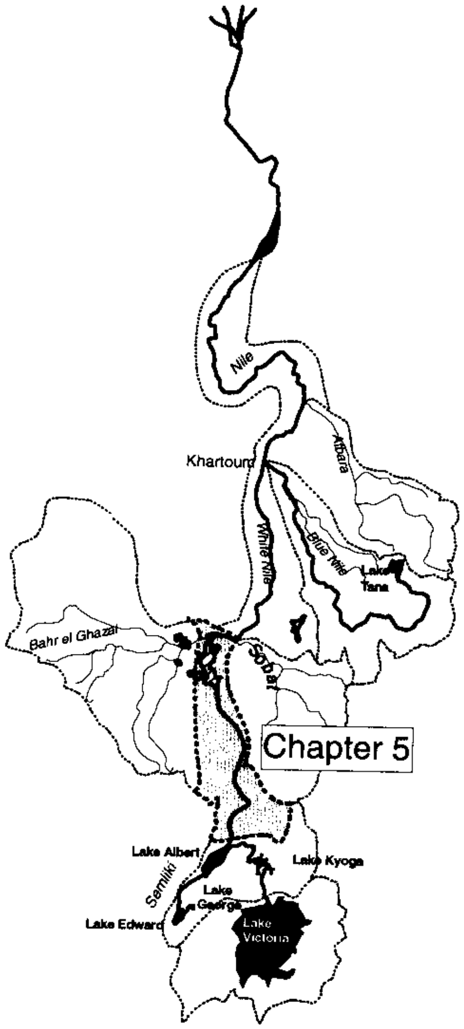
CHAPTER 5

THE BAHR EL JEBEL AND THE SUDD

INTRODUCTION

The Bahr el Jebel extends from Lake Albert to the confluence with the Bahr el Ghazal at Lake No, where the combined river becomes the White Nile (see Fig. 5.1). However, it is hydrologically more logical to take the upper limit at Mongalla, the key gauging station where the river is measured in a single channel as it enters the Sudd, and the lower limit at the confluence of the White Nile and the Sobat, where outflows from the Sudd are measured. One of the channels flowing out of the Sudd is the Bahr el Zeraf which flows into the White Nile between Lake No and the Sobat mouth.

The Bahr el Jebel is the most complex of the Nile reaches as it receives inflows from a number of seasonal torrents which are not measured directly; it loses water by spill from the river into adjacent flood plains at a rate which can only be inferred by measurements at intervals down the course of the reach; its outflow is only about half the inflow on average and has a totally different seasonal distribution. The Sudd has been studied over many years but it is only recently that the water balance has been understood to any degree. More accurate estimates of evaporation from open water and swamp vegetation, and satellite imagery have both been useful.



In this chapter brief accounts of early hydrological studies, and the available river flows, are followed by a discussion of the Bahr el Jebel inflows. A comparison of the historic inflows and outflows presents the problem of the Sudd: the cause of the losses within the reach and their historic variations. An account follows of the topography and in particular the relation between river channel, river bank and adjoining flood plain; this is based both on general observation over the whole reach and on detailed topographic surveys of sample basins. This description leads to an account of the flooding mechanism by which the higher river flows spill over the banks and flow parallel to the main river down the flood plain; they rejoin the river downstream and the process is repeated. The overall spilling has varied over the years as a function of Lake Victoria outflows.

The loss of half the inflow in the Sudd has led to a number of studies, either of the whole Sudd or of smaller reaches or individual basins. The studies are described in turn, leading to a water balance analysis over the whole period of records. The losses form an important fraction of the water resources of the region, and there have been proposals for engineering schemes, including the Jonglei Canal, to reduce these losses. The historical development of these

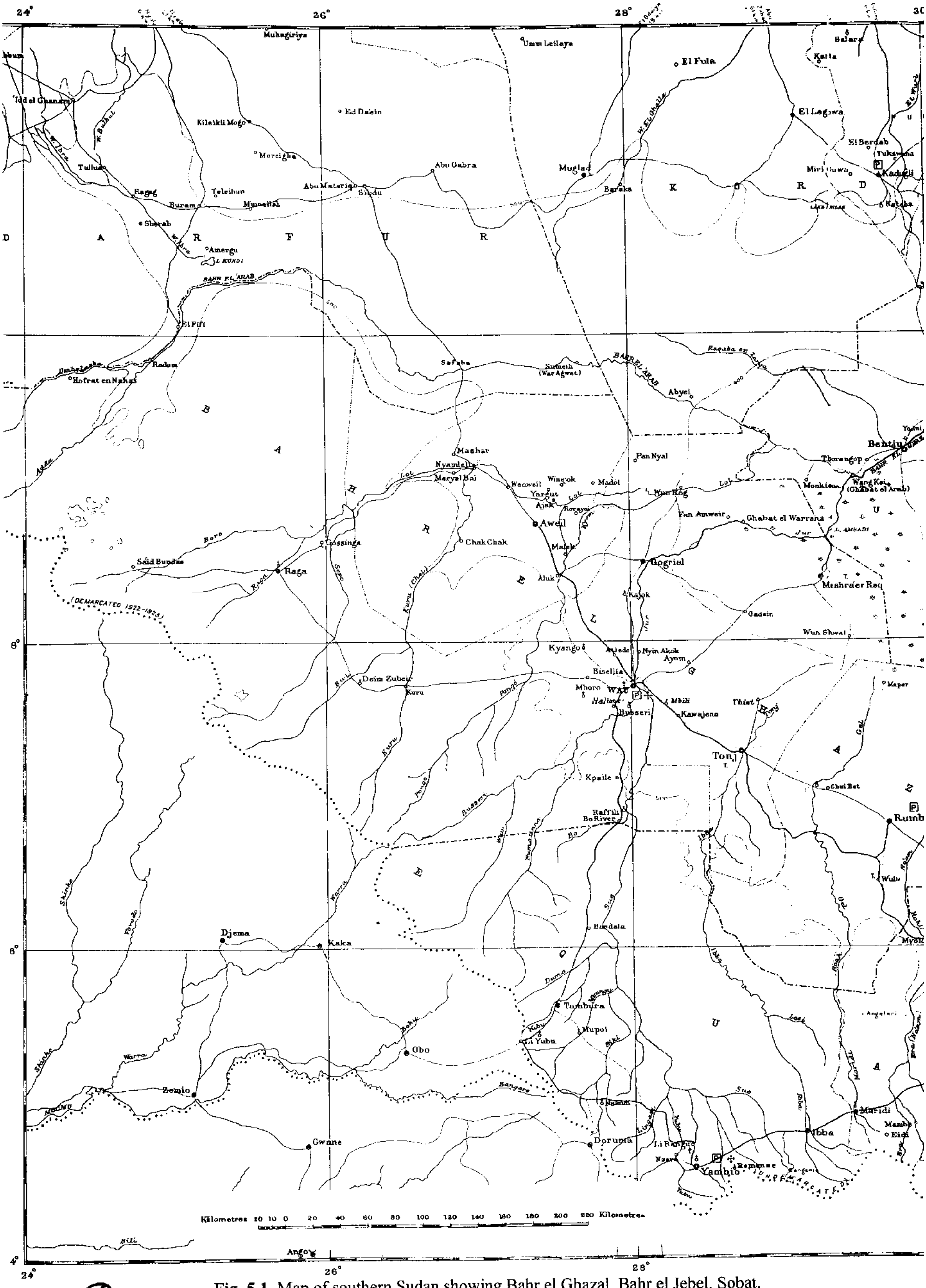
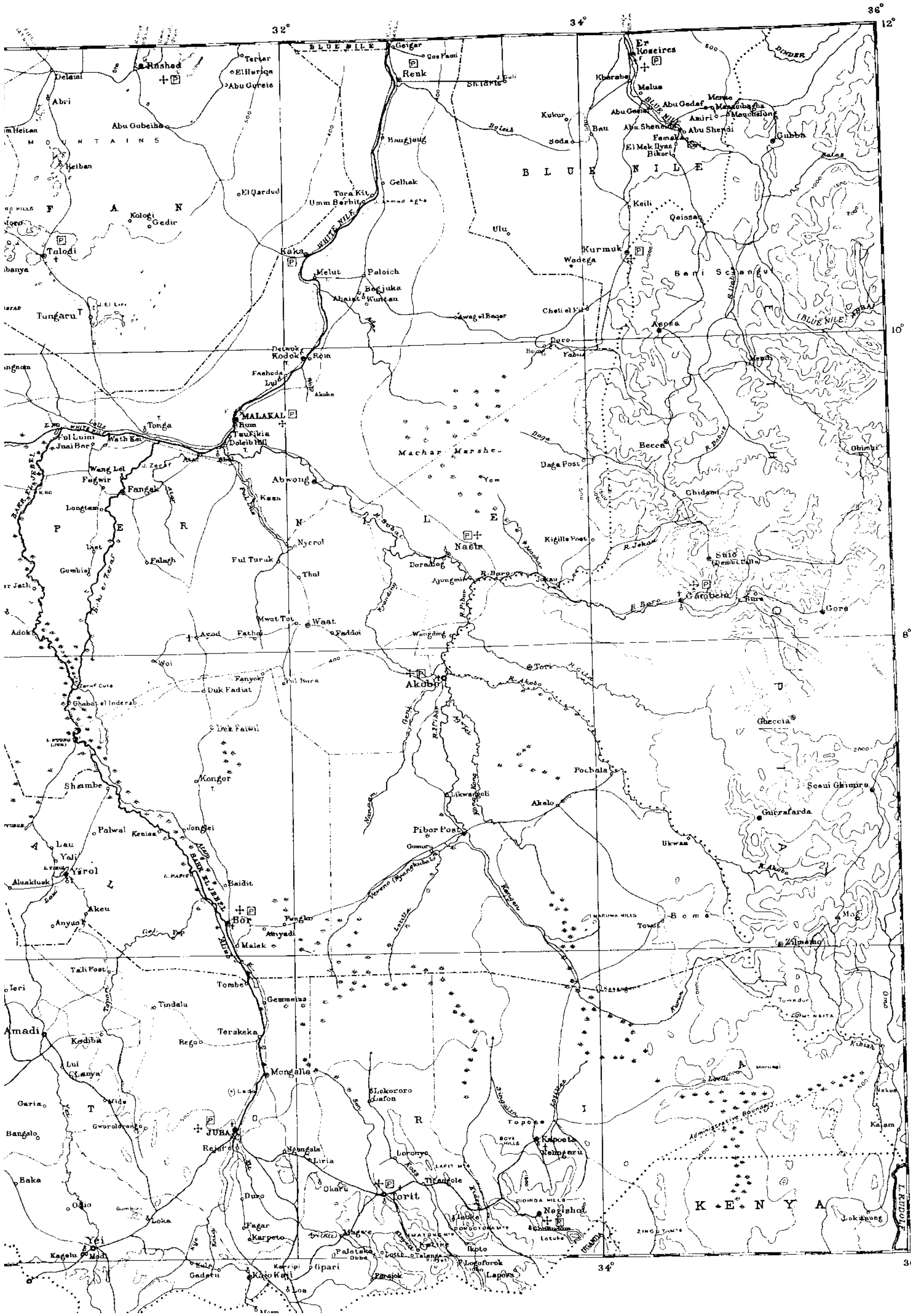


Fig. 5.1 Map of southern Sudan showing Bahr el Ghazal, Bahr el Jebel, Sobat.


32°
34°
36°
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BLUE NILE
Er Roseires
Renk
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Rashad
Tertar
El Huriqa
Abu Gubeiha
Abu Gureis
Delami
Abri
MOUNTAINS
Heiban
Kologi
Gedir
Tulodi
Tungaru
El Qardud
Tora Kit
Umm Berbit
Gelhak
Baugjaug
Kaka
WHITE NILE
Melut
Paloich
Bogjuka
Ahaiat
Wunttau
Awag el Bagar
Sh. Idris
Kukur
Soda
Bau
Kharabe
Malua
Abu Gedaf
Menze
Masaubagha
Mauchelong
Abu Shendi
Amiri
Gubba
Fomaka
El Mek Ilyas
Bikori
Keili
Qeissan
Ulu
Kurmuk
Wadega
Beni Schangul
Asosa
Cheli el Fil
Doro
Boing
Yabus
BLUE NILE (ABBAI)
Mendi
Detwok
Kodok
Rom
Fashoda
Lul
Akoke
MALAKAL
Rum
Taufikia
Doleib Hill
Tonga
Wath Kei
Ful Luini
Jnai Bor
Wang Lel
Fagwir
Fangak
Atar
J. Zeraf
Abwong
Machar Marshes
Yom
Daga Post
Becca
R. Dabus
Ghimbi
Chidami
Nasir
Kigille Post
R. Jokau
Suio
(Dembi Dollo)
Gambela
Bure
Gore
R. Baro
Jokau
Ajungmir
Doradog
Kaan
Nyerol
Ful Turuk
Thol
Longtam
Falagh
Gumbiel
Adok
BAHR EL JEBEL
Bahr el Zeraf
Mwot Tot
Waat
Faddoi
Ayod
Fathoi
Wangding
Woi
Fanyok
Ful Bura
Duk Fadiat
Akobo
Tori
R. Akobo
R. Pibor
Ghubat el Inderab
Duk Faiwil
Ghecceia
Kongor
Shambe
Pochala
Likwangoli
Akelo
Sceui Ghimira
Gurrafarda
Pibor Post
Gumuru
Jonglei
Kenisa
Palwal
Lau
Yali
Yirol
Aluakluak
Baidit
Ukwaa
Bor
Pengko
Anyadi
Malek
Akeu
Anyuo
Boma
Towot
Maji
Zilmamo
Tali Post
Tombe
Gemmeiza
Kasangore
Tindalu
Terakeka
Rego
Amadi
Kediba
Lui
Lanya
Mongalla
Lado
Lokororo
Lafon
Garia
Gworolorongo
JUBA
Rejaf
Bangalo
Tumndur
LOMI NAITA
Kibish
Moruegi
Lorilli
Administrative Boundary
Nakua
Kalam
Topoa
Kapoeta
Nalingaru
Lorinye
Ngangala
Liria
LAFIT MTS
Torit
Tirangole
Okaru
Baka
Duro
Odio
Gumbiri
Loka
Fagar
Karpeto
DIDINGA HILLS
Nagishot
Lotuke
DONGOTONA MTS
IMATONG MTS
Magore
Katire
Ikoto
Palotaka
Obbo
Loguforok
Lapoxo
Parajok
Opari
Kerripi
Kajo Kaji
Kagelu
Yei
Mode
Kulo
Gadetu
Loa
ZINGOT MTS
UGANDA
KENYA
L. RUDOLF
Lokitaung
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AL
TORIT
NILE
BLUE NILE

proposals is described together with the investigations into their interaction with the environment. The most recent proposals and the ways in which their effects might be mitigated are reviewed.

The hydrological regime gives rise to a distinctive flood-plain vegetation, which can be described in geographical terms or analysed in terms of elevations on cross-sections. The links between hydrology and ecology, or between flooding regime and vegetation species, and the nature of the controls, are deduced from local surveys. The changes over the years in the inflow have been mirrored in vegetation changes. The flood-plain vegetation, and the hydrological regime which has given rise to it, are an integral part of the economy of the area, where flood-plain grazing is important in the absence of alternatives. The link between hydrology and vegetation is described in detail in this chapter because most of the quantitative evidence has been derived from the Bahr el Jebel. However, the importance of this link applies to the Bahr el Ghazal basin (Chapter 6), the Sobat basin and the Machar marshes (Chapter 7), and the White Nile (Chapter 8), as well as the Lake Plateau.

EARLY STUDIES

Two early studies dealing with the Sudd were those of Newhouse (1929) and Butcher (1938). Newhouse noted the importance of the torrents between Lake Albert and Mongalla in providing the seasonally variable element of the Sudd inflows and stressed the need for continuous measurements. He noted numerous channels flowing from the river into the swamps and returning to the river, calling them heads and tails. He compared flows at Mongalla and Bor and noted the losses at high flows. He pointed out that gauging stations within the Sudd might not measure all the flow without cross-banks. He estimated the total loss as about 13 km^3 or half the inflow, and described the swamps as "not a reservoir where water is stored, but a sink where it is wasted".

Butcher (1938) discussed the losses in terms of areas of flooding and evaporation. He deduced from air photography that the swamp area was about 7200 km^2. He estimated annual gross evaporation from a tank filled with papyrus at 1533 mm; this explained less than half the measured loss. He noted that series of discharges measured along the river channel showed rapid fluctuations as spill left the river and returned lower down. The loss between Mongalla and Bor, for example, was due to water spilling through spill channels and over river banks into the subsidiary Aliab channel system. This bypassed Bor and returned to the river at Lake Papiu some 60 km downstream. This observation led to the concept of "latitude flow", with flows measured in a series of parallel channels across the flood plain. Examples

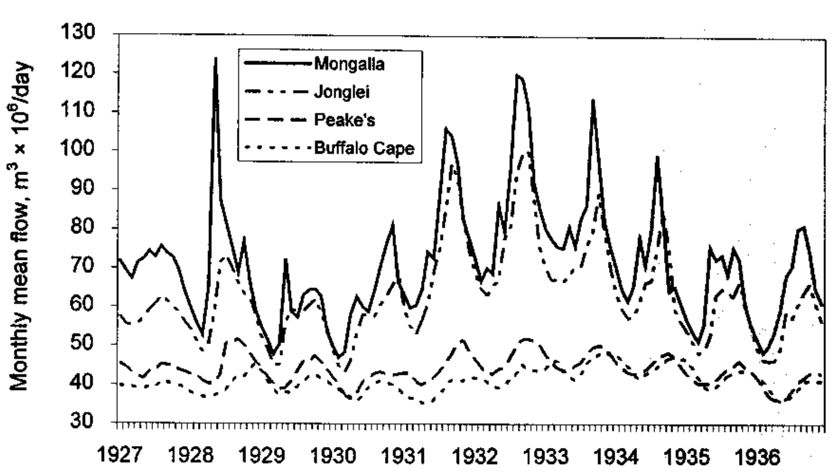

Fig. 5.2 Latitude monthly flows, 1927–1936.

are Gemmeiza and Gigging about 60 km below Mongalla, Jonglei latitude (Jonglei and Kenisa at 6°50'N), Peake's latitude (Bahr el Jebel below Peake's channel and Bahr el Zeraf below Jebel-Zeraf cuts at 7°50'N), and Buffalo Cape/Zeraf mouth. Butcher compared flows for 1927–1936 at Mongalla with these lower sites (Fig. 5.2); these flows clearly show the attenuation and losses. However, he was unable, because of the low estimate of evaporation, to explain these losses without postulating considerable spill towards the Bahr el Ghazal below Shambe. When the estimated evaporation is increased to more reasonable amounts, these spills are no longer necessary to explain the balance.

Hurst & Phillips (1938) summarized the hydrological measurements and discussed the water balance in terms of the equation of continuity. The inflow and local rainfall must equal the outflow and evaporation, after allowing for water absorption by newly flooded ground and increased storage; this was estimated from the swamp area and the change of river level at 10 key gauges. Losses to groundwater storage were neglected. They estimated the area of swamp in 1931/32 as 8300 km^2, and deduced that the evaporation estimate would have to be increased by at least 30% to provide a seasonal balance. They carried out similar balances to Butcher but dismissed the explanation of spill from the Bahr el Jebel towards the Bahr el Ghazal as untenable. They pointed out that the apparent loss was higher in terms of depth over flooded areas in the upper reaches, whereas the opposite would be true if spill to the Bahr el Ghazal below Shambe was significant. This suggested that some of the flow occurred down the flood plain without being measured at channel gauges (see Fig. 5.8 and discussion). They also derived a relation between Mongalla inflow and swamp outflow by comparing quarterly discharges with varying lag.

Subsequent hydrological analysis has been made possible by empirical measurements of higher evaporation from swamp vegetation (Migahid, 1948) and greater understanding of the evaporation process (Penman, 1948). This enabled evaporation from an open water surface or transpiration from vegetation to be estimated from records of temperature, humidity, wind speed and insolation. In fact Penman (1963) pointed out that swamp evaporation measurements in the Sudd corresponded with estimates of open-water evaporation.

STUDIES OF THE JONGLEI CANAL

These early studies led to detailed proposals (Hurst *et al.*, 1946) for the Jonglei Canal, which was planned to bypass the Sudd as part of the Equatorial Nile Project. This project included a main reservoir to be located in Lake Albert, supplemented by a regulator at the Ripon Falls to control outflows from Lake Victoria. This would be operated to augment flows for irrigation below the Sudd. The outflow from this storage would have to be carried in a Sudd Diversion Canal in order to avoid losses within the Sudd.

In a later phase, there were plans to increase flows during periods of shortage on the main Nile at Aswan, using virtual Blue Nile storage in Lake Albert supplemented by Lake Victoria. This would require "Century Storage" to equalize available water at Aswan over a period of 100 years. It would involve releasing higher flows down the White Nile in years of low Blue Nile flows. It was envisaged that storage in Lake Tana, on the Blue Nile, could form part of this project.

The studies of the Jonglei Investigation Team (1954), set up by the Sudan Government in 1946, were geared to the estimation of the effects which the Jonglei Canal and the Equatorial Nile Project, as then formulated, would have on the seasonal flooding of the Bahr el Jebel and White Nile wetlands. They traced the interaction of flooding and vegetation distribution and also the role of the wetlands in the local economy. Their hydrological studies concentrated on the effect which the requirement for "timely flow" or flow during the downstream irrigation season would have on the operation of the canal and the resulting changed flow regimes within the Sudd. The need to supplement timely flows would require high flows at Mongalla from 11 December to 20 June and lower flows during the remainder of the year. This mode of operation would have led to reversed seasonal flows from Nimule to the canal head, as the timely flows would be released in the local dry season. It would also lead to greatly reduced seasonal flooding from the canal head to points above the canal outfall near the Sobat mouth, and continued high flows downstream to Kosti. The need to supplement low flows on the Blue Nile would also affect the natural regime. In addition disastrous periodic flooding would be caused by spills from the reservoir when full, with the local population adapted to reduced natural flooding. These proposals were deemed unacceptable by the Jonglei Investigation Team (1954), and a Revised Operation in phase with the seasons was advocated, which would reduce loss of pasture by nearly half, and also provide flood protection for the area. This Revised Operation depended on equalizing annual discharges at Mongalla, using storage in Lake Victoria and Lake Albert, with a reserve for flood control in Lake Albert. It would be operated to reproduce the natural seasonal regime at Mongalla.

The basic information collected by the Jonglei Investigation Team is still relevant. For instance, an overall review of the hydrology of the area was supplemented by a detailed survey of the Aliab valley opposite Bor (see Fig. 5.7 and Plates 4 and 5) which was completed under favourable low flow conditions during the 1950/51 field season. This survey was extended to the whole reach from Juba to Bor in 1951/52 and provided information from a sample reach on topography, hydrology, seasonal flooding, vegetation distribution and grazing use. This information was used in an account of the area (Jonglei Investigation Team,

Plate 4 Aliab valley: survey party (including the first author!) traversing cross-section 15 (cross-section P in Fig. 5.7) (after Howell, 1953).

Plate 5 Aliab valley: inserting survey peg on cross-section 15 (cross-section P), February 1951.

1954, vol. III), and was further used by Sutcliffe (1957, 1974) in a hydrological study which also quantified the hydrological controls of vegetation.

The rise of Lake Victoria in 1961–1964 led to doubled inflows to the Sudd. The resulting increase in the area of the swamps and the losses within the Sudd not only led to the need to reappraise the hydrology but also provided further evidence of the importance of upstream conditions on the Bahr el Jebel. The construction of the Aswan High Dam after 1959 made the concept of "timely flow" unnecessary and reduced the need for over-year storage in the East African lakes. The changed political situation in the upstream basin led to different proposals for the Jonglei Canal which did not depend on upstream storage (Abdel Mageed, 1985). In Phase I of the revised Jonglei Project a canal was planned to divert part of the natural flows around the swamps and thus to increase the downstream flows by about 4 km^3, which was to be shared between Sudan and Egypt. Construction of the canal was begun in 1978 but was suspended in 1983. The changed conditions and design led to a new investigation in 1979–1983 of the potential effects of the Jonglei Canal, which has been summarized in Howell *et al.* (1988). As part of this investigation a hydrological study of the Sudd and the effect of the canal on flooded areas was carried out in 1982 by the Institute of Hydrology (Sutcliffe & Parks, 1982, 1987, chapters 5 and 16 in Howell *et al.*, 1988). This analysis was based on the earlier analysis of the sample areas, but was applied to a wider area. A visit was made to these sample areas and changes of spill channels, flooding and vegetation were observed from the air (Fig. 5.15).

Thus the study of this reach of the overall Nile covers the upstream hydrology, including the outflows from the lake system and the flows of the seasonal torrents. It also deals with the Bahr el Jebel channels and the adjacent flood plain, the combination of these factors in controlling seasonal flooding, and the effect of this flooding on the flood-plain vegetation. This in turn affects the local economy, in which seasonal grazing is important.

FLOWS OF THE BAHR EL JEBEL

Available river flow records

The recorded outflows from the East African lakes have been discussed in Chapters 3 and 4. The record at Mongalla, where flows have been measured since 1905, is the key record of inflow to the Sudd. The numbers of gaugings on which the inflows and outflows were based have been discussed in Chapter 2. Few gaugings were carried out at Mongalla between 1905 and 1921, with only 35 measurements in the first 17 years. More frequent measurements began in 1922, with an annual average of 260 measurements from 1922 to 1931. After 1940, the frequency of gaugings fell to about 2 a month, to monthly after 1954 and fewer after 1974. There were gaps from September 1964 to June 1967, at a time when the river flows had doubled, and gaugings ceased in 1984. The flows were derived from a general rating curve from 1905 to 1921, by interpolation between measured discharges from 1922 to 1931, and on annual rating curves from 1932 until 1963. The record for 1964–1967 was based on a mean rating derived for the period 1963–1969, and thereafter on annual ratings; records ceased in 1983. The quality of the flow record must have varied with the frequency of gauging but in general has been reasonable. However, comparisons with upstream records showed that flows in 1963–1964, during the rise in lake levels and a rapid change of rating, were not reliable. Comparison of 1978 flows with gaugings shows that the published flows are incorrect; the provisional flows obtained for the 1982 study are more acceptable.

A comparison of the rating curves at Mongalla over the period of record reveals that from 1905 to 1963 there had been a steady rise of about 0.5 m in the river level corresponding to a given flow; this was also observed at other sites (Sutcliffe, 1957). This trend was disrupted by the increase in flows in 1963 (Sutcliffe & Parks, 1994a). After gaugings were resumed in 1967 the earlier rise had been reversed and by 1980 the level was about 1.0 m below 1962 levels (Fig. 5.3). The changes in level were mirrored in bed levels, so that it is possible that a period of aggradation occurred after the period of high lake levels at the end of the nineteenth century, but was reversed by the recent high flows. At the same time, new spill channels were formed. These changes must be considered in terms of the relation between river flows and flooding, at least in the upper reaches.

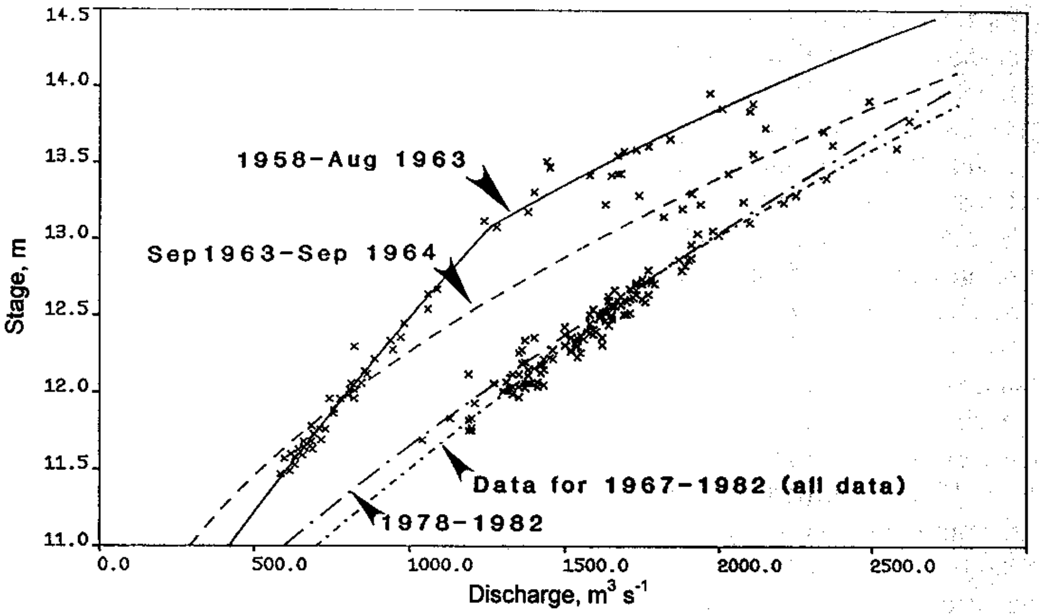

Fig. 5.3 Bahr el Jebel at Mongalla: rating curves, 1958–1982 (after Sutcliffe & Parks, 1994a).

The outflows from the Sudd have been measured directly for short periods, but the only long-term flow record is derived from the difference between the flows of the White Nile at Malakal and the Sobat at Doleib Hill near its mouth. Measurements at Malakal have been regular since 1906, and have continued to the present. Gaugings at Doleib Hill began in 1906, and continued until 1983; the outflows, like the inflows, are not known since 1983. These records are discussed further in Chapters 7 and 8; the records at Malakal are reliable, but the Sobat flows are less reliable after the outflows from the Sudd increased in 1964. In some years (e.g. 1979 and 1981) the published flows appear to be incorrect as they diverge markedly from the norm. Although flows had been measured at a number of "latitude sites" within the Sudd before 1964, after the lake rise and doubled inflows it was not possible to measure complete flows.

Published river flow records

The inflow record at Mongalla for 1905–1983 (Fig. 5.4) illustrates the seasonal component of the Sudd inflows. The graph shows the marked effect of the 1917–1918 flood, and the high proportion of the flow which is relatively steady and due to outflow from lake storage. It also shows the great increase in this lake outflow which occurred after 1961, and the decline which occurred after this rise. The flows at Mongalla have not been measured after 1983, but an indication of the flows since that date can be inferred from the Lake Victoria level or outflow series (see Chapter 3); the decline has continued fairly steadily, interrupted by rises in 1978–1980 and 1998 and by seasonal variations.

In spite of the marked effect of the lake level on the "baseflow" component of the Mongalla flows, there is no evidence from the flows before and after 1961 of a corresponding increase in the seasonal torrent flows. The average flows at Mongalla are compared in Table 5.1 for different periods; although the total inflow nearly doubled between 1905–1960 and 1961–1983, the seasonal component which reflects the torrent flows below Lake Albert did not change. Another method of estimating the torrent flows, described in Chapter 4, was

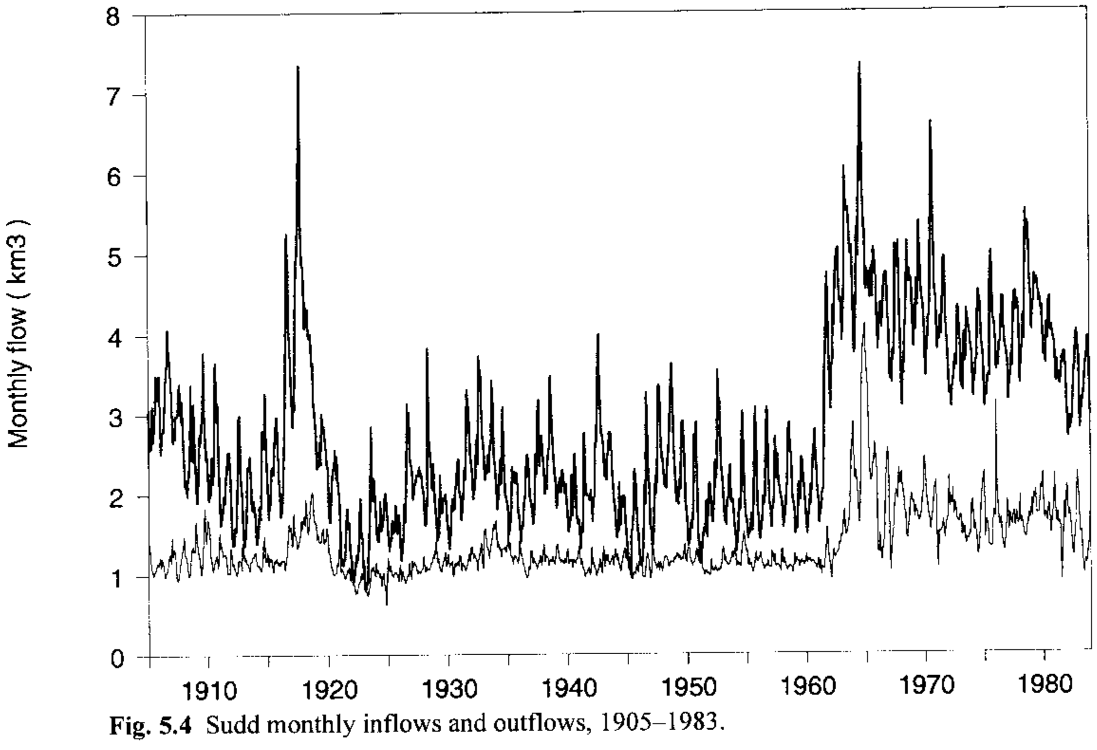

Fig. 5.4 Sudd monthly inflows and outflows, 1905–1983.

Table 5.1 Comparison of Sudd inflows, torrent flows and outflows ($m^3 \times 10^6$).

Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Sudd inflows, 1905–1960												
1979	1692	1795	1850	2260	2169	2398	2771	2754	2650	2362	2151	26831
Sudd inflows, 1961–1983												
3885	3366	3624	3602	4001	3864	4190	4646	4610	4690	4468	4213	49159
Sudd inflows, 1905–1983												
2534	2180	2327	2360	2767	2663	2920	3317	3295	3244	2975	2751	33332
Torrent flows, 1907–1960												
8	0	3	137	474	419	583	910	853	643	347	82	4459
Torrent flows, 1961–1980, excluding 1964												
0	0	0	100	327	291	431	902	895	738	516	176	4377
Torrent flows, 1907–1980, excluding 1964												
6	0	2	127	434	385	543	908	864	668	391	107	4436
Sudd outflows, 1905–1960												
1337	1188	1236	1140	1131	1058	1109	1159	1176	1242	1150	1230	14157
Sudd outflows, 1961–1983												
1950	1634	1771	1619	1582	1504	1513	1589	1697	1936	1940	2064	20799
Sudd outflows, 1905–1983												
1515	1318	1392	1280	1262	1188	1227	1284	1328	1444	1379	1473	16091

based on a comparison of dry season Mongalla flows and Lake Albert levels to estimate the lake outflows. The lake outflows reach their maximum in October–December, after the peak of the torrent flows. Approximate torrent flows were deduced and published in *The Nile Basin*, vol. V (Hurst & Phillips, 1938) and subsequent supplements to vol. IV. Figure 5.5 illustrates these monthly flows and their extreme seasonal and annual variability. Table 5.1 includes these estimated torrent inflows for the periods 1907–1960 and 1961–1980, excluding the dubious value for 1964. The annual totals average 4.4 km^3, but range from 1.3 to 11.8 km^3 with a standard deviation of 1.9 km^3.

These seasonal flows contribute to the annual high flows whose spilling inundates the areas of the flood plain, which are later uncovered and provide the seasonal grazing of importance to the local population. As the torrent inflow did not increase after 1961 and the average area of flooding more than doubled, the average range of flooding in terms of depth will have decreased.

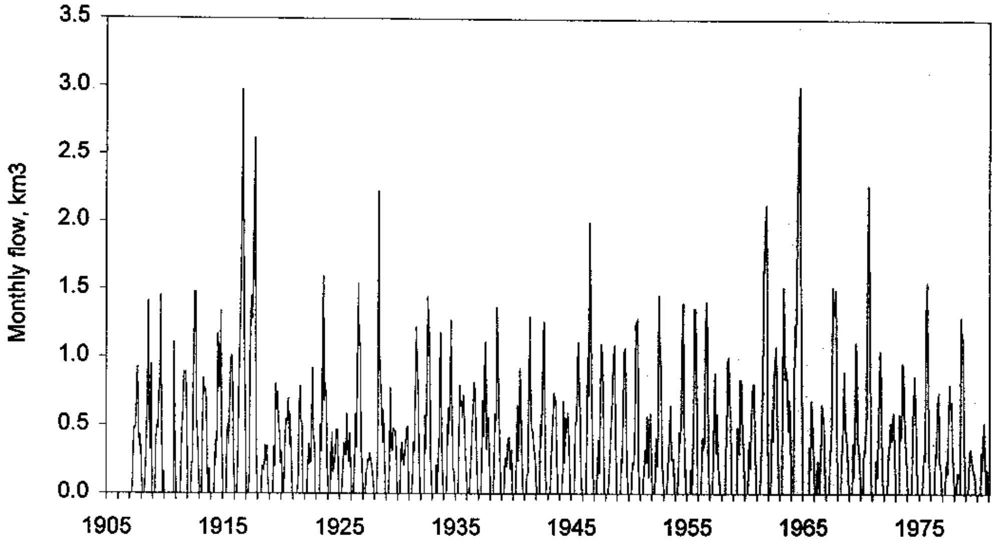

Fig. 5.5 Torrent flows: Lake Albert to Mongalla, 1907–1980.

The outflows, deduced from flows at Malakal and the Sobat mouth, include the outflows of the Bahr el Zeraf as well as the Bahr el Jebel. They also include the outflows of the Bahr el Ghazal, but these flows are small by comparison with other components and have not been deducted. The outflows from the Sudd are also illustrated in Fig. 5.4.

The losses over the whole reach from Mongalla to the Sobat mouth can be derived from the difference between the inflows and outflows. The losses in the early years 1905–1960 averaged 47.2% but increased to 57.7% in the years 1961–1983 because of the higher inflows. The reason for these losses must be sought in the interaction between the inflows and the topography.

THE BAHR EL JEBEL SWAMPS

Below Mongalla the channel carrying capacities are less than the high flows, and the alluvial channels themselves are built up above the adjacent flood plain (Figs 5.6 and 5.8). The excess flows leave the river through small channels which pierce the river banks, or spill over the banks themselves at higher flows; they then inundate large areas on either side of the river. In the southern part of the swamps this flooding is limited by higher ground flanking the flood plain, but further north (Plate 6) the lateral spread of water is not limited in this way. High river flows from the torrents are based on rainfall to the south of Mongalla; the timing coincides with the rainfall within the swamps, which contributes to the inundation. The maximum extent of flooding occurs after the rainfall season, when net evaporation is comparatively high, and much water is lost from the swamps by evaporation and transpiration. As a result the outflow is relatively constant, with little seasonal variation and with annual

Plate 6 River transport on the Bahr el Jebel, showing papyrus beside river (after Howell, 1953).

totals about half the inflow. There has been some discussion as to whether the spilled water returns to the river in significant amounts, and thus whether the swamps act to any degree as storage or simply as a sink. This varies with the topography, but in general terms there is return flow in the higher reaches and less return flow in the lower reaches of the Sudd.

The overall effect of these processes is that varying areas are inundated "permanently" or seasonally, with the uncovering of the seasonal swamp coinciding with the dry season when grazing is not available elsewhere. The areas of permanent swamp depend on the baseflows from the East African lakes, and reflect the medium-term variations of the baseflows. The seasonal swamps also reflect the seasonal variations of the lake outflows, but depend mainly on the seasonal flows of the torrents and the seasonal balance between rainfall and evaporation within the swamps.

The influence of topography

Because the flooding regimes of the different parts of the Sudd vary, some description of the topography is needed to understand the hydrology. The river is incised within an even plain sloping gently north or slightly east of north, while the Bahr el Jebel north of Gemmeiza runs west of north at an angle to the ground slope. North of Juba the river runs in an incised trough, bounded by scarps with a rise of a few metres marking the limit of the woodland on either flank. The scarps decrease in height from south to north, and disappear just north of Bor on the east bank, and south of Shambe on the west.

From Juba to Bor the river meanders (Fig. 5.7) 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 lie below the levels of the alluvial banks of the river, through which a

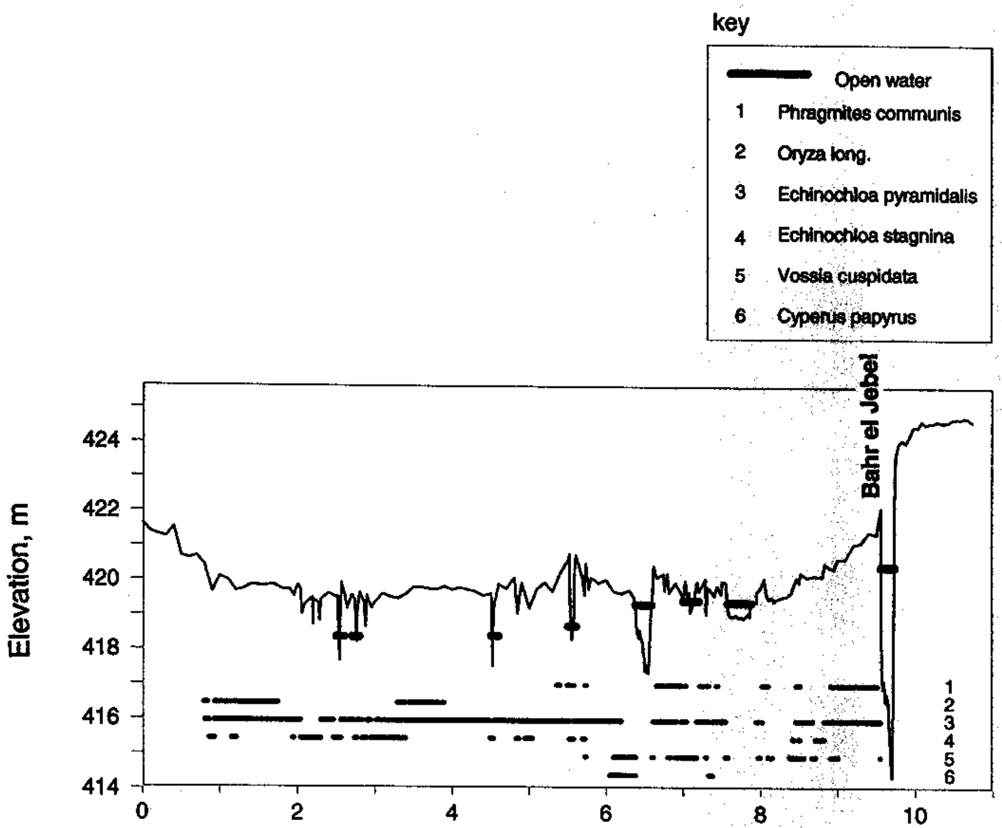

Fig. 5.6 Aliab valley cross-section CS 12 (cross-section O in Fig. 5.7) (after Sutcliffe & Parks, 1996).

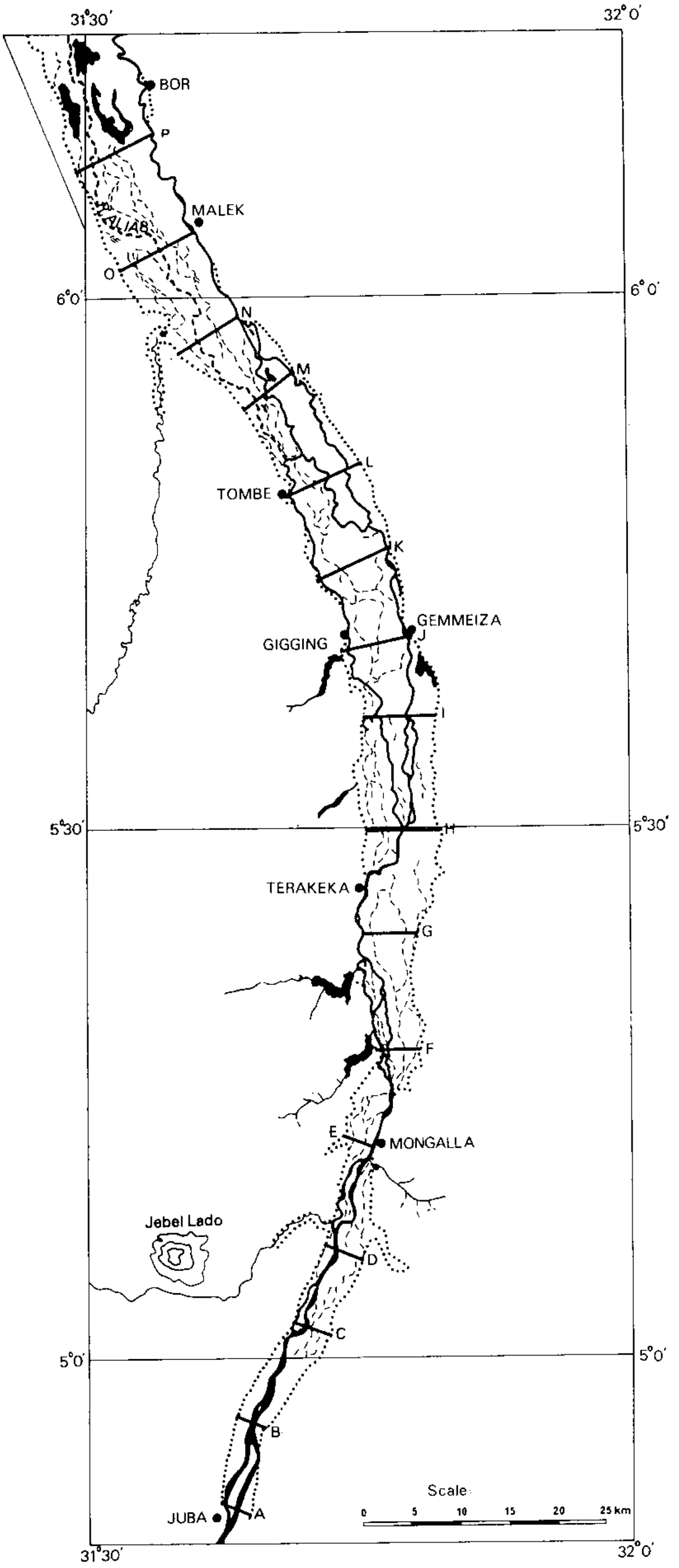

Fig. 5.7 Map of Bahr el Jebel flood plain from Juba to Bor (after Sutcliffe, 1974).

number of small channels carry spill. At the downstream end of each basin, where the river meets the high ground, a large channel carries spill back into the river. Further north, where the basins are not confined, the system of channels becomes more complicated but the pattern can be visualized as a series of basins receiving spill and discharging some spill back to the river.

Between Bor and Jonglei the river flows in a shallow trough about 15 km wide, and in the southern part there is little lateral spill outside the trough. About half way between the two sites, the eastern margin of the trough becomes less distinct and a belt of seasonally flooded grassland increases in width. The river flows in three distinct channels with interconnecting lakes throughout this reach and there have been changes since the 1960s.

From Jonglei to Shambe the main complex of channels and lakes remains in a band about 15 km wide, but there is no eastern limit to the trough and there is extensive spillage to the east resulting in large areas of seasonally flooded grassland and permanent swamp. Between Shambe and Adok the Sudd is at its widest, with large inaccessible swamps and fewer side channels. Some of the eastern flow forms the Bahr el Zeraf. There are a number of small channels flowing west of the Bahr el Jebel, some of which rejoin the main channel south of Adok; some may be linked with the Bahr el Ghazal system to the west, though any outflow is likely to be small.

Between Adok and Malakal the Bahr el Ghazal joins the main river from the west at Lake No, where the river turns east and becomes the White Nile; it is joined by the Bahr el Zeraf and the seasonal Sobat.

The flooding regime

The complexity of the area is such that it is difficult to describe the flooding process, except in sample areas. At a time when inflows and flooding levels were low, it was possible to survey

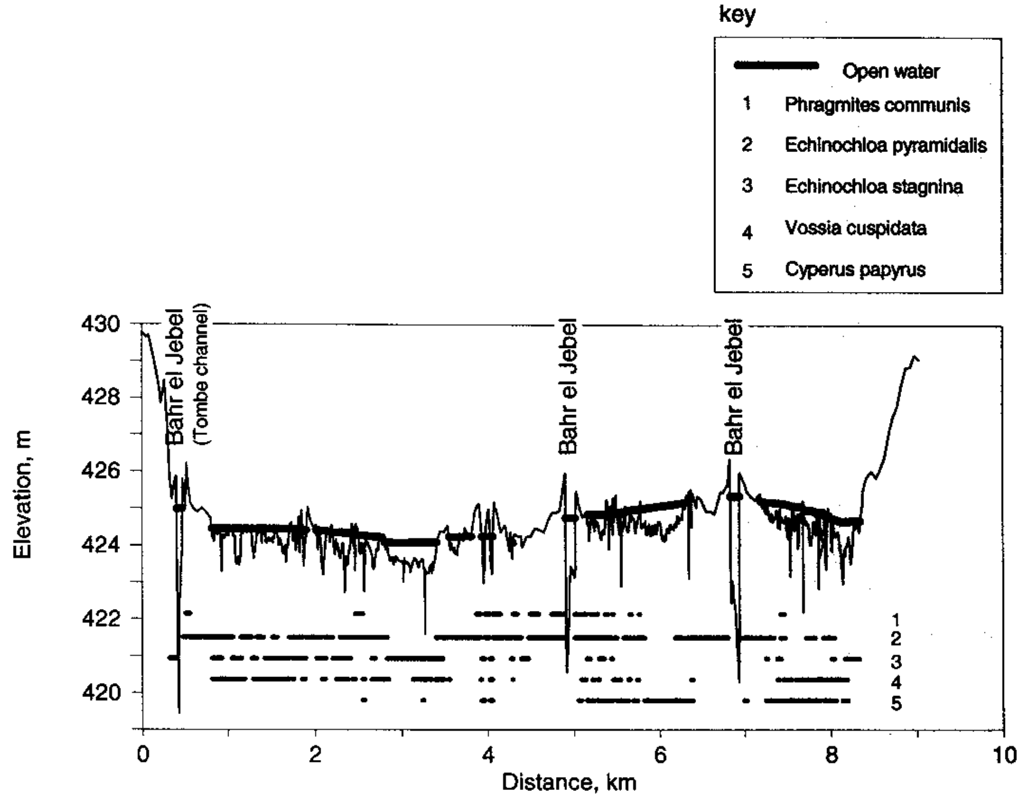

Fig. 5.8 Bahr el Jebel valley cross-section east from Tombe (cross-section L in Fig. 5.7).

sample reaches between Juba and Bor. Some detail on how spill leaves the river may be deduced from cross-sections of the flood plain and sections along the river bank. This spill flows down the flood plain and either returns to the river or is lost by evaporation. A detailed account of the sample reach is given elsewhere by the present authors (Howell *et al.*, 1988, Chapter 5) but a general summary may illustrate the processes. At moderate flows and levels, river spilling occurs through the alluvial banks of the main channel in a succession of spill channels. Some of these are deep and may become part of the main channel network, while others are simply cattle watering points or hippopotamus access points which carry spill through the bank. Some 370 spill channels were surveyed in 1952 along 58 km of the west bank of the Bahr el Jebel bordering the Aliab valley from Tombe to opposite Bor. A similar survey along the east bank from Mongalla to Gemmeiza revealed about 170 spill channels over 57 km. When river levels are high, widespread spilling occurs over the banks of the main river.

There is evidence from successive maps and observation that spill channels develop from small breaks in the bank. These grow into major channels in periods of higher flows, and finally silt up at their head and become obsolete, with their high alluvial banks forming barriers to the lateral flow of spill. The River Aliab is an example of such a river. When the reach was surveyed by Gordon in 1874, this was the main navigation channel; by 1951–1952 it was obsolete and formed a barrier to lateral flooding, but in 1982 it was observed from the air to be carrying spill again.

A cross-section (cross-section L in Fig. 5.7) from Tombe to the east of the valley illustrates several features of the topography (Fig. 5.8). The problem of access across the flood plain is clear, even in March 1952 when the Tombe gauge was at the normal minimum before the rise of Lake Victoria; the Mongalla flow was 54 $m^3 \times 10^6$ day^{-1}. The section crosses three branches of the Bahr el Jebel, including the Tombe and the eastern channels. A number of small channels in the flood plain, including Khor Kongolayum ("Alum was eaten by a crocodile") contribute to the flooding, with flows of 0.25 to 0.3 $m\ s^{-1}$. The lateral flow of water is clearly illustrated by the gradient away from the main river or spill channel. Spilled water also drains down gradient parallel to the river, either through drainage channels or through the swamps; velocities of 0.025 up to 0.167 $m\ s^{-1}$ were noted. The protection provided by the alluvial banks is illustrated near the main channels. There is a striking contrast in vegetation between papyrus on the eastern part of the section and pasture grass like *Echinochloa stagnina* on the western island. The flooding depends on the detailed topography.

Where the river crosses the flood plain and touches the high ground, as at Gemmeiza (Fig. 5.7), a channel invariably carries upstream spill back into the river. Thus the basins of the flood plain, especially above Bor, act as a series of reservoirs which receive flood water from the river and return water lower down. The amount in passage or temporary storage increases as the river rises and decreases as it falls. In fact the return channel is a sensitive indicator of flooding conditions within the basin. For example, the large channel returning to the river at Gemmeiza was stagnant in March 1952 when the Mongalla basin was receiving little spill, but was flowing strongly in February 1982 when higher river flows caused large-scale spilling upstream.

Between Juba and Bor the flood plain is eroded below the woodland fringe and flooding is confined by higher ground. These limits disappear downstream of Bor on the east and near Shambe on the west and the constraint on lateral flooding is lost; also the river banks and channel capacities are smaller and spilling is more continuous. There is no barrier to the east in the direction of the overall slope and flooding extends further during high flows; much of the spill does not return to the river. The outline of flooded areas after 1964 (Fig. 5.9 and Fig. 6.4) shows that most of the increased flooding occurred to the east of the river.

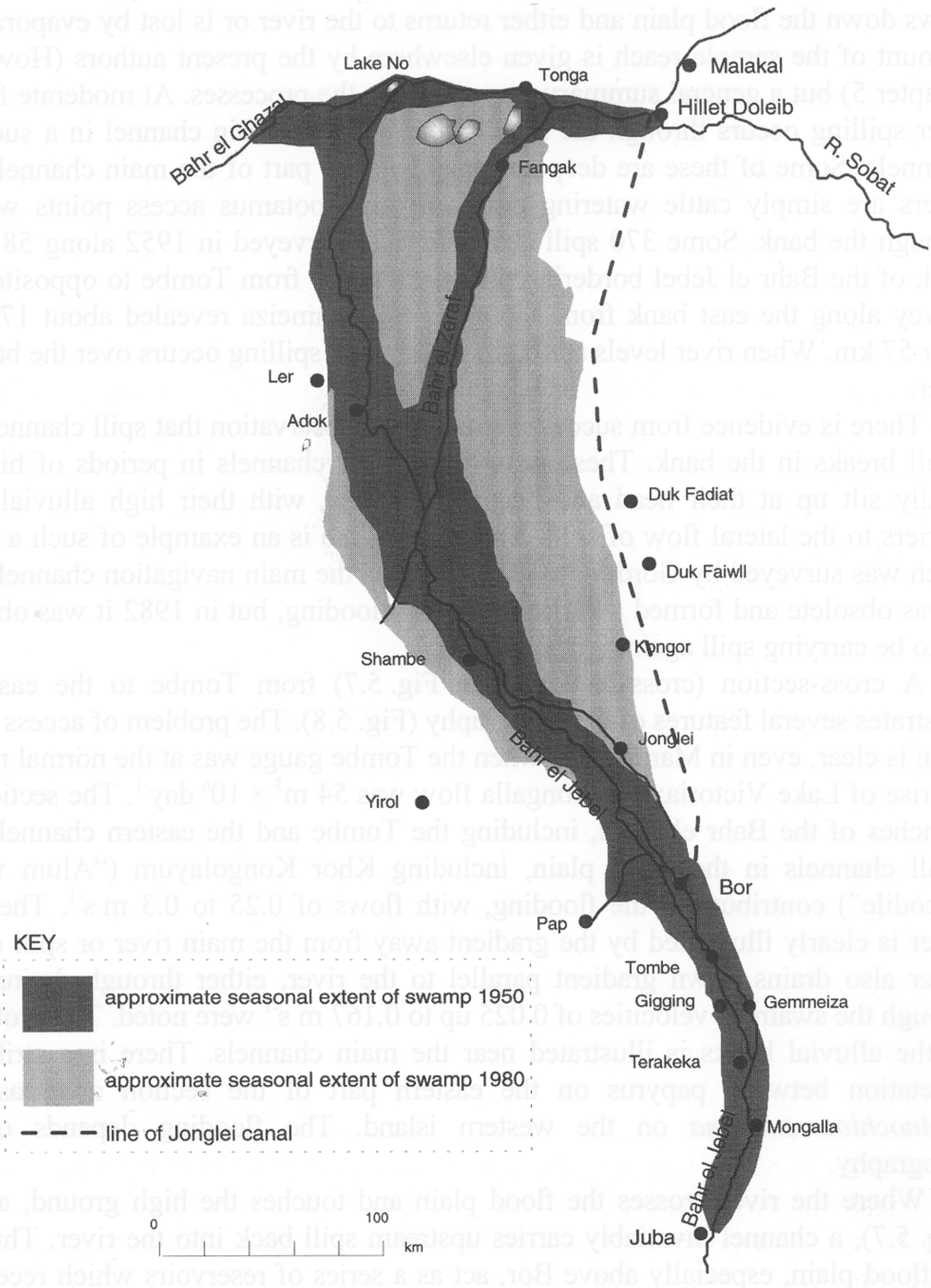

Fig. 5.9 Map of the Sudd (after Howell *et al.*, 1988).

The pattern of flooding appears to be fairly similar to that described for the upper reaches, with spill spreading from the river to inundate a wide area but with some spill flowing parallel to the river in drainage channels like the Atem which rejoin the main river downstream. As a result of these successive spills the seasonal variations of inflows are damped to a fairly steady and lower outflow (Fig. 5.4), except in periods of sustained high inflows as in 1961–1966. The area of inundation increased markedly after 1961, as indicated by comparisons of sample areas between Juba and Bor and by satellite imagery of the whole area. In spite of the complexity of the physical situation, it may be represented by a simple hydrological model of a reservoir which rises and spreads as the inflow increases.

Study of a sample reach

A detailed study of a sample reach between Mongalla and Gemmeiza (Sutcliffe, 1957, 1974) showed that it was possible to reconstruct volumes and levels of flooding from inflow records at Mongalla and outflow records at Gemmeiza and Gigging. It was necessary to estimate unmeasured outflow between Gemmeiza and Gigging during high flows. Comparison of flooding levels and vegetation species showed that not only do hydrological factors control the vegetation, but also the vegetation distribution can reveal the shape of flooding parallel to and away from the river channel. The volumes of flooding were related directly to Mongalla inflows, and in turn to frequency and duration of flooding. This study is discussed later in relation to vegetation.

This procedure can be extended to develop a simple hydrological model to describe the behaviour of the whole of the Sudd over the period of flow records. The model must take account of river inflows and outflows, rainfall on the flooded area and evaporation from this area. It should be able to reflect the increased Bahr el Jebel inflows after 1961, and the subsequent increase of both permanent and seasonal flooded areas and of evaporation losses. The model should use actual measurements as far as possible, in order that the results should be physically reasonable.

HYDROLOGICAL MODEL OF THE SUDD

After construction of the Jonglei Canal had begun, interest in the effects of the canal was renewed and an environmental study was carried out between 1979 and 1983 (Howell *et al.*, 1988). As a complement to this study a hydrological analysis of the Sudd was carried out by the Institute of Hydrology (Sutcliffe & Parks, 1982, 1987; chapter 5 of Howell *et al.*, 1988). The area was treated as a simple reservoir, and the volumes and areas of flooding were estimated for the period 1905–1980. This demonstrated the dramatic rise in the area of flooding, which trebled after 1964. The effect was concentrated on the permanent swamp rather than the seasonal flood plain, as the torrent flows had not increased.

The whole of the Sudd was taken as the limits of the model, as flow records were not available for a smaller area after the rise of Lake Victoria and Bahr el Jebel flows. The inflows at Mongalla and the outflows from the swamps were available from 1905 to 1980. The flows have been estimated from regular level and discharge measurements, using rating curves deduced generally from contemporary gaugings.

Monthly rainfall records at eight stations were used to derive a swamp rainfall series for the period 1905–1980. Long-term variations (Howell *et al.*, 1988, Fig. 5.8), showed that the high flows around 1917 coincided with a period of high local rainfall but the period of high flows since 1961 was not reflected in Sudd rainfall. In other words, the high flows after 1961 were based on high rainfall in the lake region alone. This is important when comparing the changes in permanent and seasonal flooding.

A reasonable estimate of swamp evaporation is important to modelling of the Sudd. Early estimates were based on papyrus grown in tanks, but it was difficult to maintain vigorous growth. Penman (1963), discussing improved experiments by Migahid using tanks filled with papyrus and open water, suggested that the transpiration from the papyrus and evaporation from the open lagoon would be nearly equal. Open-water evaporation, estimated by the Penman method from temperature, humidity, sunshine and wind speed at Bor, corresponds to 2150 mm year^{-1}, and average values were used in the model. Table 5.2 gives monthly average rainfall and evaporation totals used in this study.

Table 5.2 Average Sudd rainfall (1941–1970) and open water evaporation (mm).

Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Rainfall												
2	3	22	59	101	116	159	160	136	93	17	3	871
Evaporation												
217	190	202	186	183	159	140	140	150	177	189	217	2150

The model is simply based on the equation of continuity and treats the swamp as a reservoir which receives 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. This was estimated as 200 mm at the beginning of the wet season and reduced to take account of net rainfall during this season. To complete the water balance a relation between volume V and area A of flooding was required, and evidence from the Mongalla basin and studies of the White Nile and Sobat suggested that a simple linear relation was reasonable. Thus $A = kV$ was used which implies a constant mean depth $(1/k)$ as the area of flooding increases; $1/k$ was estimated as 1 m.

The hydrological model

The model may be expressed as follows:

$$\delta V = [Q - q + A(R - E)]\delta t - r\delta A$$

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 recharge, which is positive when δA is positive and zero when δA is negative. The analysis for month i is:

$$V_{i+1} = V_i + Q_i - q_i - kV_i(E_i - R_i) - kr_i(V_{i+1} - V_i)$$

whence

$$V_{i+1}(1 + kr_i) = V_i(1 + kr_i) + Q_i - q_i - kV_i(E_i - R_i)$$

which requires a second iteration to allow for the fact that evaporation occurs from $(A_i + A_{i+1})/2$. However, a linear relation between A and V leads to a direct relationship:

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

Starting from an initial storage of 8 km^3 on 1 January 1905, or 8000 km^2 of flooding, the storages and flooded areas were estimated at monthly intervals to the end of 1980. The predicted flooded areas were compared with gauge levels at Shambe near the centre of the Sudd; the seasonal fluctuations were reasonably reproduced.

Areas of flooding on specific dates were used to test the model. Measurements were found corresponding to four dates. Maps based on air photography of 1930/31 gave a swamp area below Mongalla of 8300 km^2, of which 845 km^2 was between Mongalla and Bor; these estimates (Hurst & Phillips, 1938) were assumed to correspond with the mean area. Satellite imagery of February 1973 gave a flooded area from Bor to Malakal of 21 300 km^2, illustrating the increase after 1964. Flooded areas can also be deduced from vegetation maps, and a map in the Jonglei Report (1954) suggested 2700 km^2 of permanent swamp below Bor and seasonal swamp of 10 400 km^2. Similar maps compiled from systematic aerial reconnaissance supported by satellite imagery of 1979/80 suggest an area of permanent swamp below Bor of 16 200 km^2, with additional seasonal swamp of 13 600 km^2. Thus six measurements of

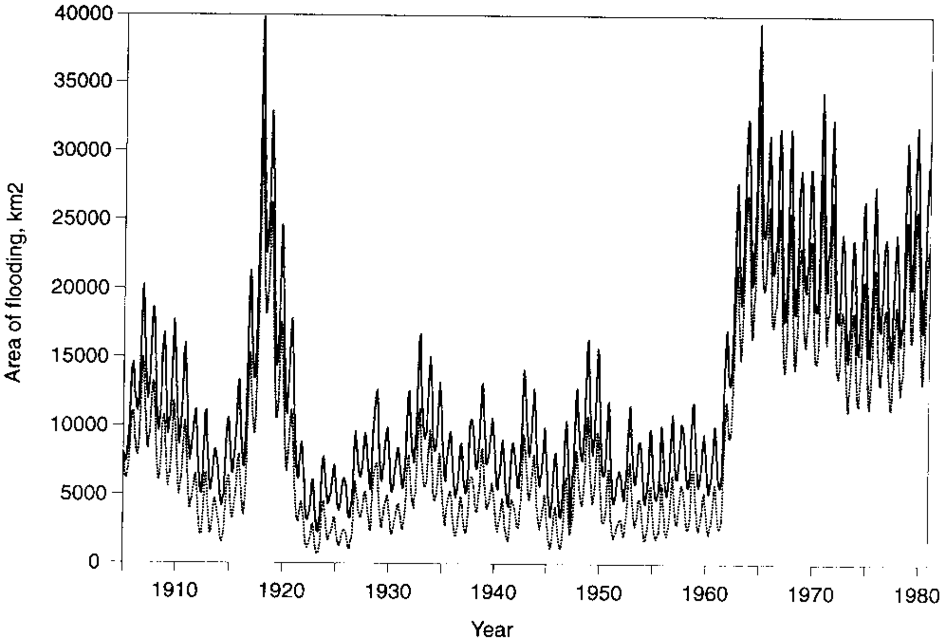

Fig. 5.10 Effects of the Jonglei Canal: estimated areas of flooding below Bor, with and without the Jonglei Canal (20 $m^3 \times 10^6$ day^{-1}).

flooded areas on specific dates were compared with the predicted values (Sutcliffe & Parks, 1987). They provided a reasonable fit on the assumption that the measured areas based on vegetation maps corresponded with average values of permanent and seasonal swamp over three years. Thus the model was taken as providing reasonable estimates of the historical areas and volumes of flooding.

The estimated areas of flooding follow quite closely the measured inflows. The time series of flooded areas (Fig. 5.10) shows clearly the short-lived increase in flooding during the 1917–1918 period, and the prolonged period of increased flooding after 1961–1964. It is clear that the area of seasonal flooding, due to the torrents, did not increase significantly after 1961, whereas the area of permanent swamp increased dramatically. The estimated areas at the start of each month are given as averages for different periods in Table 5.3. This shows the extent of the increase after 1961, and illustrates the seasonal pattern. The model was adapted, as described later, to assess the effect of the Jonglei Canal on areas of flooding, and Fig. 5.10 includes an estimate of the effect of a canal operated on a constant flow of 20 $m^3 \times 10^6$ day^{-1}.

Effect on areas of seasonal flooding

The important local effect of the operation of the Jonglei Canal would be the reduction in seasonally flooded land which provides dry season grazing to cattle and wildlife. The permanent swamp, flooded throughout the year, is less economically valuable, though it

Table 5.3 Average monthly estimated areas of flooding below Bor (km^2).

Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1905–1960											
10 148	8 786	7 727	6 947	6 753	7 370	8 114	9 382	11 123	12 483	12 711	11 642
1961–1980											
23 233	20 713	18 781	17 572	17 387	18 619	19 862	22 130	25 504	27 776	28 679	26 865
1905–1980											
13 592	11 925	10 636	9 743	9 551	10 330	11 206	12 737	14 907	16 508	16 913	15 648

Table 5.4 Estimated effects of canal on average areas of flooding ($km^2 \times 10^3$).

Canal flow	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1905–1960												
-	10.1	8.8	7.7	6.9	6.8	7.4	8.1	9.4	11.1	12.5	12.7	11.6
20	6.2	5.2	4.4	3.6	3.4	4.1	4.8	5.4	6.6	7.8	8.5	8.1
1961–1980												
-	23.2	20.7	18.8	17.6	17.4	18.6	19.9	22.1	25.5	27.8	28.7	26.9
20	18.6	16.5	14.8	13.8	13.6	14.6	15.6	17.5	20.3	22.2	23.0	21.6
1905–1980												
-	13.6	11.9	10.6	9.7	9.6	10.3	11.2	12.7	14.9	16.5	16.9	15.6
20	9.5	8.2	7.2	6.5	6.3	6.9	7.5	8.7	10.3	11.6	11.9	11.0

provides a refuge to wildlife. The estimated monthly areas of flooding for three periods corresponding to Jonglei Canal flows of $20\ m^3 \times 10^6\ day^{-1}$ are compared in Table 5.4 with the natural areas.

It will be seen from Table 5.4 and Fig. 5.10 that under the regime of a steady flow down the canal the area of seasonally flooded land or "toich" would decrease, but that the area of so-called permanent swamp would decrease more. In addition the effect of the canal would be very different between the low flow or high flow period before and after 1961. It would be possible to mitigate the adverse effect of the canal by choosing suitable operating rules. This can only be fully appreciated with an understanding of the way in which the hydrological regime controls the distribution of the vegetation of the flood plain, so that further discussion of the Jonglei Canal follows an account of the links between hydrology and vegetation.

The increase in naturally flooded areas after 1961, and the seasonal pattern of flooding, are relevant to one objection to the Jonglei Canal. Eagleson (1986), in discussing the prospect of hydrological forecasting on a global scale, has drawn attention to the wide region of influence of evaporation from the Sudd. More specifically, it has been suggested by others that the canal, in reducing the flooded area, would by decreasing local evaporation also reduce rainfall either locally or in the Blue Nile basin. There has been no evidence that the natural increase of flooding after 1961 affected rainfall either locally or in the Blue Nile basin; further, the maximum area of flooding and high net evaporation occur in October–December, after the rainfall season in the Bahr el Jebel or Blue Nile basins (Sutcliffe & Parks, 1993). However, it would be interesting to trace the effect of water evaporated from the area during different seasons.

HYDROLOGICAL CONTROL OF FLOOD-PLAIN VEGETATION

The linkage between flood-plain vegetation and hydrology, in particular the duration, depth and range of seasonal flooding, has been described from a hydrological viewpoint (Sutcliffe & Parks, 1996) but it is convenient to describe the findings here.

Early observations and botanical studies

After botanical investigations, Migahid (1948, 1952) identified the main species of the permanent swamp as *Cyperus papyrus*, *Vossia cuspidata*, *Phragmites communis* and *Typha australis* and identified the main controls as water depth, current velocity and ground level. He distinguished between those species like *Cyperus papyrus* and *Vossia cuspidata* with superficial rhizomes which can float on the surface of rising water, and such species as *Phragmites* and *Typha* which are anchored by their roots and unable to survive deep flooding. Further, the papyrus roots can only penetrate the clay soils of the Sudd where these are nearly permanently flooded, while those of *Vossia* can penetrate relatively dry soil. Thus both papyrus and *Vossia* can tolerate deep flooding, but papyrus requires considerable duration of flooding. *Vossia* can tolerate higher current velocities.

Migahid also observed that hydrological conditions varied along the course of the Bahr el Jebel from Lake No to Mongalla. The river banks and the swamp rise relative to the river level, while the annual range of river levels increases. The time the bank remains above the river level increases from north to south, and the swamp itself is uncovered for varying periods. Thus he drew attention to the influence of depth and duration of flooding, and the importance of relative levels of river level, bank and swamp.

Botanical studies of the Jonglei Investigation Team

The studies of the Jonglei Investigation Team from 1948 to 1954 concentrated on the grasses of the seasonally flooded areas, the vital component of the grazing cycle. The importance of depth and duration of flooding was accepted. Distinction was made between the deep-flooded species of *Cyperus papyrus*, *Vossia cuspidata* and *Echinochloa stagnina* with floating rhizomes, and the shallow-flooded species of *Phragmites communis*, *Echinochloa pyramidalis* and *Oryza spp.*, which are anchored by their rhizomes and root systems. The duration of flooding was accepted as important through its relation to root resistance. However, depth and duration of flooding, and other hydrological factors, are inter-related at any one site; the important controls can only be determined from detailed surveys.

The elevations of different species were studied (Jonglei Investigation Team, 1954, p.154 *et seq.*) at sites on the White Nile, the Sobat, and the Bahr el Ghazal. These observations covered different hydrological regimes, in particular ranges of flooding. The levels of the boundary between the shallow-flooded species and deep-flooded species are related to the maximum depth of flooding. The presence or absence of papyrus indicates that range of flooding is important.

Juba–Bor survey

Detailed evidence of the link between hydrology and vegetation was obtained from surveys carried out between Juba and Bor (Jonglei Investigation Team, 1954, pp. 823–847; Sutcliffe, 1957, 1974). A survey of the Aliab valley west of the Bahr el Jebel above Bor was completed in January–May 1951. Some 15 cross-sections were surveyed, with changes of slope and vegetation species recorded. An example is given in Fig. 5.6. The flood plain is well below the level of the river and the water level does not correspond directly with that in the river channel. A vegetation map (Jonglei Investigation Team, 1954, Fig. H3) showed that all six main species were found in the sample reach, and their distributions on each cross-section were clearly related to elevation. There was also a progression of species along the valley. The lower end of the reach, opposite Bor, was dominated by *Cyperus papyrus*, *Vossia* and open water, while the upper end was occupied by *Echinochloa pyramidalis*, with *Phragmites communis* along the alluvial banks of the channels. The lower ground was occupied by *Echinochloa stagnina*, with *Oryza spp.* in an inland basin protected by the obsolete Aliab channel and watered by Khor Gwir.

In 1951–1952 the survey was extended to the whole reach between Juba and Bor (Fig. 5.7, 16 cross-sections A–P). A second sample basin on the right bank between Mongalla and Gemmeiza (12 cross-sections) was investigated; the alluvial banks of the main river were also surveyed as spills over and through the banks were observed to be a key to basin flooding. These showed that the bank slope was greater than the water slope, not only over the whole reach, but also within each basin, and that the slope of the flood plain was even greater. A similar progression of vegetation was found in this basin, but *Cyperus papyrus* and *Vossia* were confined to a small area at the lower end of the valley, and *Echinochloa pyramidalis* and *Phragmites communis* dominated much of the basin. This qualitative information was analysed further in comparison with hydrology to deduce the precise mechanism.

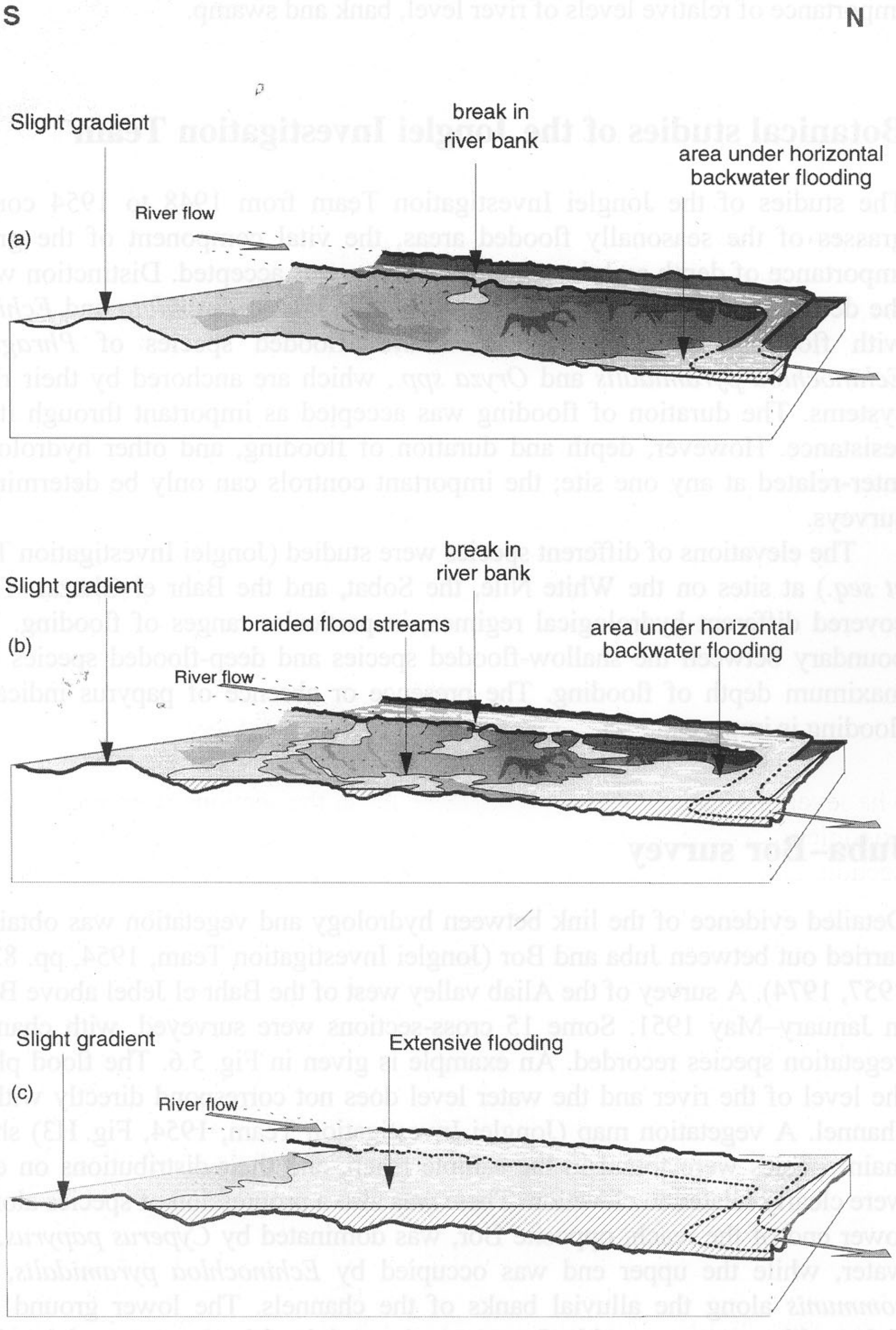

Fig. 5.11 Flood plain inundation and flow mechanisms: (a) low wet season flows; (b) moderate wet season flows; (c) high wet season flows (after Sutcliffe & Parks, 1996).

Description of flooding mechanism

Detailed study of these sample basins confirms the mode of flooding. As the relative levels of the river and bank change downstream, there is for any given inflow a point below which the bank is below river level, and water is able to flow directly across the flood plain. The limit of the overbank flow moves upstream as the inflow increases. Above this point the spill is confined to channels through the bank, and is related to river level. This process is illustrated in simplified form in Fig. 5.11. At the foot of the basin a channel connects the flood plain with the river and the spill flows back into the river. At very low flows (a) the flooding is dependent on this channel alone and the range of flooding corresponds with the range of river level. As the inflow increases (b) the point at which the bank was below the river migrates upstream, while flooding above this point increases. At very high flows (c) the river level is above the bank along the whole basin, and the flooding spreads laterally across the valley and then downstream at a slope which approximates to the river slope. Because the upper end of the basin is protected by the bank at low flows, the range of flooding is much higher at the upstream than the downstream end of the basin, and the flooding profile swings about a hinge at the lower end of the valley where the connection with the river is direct. Thus the sample basin contains not only a variety of levels and depths of flooding on each cross-section, but also differences in range of flooding from upstream to downstream.

The flood-plain topography is illustrated (Fig. 5.12) by four of the 12 sections of the Mongalla basin, which include the vegetation distribution. The river level rises in relation to the bank level as one proceeds downstream, while the flood plain is deeper below the bank level at the lower end of the basin. The increased flooding at the lower end of the basin is indicated by the surveyed water levels and the corresponding progression in vegetation type.

As described earlier, by comparing the inflows at Mongalla with the outflows between Gemmeiza and Gigging, it was possible (Sutcliffe, 1957, 1974) to deduce the volume of flooding. Because the time lag between Mongalla and Gemmeiza was not large, there was a direct relation between Mongalla flow and flooding volume, which was a function of the relative geometry of river level, bank level, and flood plain. Given the shape of the flooding surface, the depth of flooding at any point on the flood plain could be deduced.

Statistical analysis of vegetation distribution

The level and the vegetation for each point on the sections were recorded. Therefore it was possible to deduce the percentage of each species found at each range of level on each cross-section, and even on each kilometre of each section. Vertical histograms of vegetation were deduced for each segment of each section, and it was found that the pattern of distribution was similar in each case. A distinct boundary between shallow- and deep-flooded species sloped away from the river and downstream parallel to the high river level. Examples of these histograms for the complete Mongalla sections are shown as Fig. 5.13. Because of the manner in which the water surface swings about the lower end of the reach, it was possible to deduce from the longitudinal profile (Fig. 5.14) the precise nature of the control. Because the vegetation boundary is parallel to the maximum river level profile, and therefore the maximum flooding profile, it was clear that the boundary is controlled by the maximum depth of flooding; comparison with flooding volumes showed that the critical depth is about 1.30 m. Papyrus was only present at the lower end of the reach, and the range of flooding increases upstream. It was concluded that the range of flooding was the controlling factor for papyrus; the critical range is about 1.50 m. These deductions were supported by analysis of the distribution of vegetation in the Aliab valley. It may be noted that they are supported by analysis of flooding in the Okavango, Niger and Senegal wetlands (Sutcliffe & Parks, 1989).

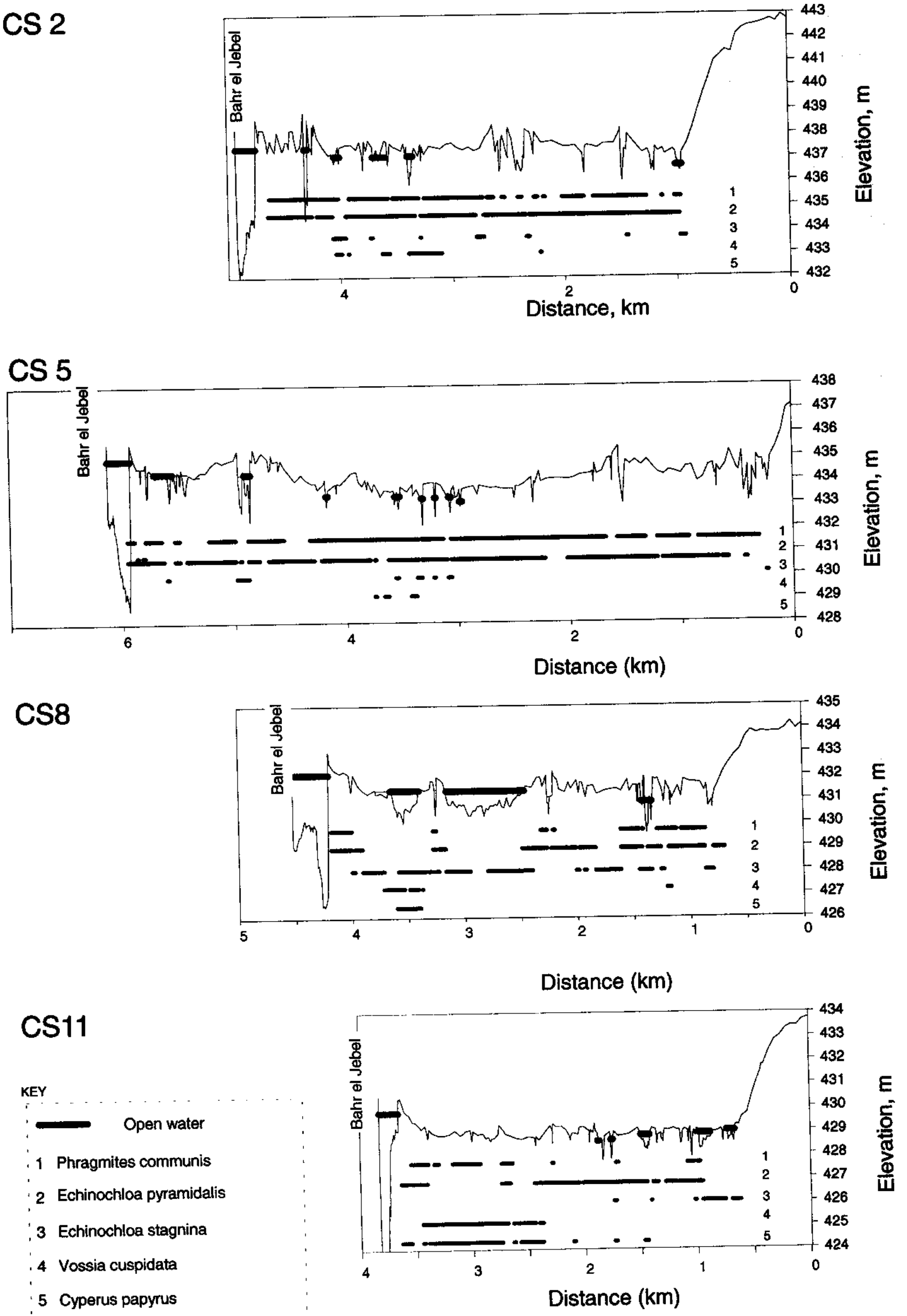

Fig. 5.12 Mongalla basin: elevation, dry season water levels and vegetation, cross-section (CS) 2 upstream to CS 11 downstream (cross-sections F–I in Fig. 5.7), 1951–1952 (after Sutcliffe & Parks, 1996).

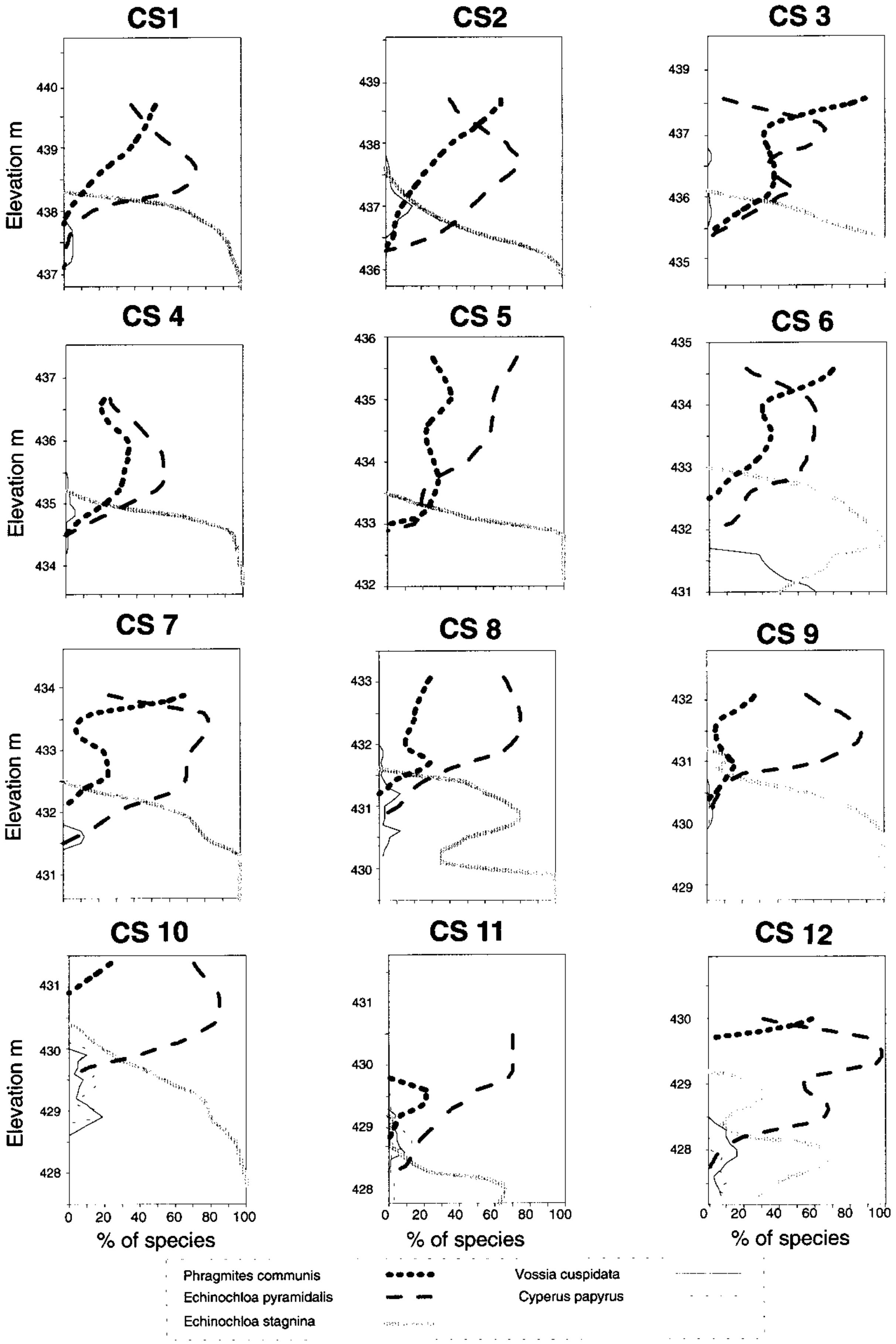

Fig. 5.13 Mongalla basin: vegetation and elevation on cross sections (after Sutcliffe &

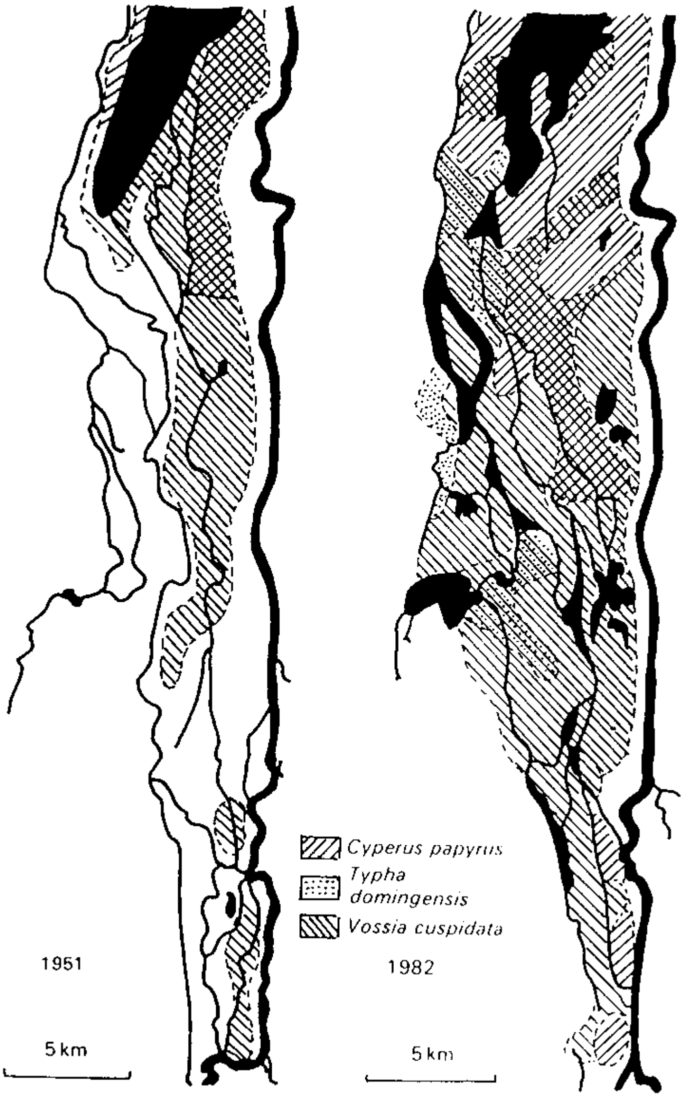

Fig. 5.15 Aliab valley: channels and vegetation in 1951 and 1982 (after Howell *et al.*, 1988).

Importance of seasonal flooding to grazing

The importance of the ecological controls is that their understanding may enable predictions to be made of the conditions which would follow the completion of the Jonglei Canal, though these would depend to some extent on the operating rules which were followed. The importance of the seasonally flooded areas was noted as early as Evans-Pritchard (1940).

The extreme seasonal variability of climate and in particular the dry season which extends from December to April (Howell *et al.*, 1988) make the seasonally flooded land or "toich" a vital component of the grazing cycle for the herds of the Nuer and Dinka in particular. They migrate from so-called high land during the rain season to intermediate land or rain-flooded grasslands at the end of the rains and also at the beginning of the rain season. They move to seasonally flooded flood plains of the main river and to a lesser extent other water courses during the main dry season. The short and relatively unreliable nature of the rainfall regime makes livestock an important part of the economy, and there is no alternative to the toich in a grazing economy without recourse to irrigated grassland.

The flood plain between Juba and Bor illustrates this dependence. The Aliab valley was used extensively for grazing in 1951 during the dry season (Plate 7), from cattle camps sited on

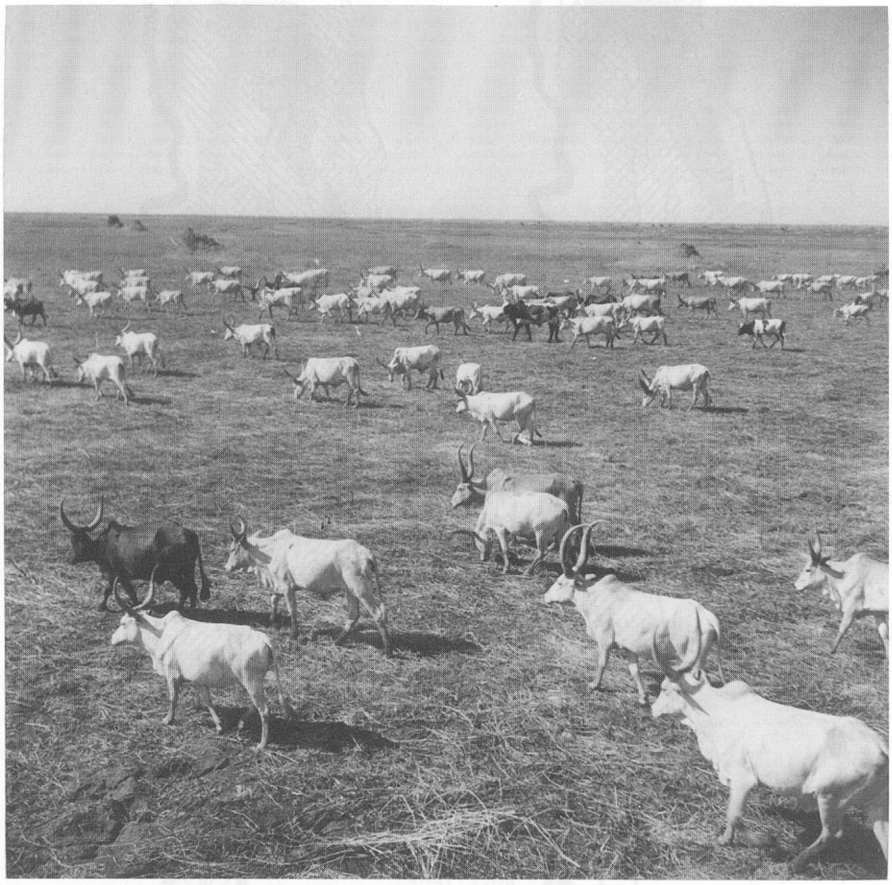

Plate 7 Dinka cattle in the Aliab valley.

the alluvial banks of the main river and the Aliab channel. During the early dry season the mature growth of *Echinochloa stagnina* was used, while the shallow-flooded *Echinochloa pyramidalis* was burned to produce regrowth; both species were grazed later in the dry season. In February 1982 access to the Aliab valley had been made difficult by new channels down the valley and the spread of papyrus, but the cattle camps along the main Bahr el Jebel were largely in the same positions. In the Mongalla basin, the situation was the reverse. Whereas in 1952 there was little grazing because of the dominance of *Phragmites* in the relatively low flow regime, in 1982 large numbers of cattle were observed grazing *Echinochloa pyramidalis* within the basin.

EFFECTS OF THE JONGLEI CANAL

Because the objective of the Jonglei Canal is to reduce evaporation losses within the Sudd, it is clear that the area flooded would be reduced. However, the economic value of the permanent swamp is mainly limited to the refuge which it affords to wildlife and in particular to the elephant population. The effect of the Jonglei Canal can be assessed not only in terms of the reduction caused in the areas of seasonally flooded land, but also in the timing of the flooding and uncovering to coincide with the dry season, and also the effect of depths and level range of flooding on the vegetation.

Assessment of the effects of the Jonglei Canal

The hydrological model described earlier was adapted (Sutcliffe & Parks, 1982, 1987; chapter 16 and Appendix 9 in Howell *et al.*, 1988) to simulate the effect which the Jonglei Canal would have on areas of flooding. This was done by obtaining a relation between Sudd inflows and outflows, and then running the model with historic inflows reduced by diversions to the canal while assuming that the relation between inflows to the natural river and outflows would remain unchanged. The outflows then take account of the reduced losses due to the reduced inflows to the natural river.

The key to this analysis was the relation derived between inflow to the Sudd at Mongalla and outflow at Malakal less the Sobat inflow. Although the flows at Mongalla were less reliable before 1922, when a general rating curve was based on a small number of gaugings, records between 1916 and 1972 were used to include the flows of the high flood of 1916–1918. However, the years 1963–1966 were omitted as a gap in the measurements at Mongalla coincided with an abrupt change of the rating curve. Monthly outflows were compared with monthly inflows with different time lags; it was found that the regression improved as the assumed lag increased to three months, but improved little for longer lags. The shape of the relation suggested that it was appropriate to use a logarithmic form with a three-month lag. The regression was improved by averaging inflows and outflows over calendar quarters to give a relation $\ln q_t = 3.928 + 0.411 \ln Q_{t\text{-}3}$ where outflow q and inflow Q are in $m^3 \times 10^6$ month^{-1}. This implies that outflows exceed inflows for values of inflow below 800 $m^3 \times 10^6$ month^{-1}. This is based on extrapolation below the range of measured flows, and is not appropriate to predict the effect of reducing the inflows to the Sudd by diversion through the canal. In order to represent the relation between inflow and outflow over a period of steady flows, it is logical to assume that losses from the river would occur at all flows above zero. The relation should meet the conditions $q = Q$ when $Q = 0$ and $dq/dQ = 1$ when $Q = 0$. This is met by a quadratic $q = Q - aQ^2$ and the equation which joins the regression equation above without discontinuity of gradient is $q = Q - 0.000\,214\,4\ Q^2$ when $Q < 1730$. The details of this analysis have been reproduced in Howell *et al.* (1988, Appendix 9). The relation derived is compared with annual inflows and outflows for 1905–1983, excluding 1963–1966, in Fig. 5.16 and this suggests that a reasonable relation has been deduced.

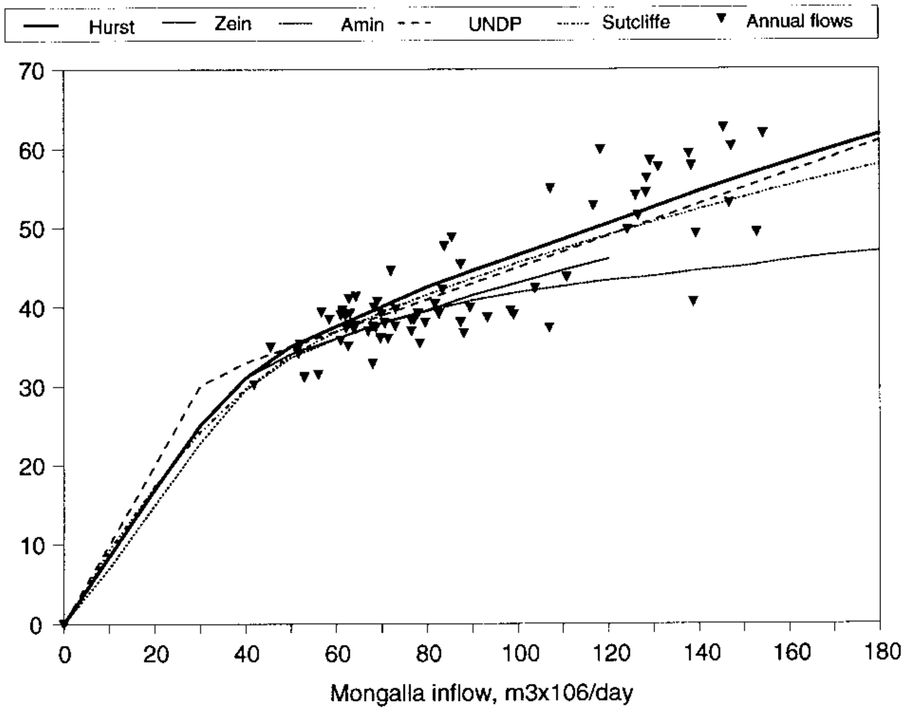

Fig. 5.16 Sudd inflows and outflows: relations estimated in various studies and annual flows, 1905–1983, excluding 1963–1966.

The form of the relation, particularly at low flows, is important in estimating the effect of the canal; it is useful to compare this relation with those used by others. Figure 5.16 includes that derived by Hurst *et al.* (1946) from 1912–1945 flows, with those of Soghayroon el Zein (El Zein, 1974) from 1905–1965 flows, and those of El Amin & Nasser Ezzat (1978) based on 1905–1962 flows. These have similar losses at low flows to those of Sutcliffe & Parks (1982). On the other hand, UNDP, IBRD & Ministry of Irrigation (1981) compared inflows and losses for the period 1912–1975, without lag, and deduced that outflows equalled inflows until Mongalla inflows exceeded 30 $m^3 \times 10^6$ day^{-1}, and then equalled 25 $m^3 \times 10^6$ day^{-1} + 20% of the inflow. Georgakakos & Klohn (1997) similarly assumed that losses were negligible until Mongalla flows reached 35 $m^3 \times 10^6$ day^{-1}. It is true that the losses, expressed as the difference between inflows and outflows, are well related to inflows, with an intercept at about 30–35 $m^3 \times 10^6$ day^{-1}. However, the assumption that losses do not start until this inflow differs from the other relations and seems to be at variance with the physical evidence. In February–March 1951, when the Mongalla flow averaged 39 $m^3 \times 10^6$ day after moderate torrent flows, cross-section P (see Fig. 5.7) of the Aliab valley above Bor (Jonglei Investigation Team, 1954, Fig. A 9), contained over 4 km of open water and papyrus (see Plates 4 and 5) out of 8 km of flood plain. This cross-section is at the upper limit of the Sudd proper. The extrapolation of an inflow–outflow relation below the range of observations is somewhat subjective, but it does not seem likely that losses are negligible in these conditions; it seems probable that these outflows which equal low inflows include some return of stored water.

Because the offtake of the canal is sited at Bor rather than Mongalla, the relations had to be adjusted. The inflows measured at Mongalla were converted to flows at Bor latitude, together with the relation between inflows and outflows. The assumption must be made that the relation between inflow and outflow is valid after part of the natural inflow has been diverted into the canal. It is then possible to estimate the effect on areas of flooding of different regimes of the Jonglei Canal over the period of historic flows. Initial trials were based on constant flows down the canal of 20 $m^3 \times 10^6$ day^{-1}, modified by implementing the PJTC (Permanent Joint Technical Committee) rules, with canal flows reduced during periods of low flow to allow navigation in the river. The effect of this combination on areas of flooding during the period 1905–1980 is included in Fig. 5.10.

The results of this modelling, based on historical flows and simple water balance considerations, are summarized in Table 5.5. Two main canal flows were tested, 20 and 25 $m^3 \times 10^6$ day^{-1}, modified by the PJTC rules. The effect of the canal operation would have been very different in the period of relatively low Lake Victoria outflows before 1961 and the period of high flows after 1961. The important figure, the reduction in seasonally flooded land, would have been 26% for a diversion of 20 $m^3 \times 10^6$ day^{-1} during the early years and

Table 5.5 Estimated effect of canal on areas of flooding (km^2 and % reduction).

Canal flow ($m^3 \times 10^6$ day^{-1})	1905–1961			1961–1980			1905–1980		
	Perm. swamp	Seasonal swamp	Total	Perm. swamp	Seasonal swamp	Total	Perm. swamp	Seasonal swamp	Total
0	6700	6200	12 900	17 900	11 000	28 900	9500	7400	16 900
20	3600	4600	8200	14 000	9100	23 100	6200	5700	11 900
	46	26	37	21	17	20	35	23	29
25	3000	4200	7200	13 100	8700	21 800	5500	5300	10 800
	56	32	44	27	21	24	42	28	36
25 Nov.–April	3300	5400	8700	13 700	9900	23 600	5900	6600	12 500
15 May–Oct.	51	12	32	23	10	18	38	11	26
15 Nov.–April	3800	3900	7700	14 400	8400	22 800	6500	5000	11 500
25 May–Oct.	43	38	41	19	24	21	32	32	32

17% in the later years; the equivalent figures for a diversion of 25 $m^3 \times 10^6$ day^{-1} would have been 32 and 21%. However, at the request of the Jonglei Executive Organ, the effect of varying the flows down the canal and river according to season was examined. The model suggested that the loss of seasonally flooded land could be reduced to 12 and 10% by varying the canal flow between 25 and 15 $m^3 \times 10^6$ day^{-1} according to season, with little effect on the predicted benefit downstream. Thus control rules for the flows down the canal could be developed to maximize the seasonal swamp at the expense of the permanent swamp.

Such an operating policy would have other benefits. It has been shown that the level range of flooding decreased after 1961, mainly because the seasonal runoff did not increase when the Lake Victoria outflow increased. Meanwhile the area over which this seasonal component was spread doubled after 1961. The range was estimated to decrease over the whole swamp from 0.66 m before 1961 to 0.48 m after the rise in lake level; this estimate is broadly in line with measured river levels. The decreased range is likely to have been at least partly responsible for the increase of papyrus. If the flows down the canal were adjusted seasonally to favour the seasonally flooded area (Sutcliffe & Parks, 1993), this would not only reduce the loss of the valuable seasonally flooded area but would also increase the range and encourage useful deep-flooded grasses like *Echinochloa stagnina* at the expense of papyrus.

This analysis has not taken any account of the inflow regime to the Sudd which could result from the control by storage in Lake Albert or in Lake Victoria. In fact the proposals for Jonglei Stage II imply that the outflows from the lake would be equalized seasonally, and possibly that the torrent flows would be stored virtually in Lake Albert. The effect of such plans would be far-reaching but are difficult to predict without more detailed accounts of the proposed mode of operation. However, the interests of the inhabitants of the Sudd would be affected by any sudden increases or decreases in the outflow from the East African lakes which might result from upstream control, while any attempt to reduce the seasonal regime of the torrents above Mongalla would directly destroy the grazing potential of the Sudd.

CONCLUSION

The Bahr el Jebel receives the outflow from the East African lakes, which has varied dramatically over the historic period, and also the highly seasonal flows of torrents above Mongalla. As a result of spill from channels into wide flood plains, about half the inflow is lost by evaporation and the outflow is fairly constant. A water balance study shows that the total area of flooding doubled after 1961, but that the seasonal flooding which provides dry season grazing increased less than the permanent swamp. The effect of the Jonglei Canal, proposed to increase the flow downstream, has been estimated by an extension of the water balance study. The effect on flooding and thus on grazing potential would be affected by operating policy.