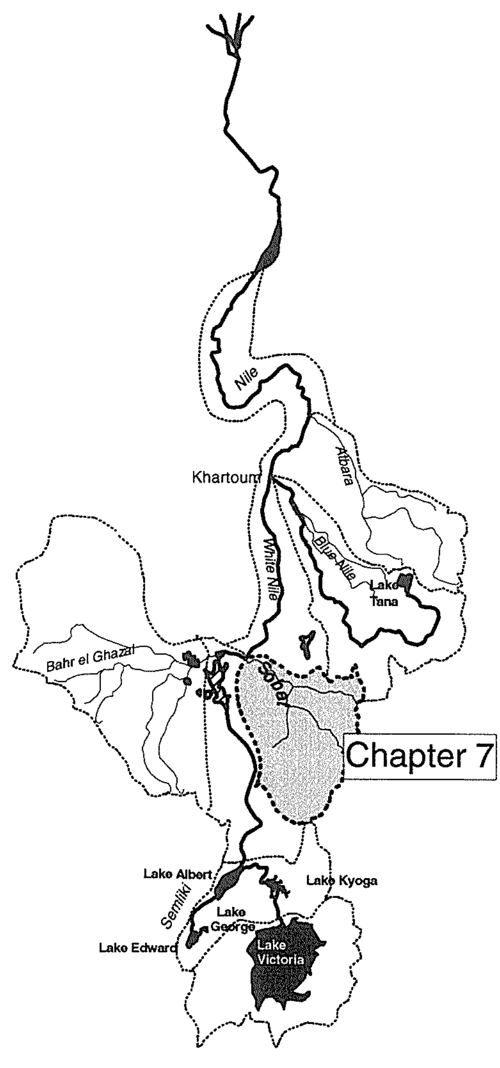
CHAPTER 7

THE SOBAT BASIN AND THE MACHAR MARSHES

INTRODUCTION



The Sobat contributes about half the flow of the White Nile and about a sixth of the whole Nile; its flow is therefore almost equal to the outflow from the Sudd. The basin derives most of its runoff from the Ethiopian mountains and in the absence of lake storage provides the seasonal element to the flows of the White Nile. It also receives occasional contributions from the Pibor which drains a wide area to the south. During years of heavy rainfall on the Baro and other Ethiopian tributaries, high flows are spilled from the river system to the Machar marshes and other wetlands. For this reason the river was studied for one of the early water-saving or conservation schemes to reduce evaporation losses in these wetlands. However, the hydrology of the basin is relatively little known as the river straddles the border between Sudan and Ethiopia, and access has not been easy to determine the flows at key points of the river network and in particular the spills from the main rivers into adjoining wetlands.

In this chapter a description of the river network and the climate of the basin is followed by an account of the flow regime as indicated by the existing hydrological records. This leads to an analysis of the interaction of the inflows, spillage and storage within the wetlands and the channel of the main Sobat. Sources of information include *The Nile Basin*, vol. I (Hurst & Phillips, 1931), with a chapter illustrated with photographs describing the Sobat basin, and vol. VIII (Hurst, 1950), discussing the hydrology of the Sobat and White Nile. Other accounts include the Jonglei Investigation Team (1954) on the Machar marshes and the hydrology of the Sobat, the analysis by El-Hemry & Eagleson (1980) of the water balance of the Machar marshes, and recent analysis by Sutcliffe (1993) of the hydrology of the area.

GEOGRAPHY OF THE SOBAT BASIN

The Sobat (Fig. 5.1) flows to the White Nile from the confluence of its two major tributaries: the Baro and the Pibor. The Baro (41 400 km^2) drains an area of the Ethiopian mountains east of Gambeila rising to a peak of 3300 m. The Pibor (109 000 km^2) receives 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, from which there is little runoff in most years but high flows in some years. The mountain catchment is largely thickly wooded, with vegetation ranging from thorny savannah to thick tropical forest. On the plains at the foot of the hills the woodland gives way to the west to open grassland, which is swampy in the rains but nearly waterless in the dry season (Hurst & Phillips, 1931).

The upper Baro above Gambeila (23 500 km^2) collects a number of mountain streams descending from the Ethiopian plateau through deep gorges. Below Gambeila it flows west towards the Pibor junction through a tree-bordered channel which emerges into a grass-dominated area. About 100 km above the junction it splits into the Adura and the Baro which rejoin 70 km downstream; the Baro receives the Jokau tributary but several spill channels to the north connect the river with the Machar marshes, and at high flows the river is also liable to overtop its banks and inundate large areas.

A recent detailed account of the Mekoy tributary of the Baro (Woube, 1997) describes the river originating in the highland, spreading in a braided channel over the plain, and forming swamps and seasonal wetlands due to backwater from the main rivers. The mean runoff is 0.51 km^3 or 183 mm derived from 2790 km^2 of upland basin. The area has been settled in recent years and a small dam (0.075 km^3) constructed for irrigation.

The Machar marshes are a wetland area to the north of the Baro. It has been mapped from the air but the area is little known directly because of its inaccessibility. Apart from the spill from the Baro, several other streams feed the wetland from the Ethiopian foothills. A number of channels, flanked by wetland areas, cross the plain towards the White Nile.

The Pibor above the Akobo junction forms the outlet for a number of ephemeral streams draining a large area of the plain to the east of the Bahr el Jebel. Although this area includes the larger part of the Pibor basin, the runoff is likely to be small in most years as rainfall is low and the area is dry for much of the year; the streams which start as depressions in the southern part of the plain are ill-defined at first and are filled with swamp vegetation towards the northern limit. However, there is evidence that in a few years there is significant inflow from the Pibor basin. In most years the main contribution is from the Akobo and Gila, which join the Pibor within about 80 km south of its confluence with the Baro, and which drain areas of the Ethiopian plateau up to 2500 m in elevation. Downstream of the Gila the Mokwai joins the Pibor, but this is thought to carry spill from the Baro.

Below the Baro–Pibor confluence the Sobat follows a winding course about 100–200 m wide through alluvial banks in a grass plain, with adjacent grass swamps. Several small seasonal water courses, like the Khor Nyanding and Khor Fullus, join the river from the south; the Sobat catchment is about 36 800 km^2.

The climate of the Sobat basin varies greatly between the Ethiopian mountains and the plain. The rainfall of the upper Baro basin ranges from 1300 mm at Gambeila to 2370 mm at Gore, between April and October, with a tendency towards two rainfall seasons evident in individual years. The Pibor basin has lower rainfall, with an average of about 950 mm over the same months, but the rainfall on the plain is only about 800 mm.

GENERAL HYDROLOGY

Spill from the Sobat tributaries

The major wetland within the Sobat basin, the Machar marshes, is little known, but its hydrology may be indicated by comparing flow records at sites down the Baro and Sobat. A major source of inflow to the marshes is channel flow and overbank spill from the Baro, and this spill is illustrated by flows along the Baro.

The flows of the upper Baro have been measured at Gambeila. Levels have been measured since 1905 but no flows calculated until 1928. However, Hurst (1950) derived a rating from almost 700 gaugings between 1928 and 1947 (35 per year), which suggested that the relation had not changed much over the period. This relation [$Q = 100(h - 8.77)^{1.54}$ in $m^3 s^{-1}$] has now been used to convert 10-day levels to flows for 1905–1927, which extend the record. From 1928 to 1959 both levels and discharges were measured regularly and flows were calculated from gaugings during each year. These later monthly flows (*The Nile Basin*, vol. IV) are shown in Fig. 7.1. Annual flows for 1905–1959 are shown in Fig. 7.2 and monthly averages for this period are given in Table 7.1. The flows of the Baro at its mouth, above the Pibor junction, were measured almost daily in 1929–1933, and then about twice a month from June to December in 1941–1962, when gaugings became less frequent. Flows have been published for the years 1929–1932, for the high flow season from 1941 to 1963, and intermittently until 1981. These flows from 1929 to 1959 are included in Fig. 7.1.

Comparisons of flows at Gambeila and at the Baro mouth, 200 km downstream, illustrate the spilling of high flows; Fig. 7.1 shows that the flows are similar until a flow of about 1.5 km^3 $month^{-1}$ is exceeded, when the downstream flow is virtually constant at that figure. On the other hand, comparisons of Baro and Pibor flows above their confluence, with the Sobat below the junction, show a net gain at the junction, attributed to left bank spill from the Baro returning through the Pibor.

The overall losses on the Baro system may also be illustrated (Fig. 7.3) from annual flows at Gambeila and the Baro mouth. An increase in flow has little effect downstream. However, the complex pattern of spilling, with outflows and return inflows through channels, can be deduced by direct measurement or by measuring flows upstream and downstream of each junction. Overbank spilling also occurs over both banks and can only be estimated using successive measurements and observation of the proportion of spill over each bank. For this reason detailed study, described later, is required to estimate the spill to the Machar marshes.

The Sobat flows below the Pibor confluence have also been calculated from annual rating curves based on gaugings below the confluence and at Nasir, some 60 km downstream. These flows are available from 1929 to 1977, with a gap between 1964 and 1967 and only intermittent high flows measured after 1970.

The Sobat flows at Doleib Hill, 8 km above the White Nile confluence, have been calculated from annual ratings from 1905 to 1983. The ratings are looped and affected by White Nile levels; the level of the rating curves rose about 1 m after 1964. The number of annual gaugings is thus important; these averaged (Chapter 2) about 20 until 1921, reached a

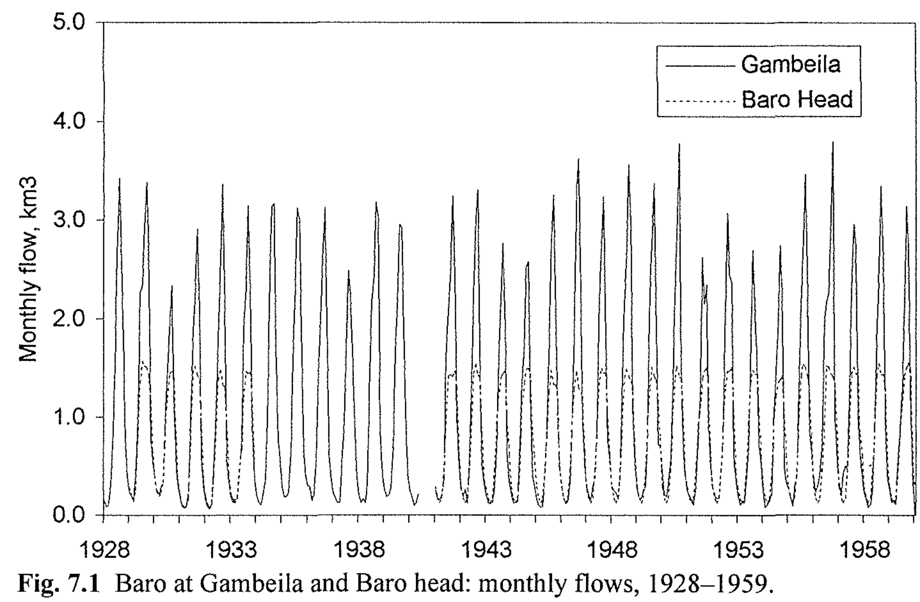


Fig. 7.1 Baro at Gambeila and Baro head: monthly flows, 1928–1959.

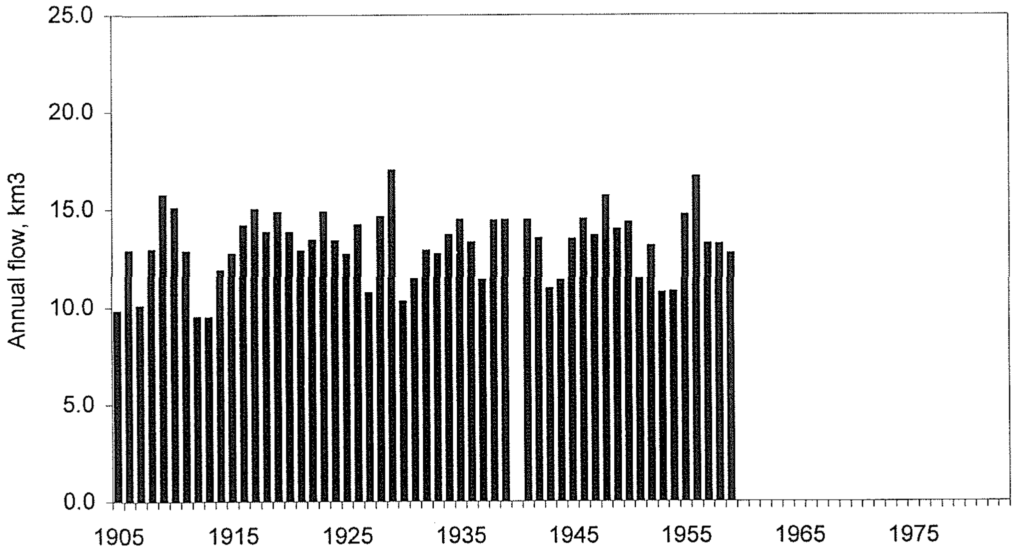


Fig. 7.2 Baro at Gambeila: annual flows, 1905–1959.

peak of 70 in 1923–1935, averaged 40 in 1936–1951, 20 in 1952–1964, and fell to about 10 until 1983. The monthly and annual flows are illustrated in Figs 7.4(a) and (b). Published dry season flows appear to have been high in certain years since 1962. Although flows could have been held up by high White Nile levels after the rise in Lake Victoria, it also appears that in some years (e.g. 1965–1967) these flows may have been overestimated because of a lack of dry season gaugings. Some of the later published flows are clearly incorrect; in 1979 and 1981 the dry season flows are implausible and have been corrected here from provisional flows obtained in 1982 or by comparison of Sudd outflows with Malakal. The monthly average flows for different periods are included in Table 7.1. The attenuation of high flows, compared with the Baro at Gambeila, is illustrated; there has been little change in average flows over the years.

The Machar marshes

The Machar marshes, in addition to spill from the Baro, also receive inflow from local streams flowing from the Ethiopian foothills north of the Baro. These so-called eastern

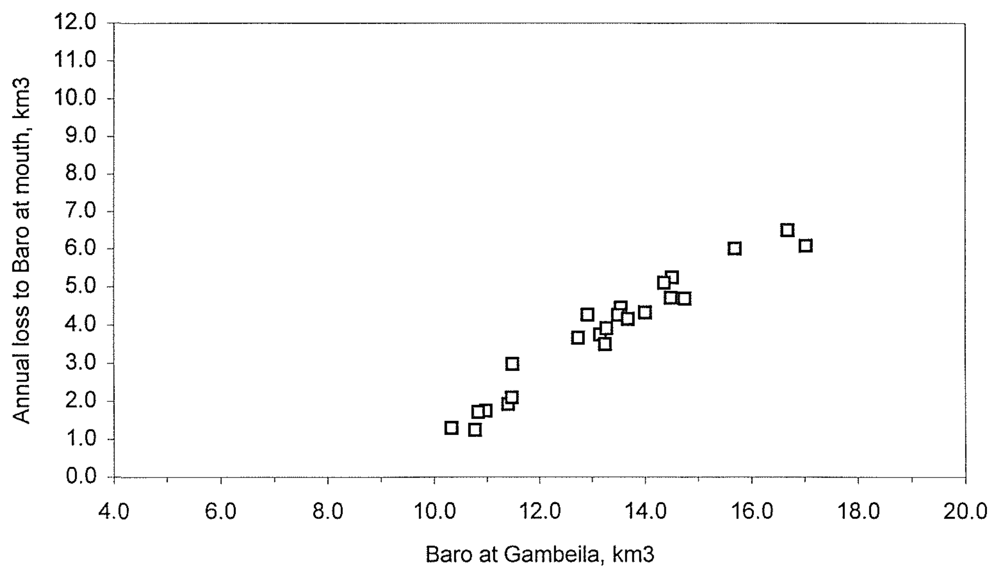


Fig. 7.3 Annual losses on Baro: 1929–1933, 1941–1959.

Table 7.1 Monthly average flows of Baro and Sobat ($m^3 \times 10^6$).

Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Baro at Gambeila (1905–1959)												
257	169	163	202	454	1154	1946	2590	2971	2022	816	440	13184
Sobat at Doleib Hill (1905–1960)												
929	363	246	222	410	870	1303	1603	1779	2008	1995	1743	13471
Sobat at Doleib Hill (1961–1983)												
1059	595	341	257	419	807	1297	1619	1781	1951	1889	1656	13672
Sobat at Doleib Hill (1905–1983)												
967	431	273	232	413	851	1301	1608	1780	1992	1964	1718	13530

torrents are ephemeral and their contributions were estimated from rainfall by Hurst (1950). The Jonglei Investigation Team (1954) initiated flow measurements in 1950 and later assessed flows. Little is known about the extent of the Machar marshes, so that a water balance is difficult to achieve. According to Hurst (1950, p. 24), the area of swamp was estimated from maps as 6500 km^2, but it was noted that experience from the Bahr el Jebel and Bahr el Ghazal swamps suggested that the area of permanent swamp would be reduced considerably when the area was surveyed directly.

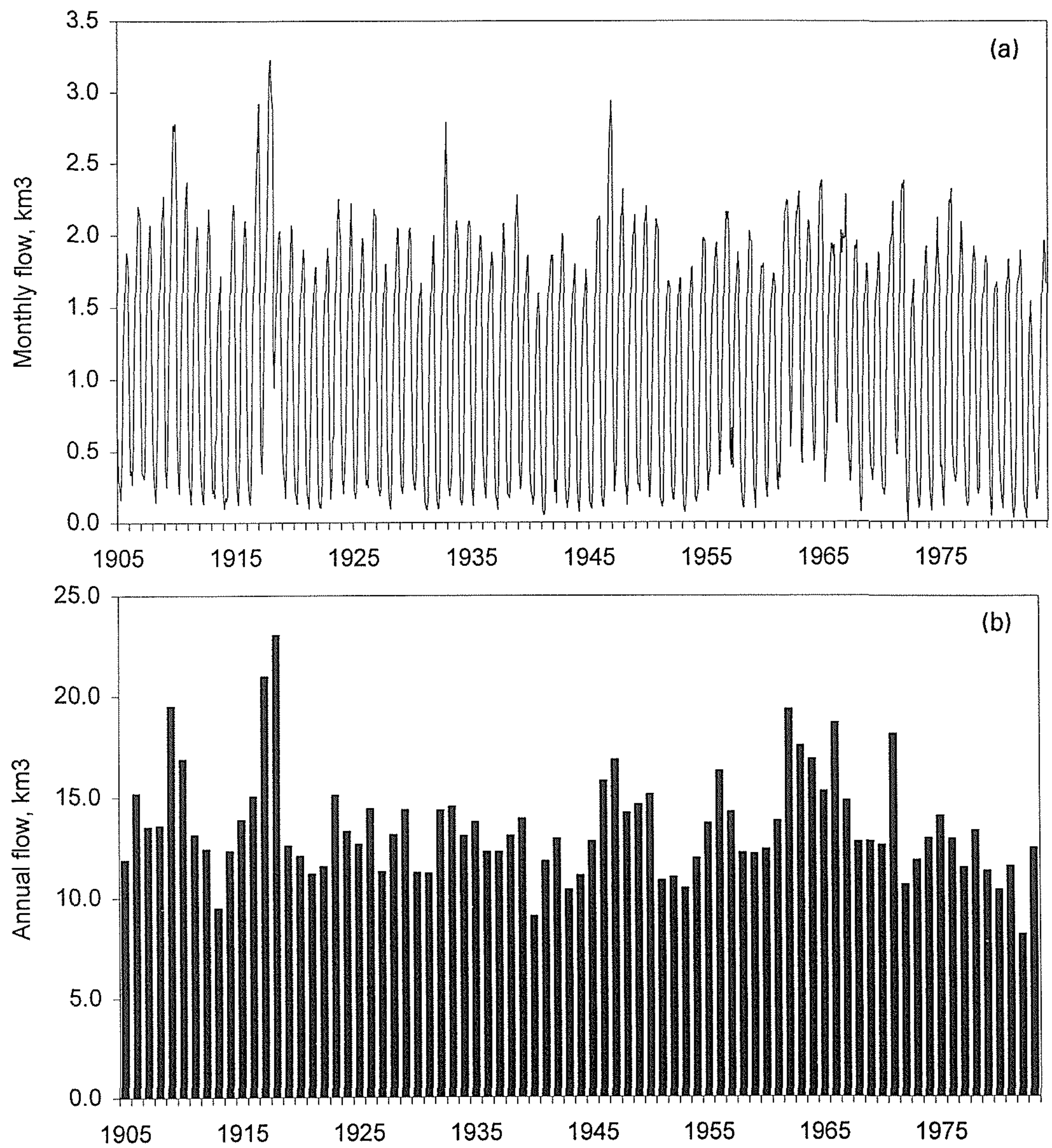


Fig. 7.4 Sobat at Doleib Hill: (a) monthly flows, 1905–1983; (b) annual flows, 1905–1983.

Khor Adar connects the Machar marshes with the White Nile through an extended grass-filled channel. The outflow through Khor Adar has been measured for short periods (0.058 km^3 in 1948 and 0.029 km^3 in 1957) and is considered negligible except after years of heavy rainfall and inflow to the swamps.

The balance of the Sobat itself was analysed by Wright (Jonglei Investigation Team, 1954, vol. III), and this suggested that there could be contributions from the Machar marshes to the lower Sobat in some years. This analysis is discussed later. The Machar marshes have also been the subject of analysis by El-Hemry & Eagleson (1980); this study was based on measurements but also made use of conceptual modelling to assess the contributions of the eastern torrents and the ungauged area to the east of the marshes.

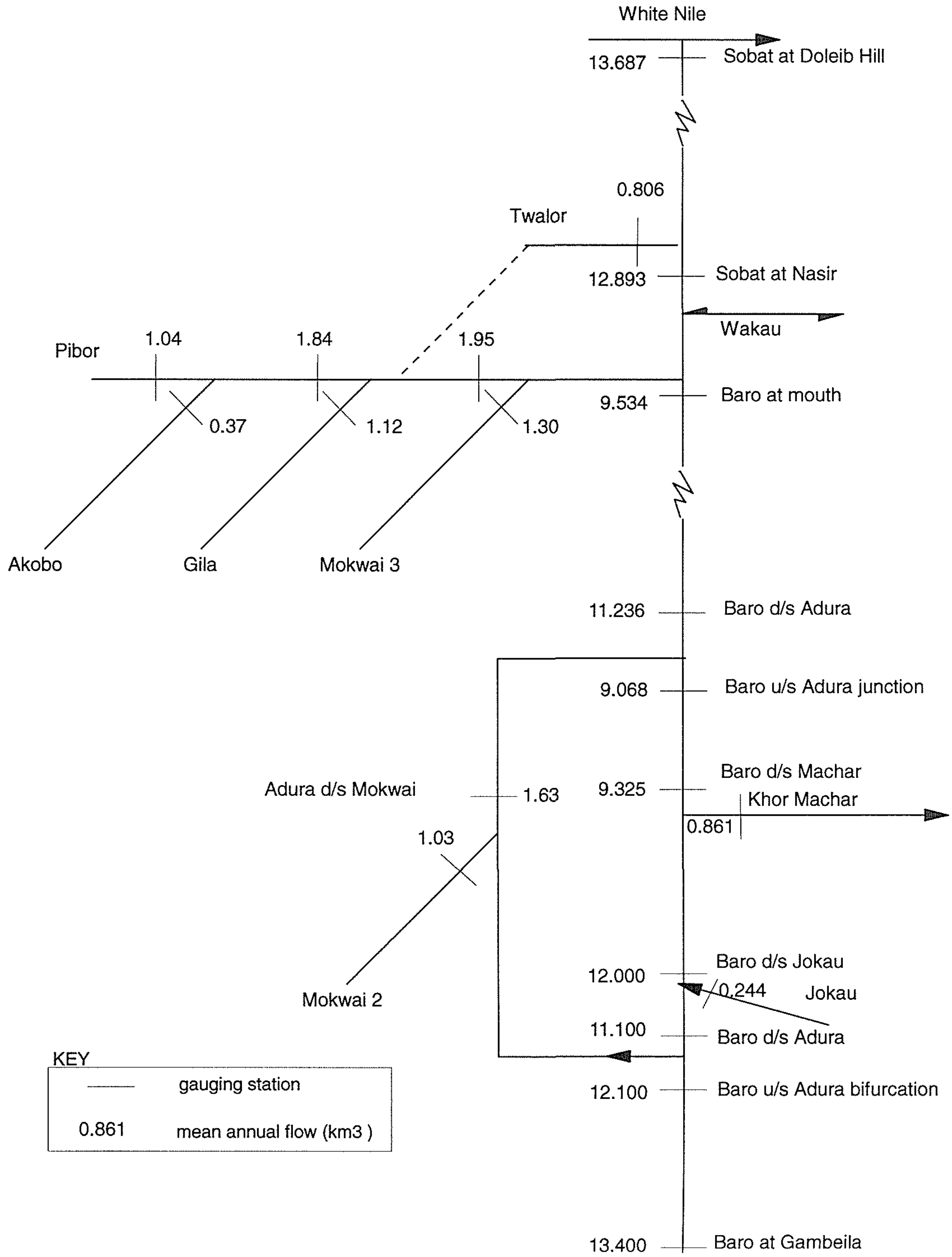


Fig. 7.5 Schematic plan of Baro–Pibor basins and mean annual flows, km^3.

Contributions of the Pibor

The River Pibor drains a wide area of plains, which in theory extends to the mountains of southeast Sudan. However, the Kidepo which drains the Didinga hills and even a small area in northeast Uganda, disappears into a swamp about 5°N and loses definition (Jonglei Investigation Team, 1954, p. 18). The Kinyeti, which rises in the Imatong mountains, drains into a swamp west of Jebel Lafon at the same latitude. It is doubtful whether significant flow reaches the Lotilla and thus Pibor Post in a normal year. Detailed surveys of the Veveno channel were obtained during study of the Veveno Pibor Diversion Scheme, which was an alternative to the Jonglei Canal (Ministry of Public Works, Egypt, 1938); it starts as a depression in the plain but develops into a channel some 4 m deep. Some flow records exist at Pibor Post for the period 1928–1931, with an average annual flow of 0.44 km^3, which is less than 1 mm over the basin, but a range from 0.14 to 1.03 km^3 over the four years of records; approximate records for the period 1929–1944 (Hurst, 1950, p. 40) average 0.57 km^3 with an estimated flow for 1932 of 4.0 km^3.

The average flow of the Pibor (Fig. 7.5) above the Akobo confluence is estimated as 1.04 km^3 (1929–1944) compared with the Akobo inflow of 0.37 km^3 (1929–1944); while above the Gila confluence the Pibor flow is estimated as 1.84 km^3, compared with the Gila inflow of 1.12 km^3 (both 1929–1947). As the average Pibor flow is 1.95 km^3 (1929–1947) at the junction downstream with the Mokwai (inflow 1.30 km^3), there is clearly spill from the Pibor. It is not easy to assess the situation in detail as the records, quoted from early periods for compatibility, are somewhat intermittent. It appears from the difference between the flows of the Baro above and below the Pibor confluence that the average inflow from the Pibor is about 3.4 km^3, but the flow of the Twalor spill channel to the Sobat below Nasir (0.56 km^3 in 1934–1947) must be supplied by spill from the Pibor.

The individual flow records reveal various interesting facts. Comparison of the annual flows of the Baro and Sobat (Figs 7.2 and 7.4(b)) with those of the Pibor above the Gila mouth (Fig. 7.6) show that the Pibor provides much of the variability of the Sobat flows. Although most of the flow of the lower Pibor is supplied by the Ethiopian tributaries, there appear to be large contributions from the Pibor itself in exceptional years. The floods of 1917 were concentrated in the area north of Lake Victoria; comparison of the flows at Gambeila and Doleib Hill, the only records available for that year, suggest that this flood was also important on the lower Sobat and probably derived from the Pibor. It is more clearly shown by the flows of the Pibor above the Gila mouth that the Pibor basin also received a significant contribution from the heavy rainfall of 1961/62, when unprecedented flows were recorded. For example, the flow of the Pibor above the Gila mouth was 7.50 km^3 in 1962, while the net inflow from Khor Twalor into the Sobat was 2.60 km^3 in 1961–1962.

This evidence of occasional contributions from the Pibor itself is supported by a comparison of the annual flows of the Pibor above the Gila mouth (Fig. 7.6) with the annual gains on the Sobat between Sobat Head and Doleib Hill (Fig. 7.7). The latter reveals significant gains in 1933, 1946–1950, and 1962–1963, which follow high flows on the Pibor above Gila mouth. These gains appear to be caused by spill from the Pibor finding its way through the Twalor to the Sobat rather than direct inflow from the plain south of the Sobat.

Spill from Baro to Machar marshes

The spills from the Baro have been indicated above by comparing the flows at Gambeila with those at the Baro mouth, which were only recorded during the flood season. These comparisons are useful in showing how the overall spills vary over the years; it is clear that losses increase markedly during years of high flows at Gambeila. For detailed analysis it is

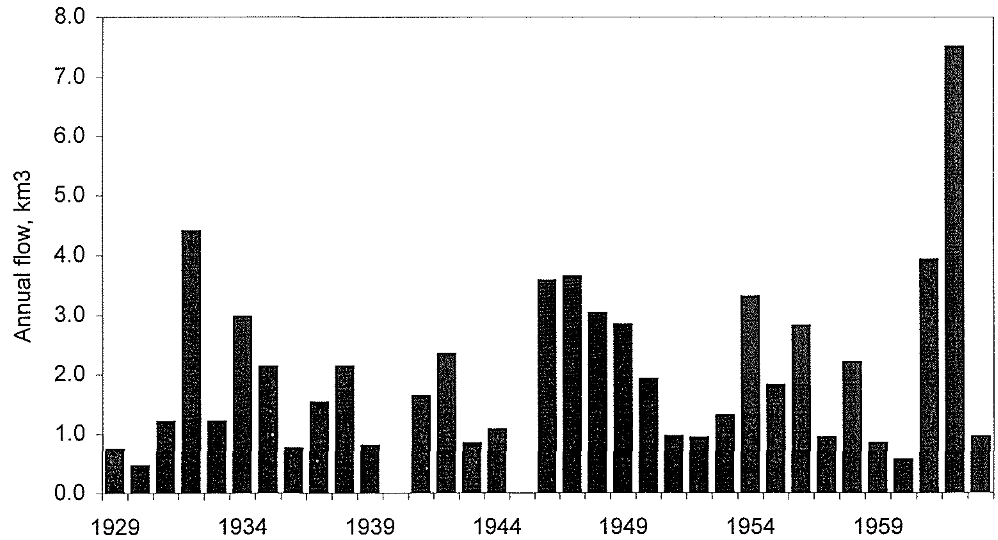


Fig. 7.6 Pibor above Gila mouth: annual flows, 1929–1963 (excluding 1940, 1945).

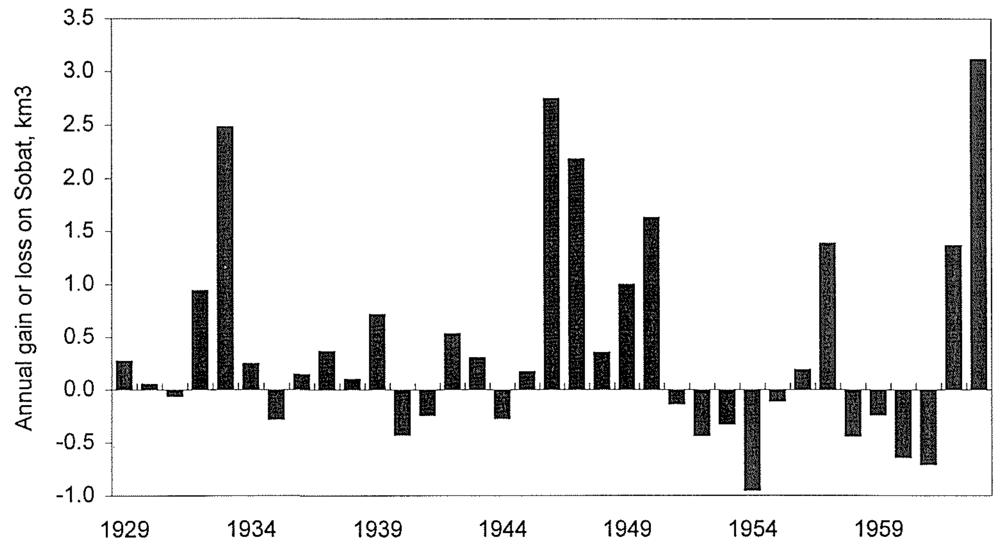


Fig. 7.7 Annual gains on Sobat: Sobat Head to Doleib Hill, 1929–1963.

necessary to study the series of flows down the Baro and estimate the proportions which spill on each bank. Some deductions may be based on average flows; however, the complexity of the river system is such that detailed analysis of individual years is essential if the spills are to be quantified.

Balance of Sobat channel

The comparison of monthly flows at Nasir and Doleib Hill for a selected period (1950–1959) (Fig. 7.8), reveals fairly limited losses and gains in normal years, and the main effect is the attenuation of the flow hydrograph by storage within the flood plain. An analysis of the balance of the Sobat channel between Nasir and Doleib Hill was carried out by Wright (Jonglei Investigation Team, 1954, vol. III). A detailed description of this follows later.

The effect of the losses from the Baro, and the attenuation in the course of the Sobat, is to reduce the total flows, especially in high years, and to delay the peak flow by 1–2 months. It is interesting to compare the duration of the high flows of the Sobat at Doleib Hill and those of the Blue Nile at Khartoum. Whereas the Blue Nile flood is concentrated between July and October, that of the Sobat extends from June to January, because of the longer rainfall season

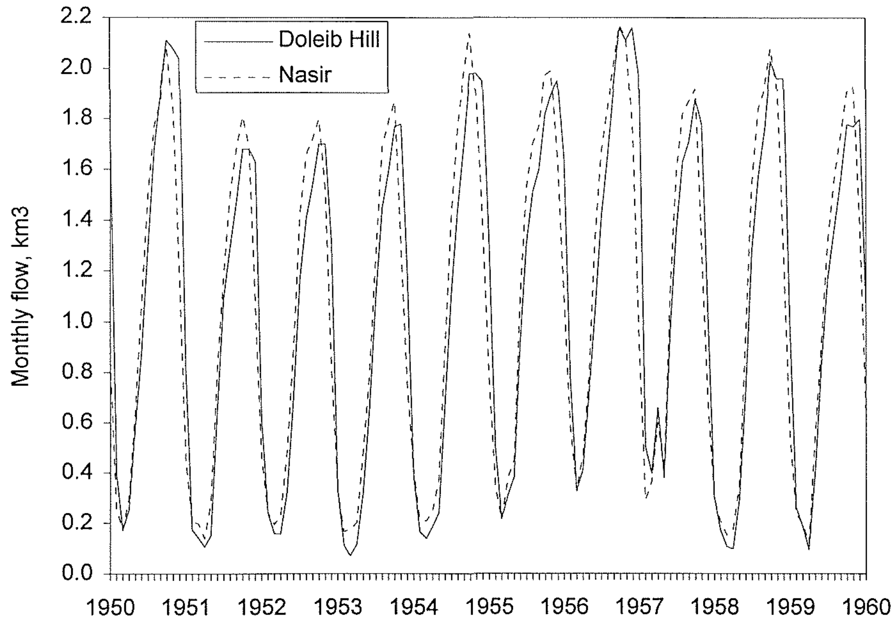


Fig. 7.8 Sobat flows at Nasir and Doleib Hill: monthly flows, 1950–1959.

and the attenuation of the Sobat flood. However, the Pibor appears to contribute an annual variability which is not present in the Baro.

WATER BALANCE OF THE MACHAR MARSHES

The Machar marshes are the least known of the southern Sudan wetlands, and the sparsity of hydrological data for aspects of their water balance makes it difficult to analyse their regime completely. Previous studies are described in *The Nile Basin*, vol. VIII (Hurst, 1950), the account of the Machar marshes by the Jonglei Investigation Team (1954, vol. III, chapter 4), the analysis by El-Hemry & Eagleson (1980), and that by Sutcliffe (1993).

Analysis by Hurst (1950)

The analysis by Hurst concentrates on the losses from the River Baro above the Sobat head. Flow measurements down the Baro illustrate the succession of inflows, outflows and overbank spills. Measurements show that there is significant flow down the Adura branch which leaves the left bank of the Baro (Fig. 7.5) and returns to the Baro downstream, having received inflow from another tributary called the Mokwai. Below the bifurcation with the Adura, the Baro receives inflow in the Jokau from the right bank, and loses water by spill over the right bank and through the Khor Machar channel towards the Machar marshes. The overbank spill and smaller channel flows occur on both banks, and assumptions have to be made on the proportions of spill on each bank. It was concluded (Hurst, 1950, p. 24) that most of the loss from the Baro between the bifurcation of the Adura and their downstream junction is to the north. Between the junction of the Baro and Adura and the Baro mouth more than half of the spill goes towards the Machar marshes.

Jonglei Investigation Team (1954)

This analysis was brought up to date by the Jonglei Investigation Team (1954), who estimated the spill to the north from the Baro by comparison of average flows at different sites. These flows (brought up to 1967) are illustrated in Table 7.2 and Fig. 7.5, where the river system is shown in diagrammatic form with estimates of mean flows at key sites. The Jonglei Investigation Team (1954) provide the only first-hand accounts of the area, but these are confined to the perimeters of the swamps. Air photography taken by the US Air Force in 1944–1945 was used to prepare air survey maps by 1949–1950. While providing astronomical fixes for this mapping, the channels flowing directly from the Ethiopian hills towards the swamps were measured. River gauges were erected on the Yabus and Daga, the largest of these rivers, and nearly 3 years of flow measurements were collected to revise the estimates of the direct inflow. Air reconnaissances in 1949–1950 provided an understanding of the flow patterns in the area, which was summarized in the Jonglei Report (1954) and the accompanying map (see Howell & Allan, 1994, p. 273).

Table 7.2 Average flows at sites on Baro and Sobat ($m^3 \times 10^6$).

Jan.	Feb.	March	April	May	June	July	Aug	Sept.	Oct.	Nov.	Dec.	Year
Baro at Gambeila (1905–1959)												
257	169	163	202	454	1154	1946	2590	2971	2022	816	440	13 184
Jokau at mouth (1942–1963)												
					6.2	38.9	57.2	62.1	57.5	22.0		244
Baro below Khor Jokau (1947–1963)												
440	240	200	270	580	964	1630	1940	2050	1910	1020	755	12 000
Khor Machar outflow (1928–1963)												
0.9	0.2	0	3.3	37	118	145	157	156	147	75.7	20.7	861
Baro above Adura junction (1945–1963)												
357	200	180	230	480	889	1280	1340	1280	1280	933	619	9 068
Baro below Adura junction (1942–1963)												
442	240	200	270	580	862	1350	1640	1760	1860	1280	752	11 236
Baro at mouth (1929–1963)												
297	162	129	176	429	925	1340	1480	1430	1430	1120	616	9 534
Sobat at Head and Nasir (1929–1963)												
588	276	211	249	489	1030	1500	1760	1860	2020	1750	1160	12 893
Sobat at Doleib Hill (1912–1967)												
1020	454	289	251	431	862	1290	1590	1770	1990	1980	1760	13 687

Note: Low flows on lower Baro are estimated by El-Hemry & Eagleson (1980).

Analysis confirmed that the Baro flow exceeding about 1.500 km^3 $month^{-1}$ spills from the river between Gambeila and the Baro mouth or Sobat confluence, and this spill is concentrated in June–November. The total spill was estimated as 3.600 km^3 $year^{-1}$, varying annually with Gambeila flow from 1 to 5–6 km^3. In order to make assumptions about the proportion of spill to the north, they refined "most of the loss" in the middle reach as three-quarters, and "more than half of the loss" in the lower reach as two-thirds. Applied to the total spill of 3.600 km^3, this led to estimated spill towards the Machar marshes of 2.820 km^3.

This average annual spill to the north of 2.820 km^3 is the major river contribution to the Machar marshes. The eastern torrents provide the second river contribution to the marshes, through runoff from the western fringe of the Ethiopian mountains. The contributing areas at the two gauging stations on the Yabus and Daga total 5000 km^2. The runoff from the whole area of 10 300 km^2 from gauged and ungauged streams was estimated at 1.744 km^3, based on average basin rainfall and the gauged runoff coefficient of 15%.

Direct rainfall on the Machar marshes was estimated from gauges around the periphery, and the annual average, based on seven stations with records from 1940–1952, was estimated as 788 mm. This contribution will vary with the area flooded, but exceeds the other sources of water input.

The air survey maps showed that water passes through the swamps by three main routes: from the eastern torrents through the Daga to the Adar; from the eastern Baro through a branch of the Machar to the Adar; and from another branch of the Machar through the Tierbor running parallel to the Sobat to the Khor Wol and the White Nile. This is supported by accounts of field visits.

There is little direct evidence of how much water reaches the White Nile. It has been deduced from the Sobat water balance that there is some spill from the Sobat north above Nasir through the Wakau, but that the average spill (0.150 km^3) is more than compensated by return flow into the Sobat (average 0.400 km^3). The main channel connecting the Machar marshes to the White Nile is the Khor Adar, which survey shows to have a channel about 2.5 m deep and 100 m wide, separated by alluvial banks from a flood plain about 800 m wide. However, the channel is normally choked with grass, and the flows are small except when exceptional floods, as in 1947, flatten these grasses. The Khor Wol is similar and the average outflow from the Machar marshes to the White Nile was estimated at about 0.10 km^3, though in exceptional years like 1947 it might reach 0.50 km^3 or even 1.00 km^3.

There was little direct evidence of the area flooded in the marshes, but from the sources of inflow it was thought to vary considerably both seasonally and from year to year. There were subjective accounts from field visits of the areas which provided grazing in the past, but these did not provide estimates of the total area flooded. The precise areas could then only be deduced from air photography, which is not easy to interpret, or by water balance methods which depend on accurate estimates of inflow and evaporation.

Analysis by MIT (1980)

Subsequent analysis was carried out by El-Hemry & Eagleson (1980). As with the concurrent study of the Bahr el Ghazal swamps (Chapter 6), an important feature of this study was that the conceptual water balance model developed by Eagleson (1978) was used to estimate ungauged runoff from rainfall and other factors.

Landsat satellite imagery of February 1973 had been used to map the drainage of the Machar area and the vegetation distribution. These maps were reproduced at a reduced scale (El-Hemry & Eagleson, 1980, Figs 4.1 and 4.2). The drainage pattern is very similar to that deduced from air photography by the Jonglei Investigation Team (1954). The area is divided in the report into 16 300 km^2 of eastern catchments, 14 100 km^2 of plains, much of which is to the west of the swamps, and 8700 km^2 of permanent swamps; however, some 60% of the swamps are noted as grass and forest, leaving 40% or 3500 km^2 as wet soil and water bodies covered by papyrus. It is not clear whether this includes seasonally flooded areas inundated at the time of the imagery.

The progression of vegetation is clear: the catchments of the torrents from the Ethiopian foothills are shown as forest, which gives way to grass with trees and bush to the west of the international boundary and then to grass plain. The lower courses of the Ahmar, Tombak, Yabus and Daga are marked as meandering river systems or marshland/swamps with fringes of seasonally flooded wetland. The area north of the Baro and Sobat which is fed from the Machar and the Wakau, and the upper reaches of the Wol, are also shown as wetland. Between these isolated areas of wetland large areas north of Nasir are shown as forest.

El-Hemry & Eagleson (1980) assembled valuable data. They assessed the vegetation for the eastern streams and derived parameters for the Eagleson model. They assembled basic rainfall data up to 1975, and derived statistics of mean annual rainfall and coefficient of variation, seasonal rainfall and number of raindays; they developed Thiessen weightings for the stream basins, plains and swamps. They assembled monthly flow data for the stations at Yabus Bridge and Daga Post installed by the Jonglei Investigation Team and continued up to

1955. These are summarized in Table 7.3; the average flows at these two stations are 0.455 and 0.420 km^3. Flow starts in June, about two months after rainfall in April–October, and some flow continues through the dry season. Very short records (July–October 1974) for the Ahmar at Kofa, the Tombak at Nela, and the Lau at Kigille provided total flows of 0.075, 0.715 and 0.300 km^3 respectively. The flow of the Tombak appears unreasonably high compared with the other rivers, being over 30% of average rainfall.

The total inflow from these five rivers was given as 1.965 km^3. This was considered an underestimate on the grounds that the stations at Yabus Bridge and Daga Post are above the mouths of the rivers, while the estimate included only one of the three branches of the Lau. It was increased to 3.30 km^3 by comparing rainfall and potential evaporation over the total tributary area, and was later increased to 4.2 km^3 by applying a single-parameter model to the separate basins. This estimate is very indirect, and the open-water evaporation used is very low at 1340 mm. Gauged stations on the Yabus and Daga are likely to be at the limit of the productive catchment. Pending further flow measurements, particularly for the anomalous Tombak station, the estimate of 1.744 km^3 prepared by the Jonglei Investigation Team from local knowledge is preferred. This was based on Daga and Yabus flows similar to those used by El-Hemry & Eagleson, and the total runoff was estimated from rainfall and measured runoff coefficients (K. E. Snelson, Jonglei Investigation Team, personal communication).

El-Hemry & Eagleson also estimated further runoff from the plains of about 1.41 km^3 by comparison of rainfall and evaporation over an area of 14 100 km^2. This estimate is also indirect and at 100 mm exceeds local experience; runoff from the Pibor and the plains south of the Sobat is seldom appreciable.

The total spill from the Baro was estimated by El-Hemry & Eagleson in a similar way to earlier attempts, using normals up to 1963, and the results were somewhat higher with a spill of 4.63 km^3. They were based on flows of the Baro below Khor Jokau which were not available previously. The proportions (two-thirds and three-quarters) of the Jonglei Investigation Team were used to divide the spill north and south of the Baro. The average flow to the north was estimated as 3.54 km^3. This total was higher than those of Hurst (1950) and the Jonglei Investigation Team (1954), but the estimates also included spill derived from estimated low flows during the dry season; this does not seem logical as even spill through the Machar channel is negligible during the dry season, and it is unlikely that spill over the bank occurs. If low flows had been eliminated from this study, then the estimated spill would have reduced the total spill to 3.664 km^3 and spill to the north to 2.873 km^3; these are similar to the Jonglei Investigation Team (1954) estimates.

The sum of the estimated runoff from the eastern torrents and plains was given as 5.61 km^3, plus 3.54 km^3 spill from the Baro. Drainage to the Sobat through the Wakau and Adar totalling 0.12 km^3 is deducted. It was concluded that more than 8 km^3 could be contributed annually from the Machar region to the White Nile by a channel diversion system. This would be twice the estimated benefit of the Jonglei Canal, Stage I. It was, however, proposed that further measurements and studies should be carried out, and it seems that the potential savings from the Machar area may have been somewhat overestimated.

Analysis of years 1950–1955 (after Sutcliffe, 1993)

It is preferable to analyse the water balance of the Machar marshes over a consistent period when all factors are available; the eastern tributaries have only been measured in 1950–1955. Flows along the Baro are also available, together with flows of the Machar channel. As before, spills towards the Machar marshes can be estimated on the basis that two-thirds of the upper Baro loss and the whole flow of the Machar channel, spill towards the north, with three-quarters of the lower Baro loss. The average estimates are given in Table 7.3. The spills occur between

July and October, and the spills from the upper Baro occur earlier in the year than those of the lower Baro. The average spill for the years 1950–1955 at 2.328 km^3 is lower than the estimate of 2.82 km^3 (Jonglei Investigation Team, 1954) based on the years up to 1947 or the average (2.87 km^3) up to 1967. This is due to the period 1950–1955 being somewhat drier than average, and the sensitivity of spilling to the flows of the Baro. The flows of the Baro at Gambeila averaged 12.56 km^3 in 1950–1955 compared with 13.35 km^3 normal from 1928 to 1959.

Table 7.3 Components of Machar marshes water balance ($m^3 \times 10^6$).

Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Spill from Baro towards Machar (1950–1955)												
					44	218	504	738	689	135	0	2328
Inflow of Yabus at Yabus bridge (1950–1955)												
9.88	4.70	3.39	3.15	8.59	17.7	30.1	88.7	118	108	42.8	19.6	455
Daga at Daga Post (1950–1954)												
1.78	1.24	0.31	1.04	5.85	16.4	48.1	113	93.8	91.5	36.3	10.9	420
Total estimated inflow (1950–1955)												
23	12	7	8	29	68	156	401	423	398	158	61	1744
Average rainfall (1950–1955, mm)												
0	2	3	31	109	126	179	241	139	77	26	0	933
Average evaporation (mm)												
217	190	202	186	183	159	140	140	150	177	189	217	2150

The monthly torrent inflows for the same period were estimated by multiplying the sum of the two measured torrents, the Yabus and Daga, by a constant to give the estimated average of 1.744 km^3. The outflow from the Machar marshes to the White Nile only occurs in exceptional years, as in 1946/47, and has been estimated to average 0.12 km^3 (El-Hemry & Eagleson, 1980). The drainage to the White Nile and the reverse flow to the Sobat have therefore been neglected. The average rainfall has been estimated from six stations (Kurmuk, Chali, Doro, Yabus Bridge, Daga Post and Nasir) around the swamps at 933 mm. The annual series for the period 1950–1955 have been estimated from these six stations by the isopercentile method, and distributed according to the monthly distributions at Kurmuk and Nasir. The averages for this period are included in the summary table, together with the Penman open-water evaporation for the Sudd which should provide a reasonable estimate for the Machar marshes.

The comparison of annual averages in this table leads to an estimate of average swamp area of 3350 km^2, which is lower than previous estimates. It seems likely that previous estimates have included areas of seasonal flooding.

An indication of the seasonal distribution of flooding has been derived from the monthly spill and inflow data, by using the water balance model developed for the Sudd. It was assumed that once the spill and torrent inflows have spread to areas outside the stream channels, the relation between flood area and volume is linear and similar to that deduced for the Bahr el Jebel flood plain. Monthly rainfall evaporation estimates have been used; soil moisture recharge has been neglected in this case as tributary inflow does not occur until local soil moisture has been recharged. The results (Fig. 7.9) show that estimated areas of flooding vary between about 1500 and 6000 km^2 over the 5-year period, which was drier than the average.

GENERAL ENVIRONMENT

There is no direct evidence for the distribution of permanent and seasonal swamp. El-Hemry & Eagleson (1980) reproduced a map based on imagery for a later year (February

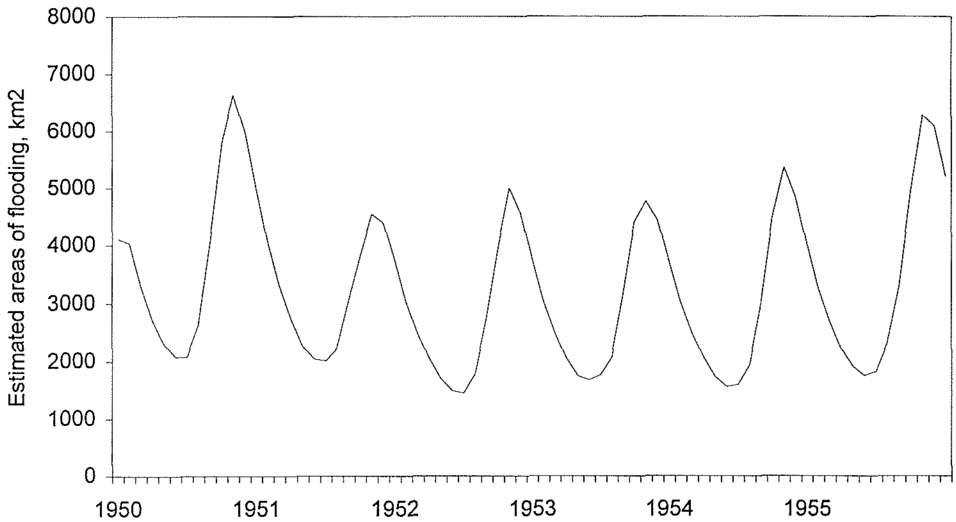


Fig. 7.9 Machar marshes: estimated areas of flooding, January 1950–December 1955.

1973). A subjective appraisal of this map is not incompatible with the hydrological analysis, but the flooded areas should be confirmed in due course with thermal infrared satellite imagery.

Little direct information is available on the vegetation of the area. According to Hughes & Hughes (1992), there are extensive permanent swamps dominated by papyrus along the water courses, or by *Phragmites* and *Typha* away from them. There is unlikely to be much papyrus except in the centre of the marshes, because of the high level range on the Sobat (over 5 m at Nasir) and the seasonal pattern of spill and flooding. The maps of population (Fig. 6.5) and seasonal cattle movements (Southern Development Investigation Team, 1955) show settlements spread along the spill channels from the Baro and Sobat, north and northeast of Nasir, and also along the lower Yabus. These must indicate the existence of grazing grasses.

There have been proposals (Hurst, 1950) to reduce the amount of water evaporated in the Machar marshes either by regulating the river flows with upstream storage to reduce spill or by constructing a channel to convey water through the swamps. As mentioned earlier, the area upstream is being developed by immigration and dam construction. Further hydrological analysis is clearly required to review the estimates of spills and torrent flows. In view of the likely difficulty of re-establishing gauging stations in this rather remote and inaccessible region, satellite imagery could be useful to estimate the seasonal fluctuations in areas of inundation. For example, the thermal infrared image of December 1986 (Fig. 6.4), which was used to estimate the areas of flooding in the Bahr el Ghazal basin, suggests an approximate evaporating area of 3000 km^2, though the interpretation is less clear than in the outline of the Bahr el Ghazal and Bahr el Jebel swamps.

ANALYSIS OF SOBAT CHANNEL STORAGE

A study of the Sobat flood was carried out by J. W. Wright of the Sudan Survey Department as a special investigation of the Jonglei Investigation Team (1954, vol. III, chapter 3). This analysis was based on the floods from 1934–1935 to 1947–1948, excluding 1940–1941 for which records were incomplete. The records comprised 10-day inflows at Sobat Head or Nasir and outflows at Doleib Hill; 10-day gauge levels at four stations, from which the storage within the reach was deduced; rainfall records at three stations and evaporation of 1760 mm deduced from Piche measurements (the only estimate then available).

It was assumed that the cumulative difference between inflows and outflows, allowing for tributary flows, was explained by temporary flood-plain storage. As there were no measured cross-sections in the upper Sobat, their form was deduced from a preliminary balance and gauge levels. The balance took into account rainfall and evaporation on flooded areas and soil moisture recharge on newly flooded ground, estimated to be about 300 mm depth. The cross-sections of the lower Sobat had a parabolic form. This seemed true of the upper Sobat only up to the average flood level; above this level the trough appeared to be incised in a plain sloping gently towards the river.

The water balance suggested that, apart from the inflows and outflows between the Sobat and the two measured tributaries, the Twalor and Wakau, the Sobat system is in nearly all years self-contained. The Twalor acts as a spill channel from the Pibor in years of high flow. The Wakau both receives spill and discharges into the Sobat. Although the eastern plains may contribute inflow during exceptional years, the losses and gains can best be explained by the flooding and drainage of a wide area of plain flanking the Sobat.

The storage is contained within the trough beside the river in average years, and spreads on to a wider plain in higher years. Apart from rainfall and evaporation over flooded areas, and absorption on newly flooded land, the river loses and gains some water through the tributaries Wakau and Twalor, but otherwise the river is self-contained and acts simply as a reservoir. Its principal effect is to delay the passage of the flood by about a month.

RUNOFF FROM THE EASTERN PLAIN

The eastern plain south of the Sobat is a potential source of inflow after periods of heavy rain. There have been a number of observations of a phenomenon named as "creeping flow", which has been defined (Jonglei Investigation Team, 1947, p. 85) as "the slow movement of large bodies of water across a plain which slopes very gently and is almost impermeable". This definition is followed by analysis of flow over a uniformly sloping plain. To illustrate the extremely limited relief of wide areas of these plains, the gradients from east of Bor towards the Sobat mouth are about 0.10 m km^{-1}; a cross-section at about 8°N (Jonglei Investigation Team, 1954, Fig. A28) shows a variation of only about 0.20 m from the mean elevation over a distance of 10 km. An eye-witness account of creeping flow in 1947 (Howell *et al.*, 1988, p. 480) describes it as advancing about 50 km in two weeks over a front of over 30 km with a depth of about 0.30 m.

Such flow would eventually reach channels like the Khor Fullus, which starts as traces in the plain. They develop into depressions about one km wide and converge into a single channel with a flood plain about 200 m wide before flowing into the Sobat. An indication of scale is given by flows measured at the mouth between 1929 and 1939. Flows only extend from August to February. The average flow is equivalent to only 12 mm from some 12 000 km^2, though the range is high. The average runoff is a small proportion of the rainfall and is not a large contribution to the flow of the Sobat. However, there is evidence from the river flow records of 1917 and 1961/62 that in exceptional years there is significant flow into the Sobat.

A detailed survey, carried out in March 1954 (Southern Development Investigation Team, 1955) included five cross-sections of the channel and flood plain near Ful Turuk (8°35'N), with details of the vegetation on all sections. The channel was about 150–200 m wide and about 1–2 m deep, filled with the deep-flooded grass *Echinochloa stagnina*, with some water sloping at about 0.04 m km^{-1} towards the end of the dry season. The channel was incised in a flood plain about 2 km wide, which was partly dominated by the shallow-flooded *Echinochloa pyramidalis* flanked by *Hyparrhenia sp.* Other tributaries contained the same vegetation. The flood plain and channel were being grazed from a Nuer cattle-camp at the time.

CONCLUSIONS

The regime of the Sobat and its tributaries is complex, with most of the runoff developed in the mountains and foothills of the Ethiopian portion of the basin, and reaching either the Sobat or the Machar marshes through a series of parallel river channels. However, the Pibor, which drains a wide area of plains to the south, contributes significantly in some years. Moreover, the main tributary, which is the Baro, loses a significant proportion of its high flows by outflow through spill channels or by overbank spilling. A proportion of the water which leaves the Baro to the south returns to the river system through various channels which flow into the Pibor above its confluence with the Baro. The water which leaves the Baro to the north flows to the Machar marshes, which also receive inflows from several tributaries draining the foothills of the Ethiopian plateau. Little of this water reaches either the White Nile or the Sobat. Analysis of the water balance of the area is made difficult by the shortage of long-term flow records at most of the key points. An attempt has been made here to produce reasonable estimates, but coincident flow measurements and satellite imagery will be required for detailed study. The balance of the Sobat between the confluence of the Baro and Pibor and its outflow to the White Nile is comparatively well known through analysis of flow records. The system is reasonably self-contained with water stored in the channel and flood plain during high flow periods returning to the channel when the flow recedes, after losing some volume by net evaporation and soil moisture recharge.