gap between 1951 and 1972, which has been filled by correlation with flows at Roseires. The long-term annual flow at Roseires has been 48.7 $m^3 \times 10^9$, but this includes a range from 20.7 $m^3 \times 10^9$ in 1913 to 69.8 $m^3 \times 10^9$ in 1929. During the 1980s flows were comparatively low, but after the second lowest flow of last century in 1984, flows have steadily recovered due to a sustained recovery in rainfall across large parts of the basin (Conway, 2005). The seasonal variation is very high, from average monthly flows of 15.2 $m^3 \times 10^9$ in August to 0.32 $m^3 \times 10^9$ in April. The recent period of low flows in the Blue Nile contrasts with the high flows occurring in the White Nile after 1964, following the marked rise in Lake Victoria.

Comparisons of annual flows between those at Roseires, including the Rahad and Dinder, with those of the Blue Nile at Khartoum, show that apparent losses along the course of the Blue Nile have increased fairly steadily over the years. This is almost entirely explained by abstractions for irrigation, but also includes channel losses and reservoir evaporation.

4.2 Floods

The Blue Nile has a greater potential for flooding than the tributaries of the White Nile, as flows on the latter are attenuated by lake storage or wetland spilling. This was illustrated in 1988, when heavy rainfall over Khartoum and further north was compounded by floods on the Blue Nile and Atbara; these combined to cause severe damage along the main river. The main damage in the Khartoum area was caused by a severe storm on the night of 4/5 August 1988 which recorded daily rainfall of 200 mm or more at sites in the city; an approximate estimate of the return

Table 3 Mean monthly flows at key sites ($m^3 \times 10^6$) (after Sutcliffe & Parks, 1999)

Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
Kagera at Kyaka Ferry (1940–1978)												
452	420	491	518	617	627	647	603	531	499	460	467	6,332
Other Lake Victoria tributaries (1956–1978)												
819	578	972	2,103	2,474	1,342	1,201	1,387	1,332	999	1,151	1,207	15,565
Victoria Nile at Jinja (1896–1997)												
2,162	1,973	2,204	2,212	2,412	2,369	2,372	2,277	2,143	2,160	2,057	2,160	26,501
Kyoga Nile at Kamdini (1940–1980)												
2,511	2,200	2,372	2,301	2,526	2,550	2,679	2,695	2,660	2,733	2,609	2,657	30,493
Semliki at Bweramule (1940–1978)												
359	292	327	363	415	371	392	417	409	423	435	419	4,622
Bahr el Jebel at Mongalla (1905–1983)												
2,534	2,180	2,327	2,360	2,767	2,663	2,920	3,317	3,295	3,244	2,975	2,751	33,332
Jur at Wau (1904–1986)												
45	17	10	19	98	212	450	818	1,115	1,149	623	176	4,730
Sudd outflow (1905–1983)												
1,515	1,318	1,392	1,280	1,262	1,188	1,227	1,284	1,328	1,444	1,379	1,473	16,091
Baro at Gambeila (1905–1959)												
257	169	163	202	454	1,154	1,946	2,590	2,971	2,022	816	440	13,184
Sobat at Doleib Hill (1905–1983)												
967	431	273	232	413	851	1,301	1,608	1,780	1,992	1,964	1,718	13,530
White Nile at Malakal (1905–1997)												
2,479	1,756	1,675	1,528	1,696	2,042	2,556	2,914	3,117	3,434	3,340	3,178	29,714
White Nile at Mogren (1911–1995)												
2,469	1,905	2,014	2,225	2,026	1,792	1,368	1,435	2,236	3,024	2,786	2,747	26,026
Blue Nile at Roseires/el Deim (1912–1997)												
762	446	364	324	612	1,659	6,763	15,228	12,111	6,484	2,559	1,348	48,658
Dinder at Mouth (1907–1997)												
0	0	0	0	0	16	318	1,005	1,009	392	51	6	2,797
Rahad at Mouth (1908–1997)												
0	0	0	0	0	2	119	346	378	228	27	2	1,102
Blue Nile at Khartoum (1900–1995)												
724	448	406	427	503	1,084	4,989	15,237	13,625	7,130	2,451	1,257	48,279
Main Nile at Tamaniat (1911–1995)												
3,099	2,302	2,378	2,555	2,490	2,860	6,398	16,151	15,584	9,996	5,067	3,810	72,691
Main Nile at Hassanab (1909–1995)												
3,146	2,320	2,286	2,428	2,359	2,690	5,937	15,607	15,859	10,460	5,351	3,894	72,337
Atbara at Mouth (1903–1994)												
17	6	1	3	8	88	1,536	5,126	3,306	770	145	46	11,052
Main Nile at Dongola (1890–1995)												
3,577	2,547	2,268	2,239	2,175	2,169	5,268	18,701	20,554	13,337	6,767	4,538	84,138
Main Nile at Aswan (Water Arriving) (1869–1992)												
3,738	2,651	2,257	2,011	1,980	1,943	4,754	18,207	21,189	14,318	7,478	4,849	85,376
Main Nile at Aswan/Dongala (1869–1995)												
3,831	2,715	2 379	2,220	2,127	2,178	5,529	19,341	21,385	14,151	7,295	4 298	88,079

period of the storm was 500 years. The river flood was also significant, with a peak level exceeded only in 1946. However, flood frequency analysis suggested that the 1988 peak flow had a return period of about 10 years, but the peak level had a return period of about 50 years. Analysis suggested that the Khartoum gauge level has risen about 0.5 m since 1902 for a typical flood flow.

It was shown during the 1988 flood that cold cloud data from satellite imagery could provide useful information on rainfall amounts, from which flow forecasts could be made (Sutcliffe et al., 1989). This has the advantage that it could be used in areas of difficult access, as it does not depend on direct rainfall measurement and transmission. This was used to develop a flow forecasting system for the Blue Nile and Atbara basins. Rainfall estimates are based on cold cloud duration below a temperature threshold, and linear regression with rainfall records. The conversion of rainfall estimates to river flows are based on conceptual models, and the transmission of the inflow flood hydrograph down the channel system is based on a dynamic flow model, which takes account of abstractions and tributary inflows. The forecasting method utilised by the Nile Forecasting System in Cairo is based on the same principles (Schaake et al., 1993).

4.3 Sedimentation

The Blue Nile, with its steep catchment and highly seasonal flow regime, carries a significant sediment load during the flood period. The annual suspended sediment load at el Deim has been estimated at 140 million tonnes. The storage available in Roseires and Sennar reservoirs is fairly limited, and has been significantly reduced since construction. The strategy for these reservoirs has been to delay filling until the peak of the flood has passed through the reservoir, as the sediment load is greatest on the rising limb of the hydrograph. Reservoir filling rules have been based on flow statistics to minimise sedimentation while ensuring that the reservoir is filled.

4.4 Atbara

The only tributary of the Nile north of Khartoum is the Atbara, which drains an area of 69,000 km^2 of northern Ethiopia and Eritrea. The upper basin, known as the Tekaze in Ethiopia, has a rainfall season which is shorter than the Blue Nile season and is largely concentrated in August and September; the mean annual rainfall of the effective part of the basin has been estimated as about 950 mm. Flow measurements near the Atbara mouth have been measured from 1903 and show wide interannual variability; seasonal patterns are similar to those of the Blue Nile but the flows at the mouth are very low for half the year.

There was some flood irrigation along the upper Atbara before the Khashm el Girba dam was built in 1960–1964 for irrigation; this dam has been subject to sedimentation.

The Atbara has suffered more severely than the Blue Nile from low flows after 1970, though the decline has been exaggerated by the effect of the Khashm el Girba reservoir on flows at the mouth.

5 Main Nile Basin

5.1 Main Nile

The main Nile from Khartoum to Aswan, apart from the contribution of the Atbara, is a channel through an arid landscape interrupted with six cataracts and rapids along its course. Much of the reach is underlain by Nubian sandstone, which gives way to Basement Complex northeast of a line from Atbara to Dongola; practically all the rapids and cataracts are found on the Basement Complex, including those between Atbara and Meroe and between Dongola and Wadi Halfa. Sixteen principal rapids between Khartoum and Wadi Halfa are listed by Hurst et al. (1959), with a total fall of 102 m over a length of 228 km.

The discharges of the river have been measured as inflows to Aswan reservoir and also at an upstream station; this station was sited at Wadi Halfa from 1911 to 1931, when the heightening of the early Aswan dam affected the discharge site. Flows were then measured at Kajnarty, 47 km above Wadi Halfa, from 1931 to 1962, when the construction of the Aswan High Dam made another move necessary, and at Dongola, 430 km above Wadi Halfa, from 1963. The composite record at Wadi Halfa/Kajnarty/Dongola is available from 1890, while the flows measured downstream at the Aswan reservoir commenced in 1869. These flows have been measured by various methods and standardised from time to time. They have been tabulated as 'Water arriving at Aswan' and also as 'Natural River at Aswan'; the latter is adjusted for water abstracted from the Blue Nile in the Gezira main canal, and from 1963 in the Managil canal; it allows for the regulation of the Sennar reservoir and the Aswan reservoir, but not for reservoir evaporation. From 1978 the Natural River flows has included estimated evaporation from the Aswan High Dam and the Jebel Aulia reservoir, but not all the effects of upstream storage and abstractions.

The values for Water arriving at Aswan are most useful, and particularly valuable for including the low flows which derive from Lake Victoria, modified by the other lakes and the Sudd. They reveal the high lake levels in 1878 and 1895, and the marked rise in 1961–64. Later records reveal the recent decline in Blue Nile and Atbara flows, and reflect reservoir storage and abstraction in the Sudan; they also show evaporation losses within the Aswan High Dam after 1964. Comparisons between the published Water Arriving at Aswan and discharges at Dongola also show the effect of reservoir evaporation after 1965.

5.2 The Aswan High Dam

The concept of the Aswan High Dam arose from theoretical work related to over-year storage in the East African lakes, where the concept of 'Century Storage' was defined as the size of reservoir required to guarantee a supply equal to the mean inflow over a period of 100 years. The range R of reservoir storage, ignoring rainfall and evaporation, should increase over a period of N years according to:

$$\log(R/\sigma) = K \log(N/2) \quad (4)$$

with K = 0.5 if the inflows are drawn from a random series of standard deviation σ. However, research using Nile flows, including Nilometer records, and other physical time series, showed that the range increased with K values varying randomly about a mean of 0.73. This meant that a markedly larger reservoir would be needed to guarantee a given draft from a natural rather than a random series. This finding has become known as the Hurst phenomenon, and has given rise to advances in theoretical and practical statistics, and in turn to a branch of applied mathematics epitomised by '*The Fractal Geometry of Nature*' (Mandelbrot, 1977). This research led also to the concept and construction of the Aswan High Dam, with over a year's discharge volume allocated for over-year storage. As a result of the reservoir, Egyptian agriculture survived the droughts of the 1970s and 1980s.

5.3 Variability in Nile Flows

Because of the importance of the Nile flood to irrigation in ancient Egypt, a number of Nilometers were built to record flood levels. The longest quantitative records are from the Roda gauge on Roda Island in Cairo. The series records the annual maximum and minimum river levels for the period 622–1921 AD. Although the record has been criticised for inconsistencies of scale and zero, and suffers from some gaps and the effect of channel aggradation, the record is a useful guide to natural variability.

Systematic measurements of Nile river flows began in 1869 and the full record shows substantial decadal and interannual variability caused by the interaction of rainfall variability and the complex hydrology of the Nile (Fig. 11). The causes of decadal and extreme events are not fully understood. Extreme wet years in the White Nile system and parts of southwest Ethiopia that drain into the Sobat and Blue Nile are associated with El Nino and Indian Ocean Dipole events, and dry years in central and northern Ethiopia are associated with El Nino events (Eltahir, 1996; Sileshi & Demarée, 1995). Decadal variability such as the dry 1980s and shifts such as the humid period before 1900 remain unexplained. At present there is no clear indication from observations or climate models of future behaviour in rainfall in the basin. Some agreement exists between climate models that rainfall may show modest increases in East Africa (McHugh, 2005), but there are no emergent patterns for the Indian Ocean and its influence on extreme events in the region (Conway et al., 2007).

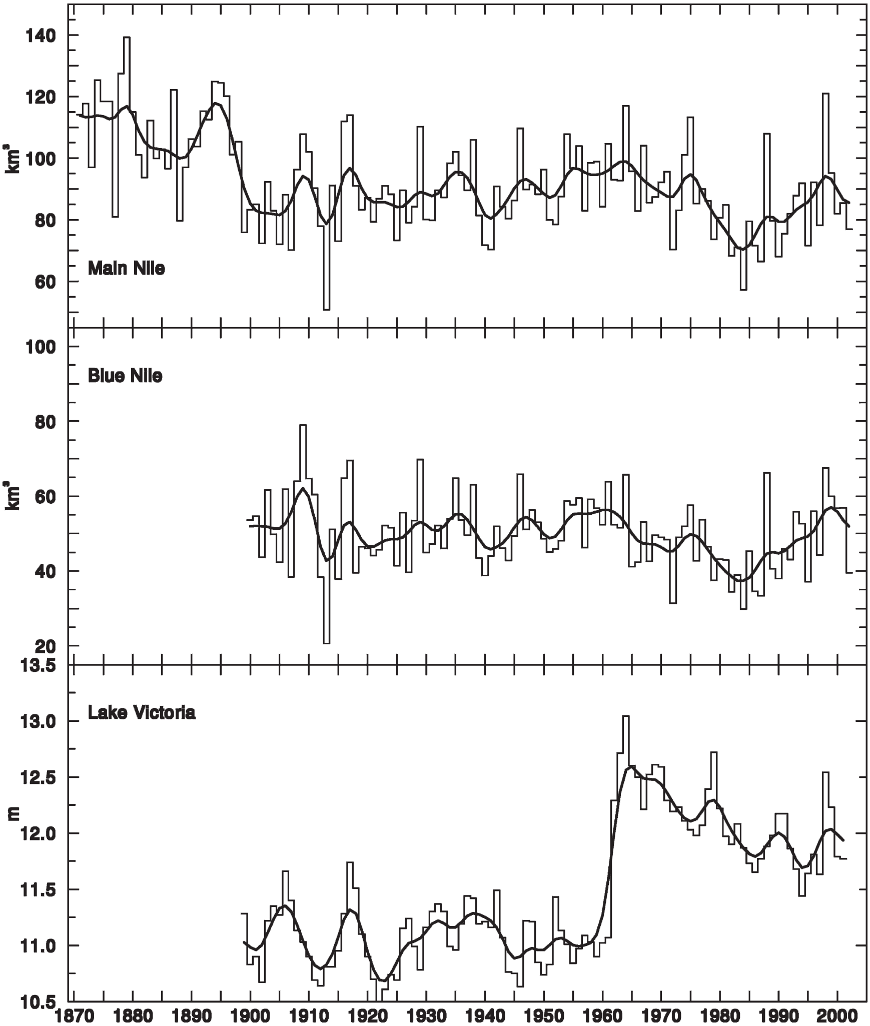

Fig. 11 Annual river flows and lake levels for various periods. Note different vertical scales. *Upper panel*: Nile flows 1870–2002 (from a combination of records at Aswan, Wadi Halfa, Kajnarty and Dongola). *Middle panel*: Blue Nile flows 1900–2002 (from a combination of Khartoum, Roseires and El Deim). *Lower panel*: Lake Victoria levels 1899–2001. *Bold line* represents 10-year Gaussian filter (reproduced from Conway, 2005)

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