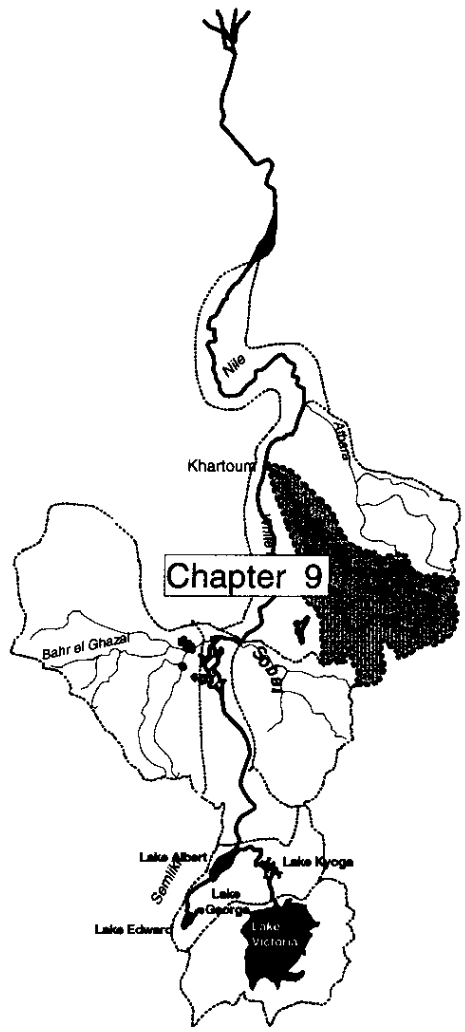
CHAPTER 9

THE BLUE NILE AND ITS TRIBUTARIES

INTRODUCTION

The Blue Nile provides the greater part (about 60%) of the flow of the main Nile. However, rather limited information about its hydrology, especially in its upper basin within Ethiopia, has been published. In this chapter the available information has been used to compare its regime with that of the other tributaries and particularly the White Nile and its components.

This chapter deals in turn with the geography of the basin, the rainfall regime, the availability of flow records and the characteristics of the longer flow series; and a comparison of key stations to monitor losses and abstractions from the main river. A review of flood potential is illustrated with accounts of the 1988 flood and the development of flow forecasting. A brief review of sedimentation is followed by a discussion of reservoir control.



GEOGRAPHY OF THE BASIN

The topography of the Blue Nile basin is described from a hydrological viewpoint in *The Nile Basin*, vols VIII and IX (Hurst, 1950; Hurst *et al.*, 1959), which are well illustrated by photographs. The description is based on personal observation and the reports of the Lake Tana mission (Grabham & Black, 1925) and others for the Ethiopian basin. The Blue Nile and its tributaries (Fig. 9.1) rise on the Ethiopian plateau, which is concentrated at elevations of 2000–3000 m, with several peaks up to 4000 m or more. The plateau country is not flat but very broken and hilly, with grassy uplands, swamp valleys and scattered trees. There are occasional rocky peaks, some of which are of volcanic origin. The curious course of the river may follow the original drainage pattern radiating from such volcanic centres. The basin is cut by deep ravines or canyons in which the Blue Nile and other rivers flow. The valley of the Blue Nile is 1300 m deep in places, and the course of the river is often difficult to cross. The whole area is intersected by streams, most of which are perennial though highly seasonal in their flow.

The plateau drops steeply to the Sudan plains where there are many isolated outlying hills, some of which are as high as the plateau. The vegetation varies with altitude; the plateau is not in general thickly wooded, doubtless because of the seasonal nature of the rainfall. The extent of woodland appears to have decreased over the past 50 years. The Sudan plain, which

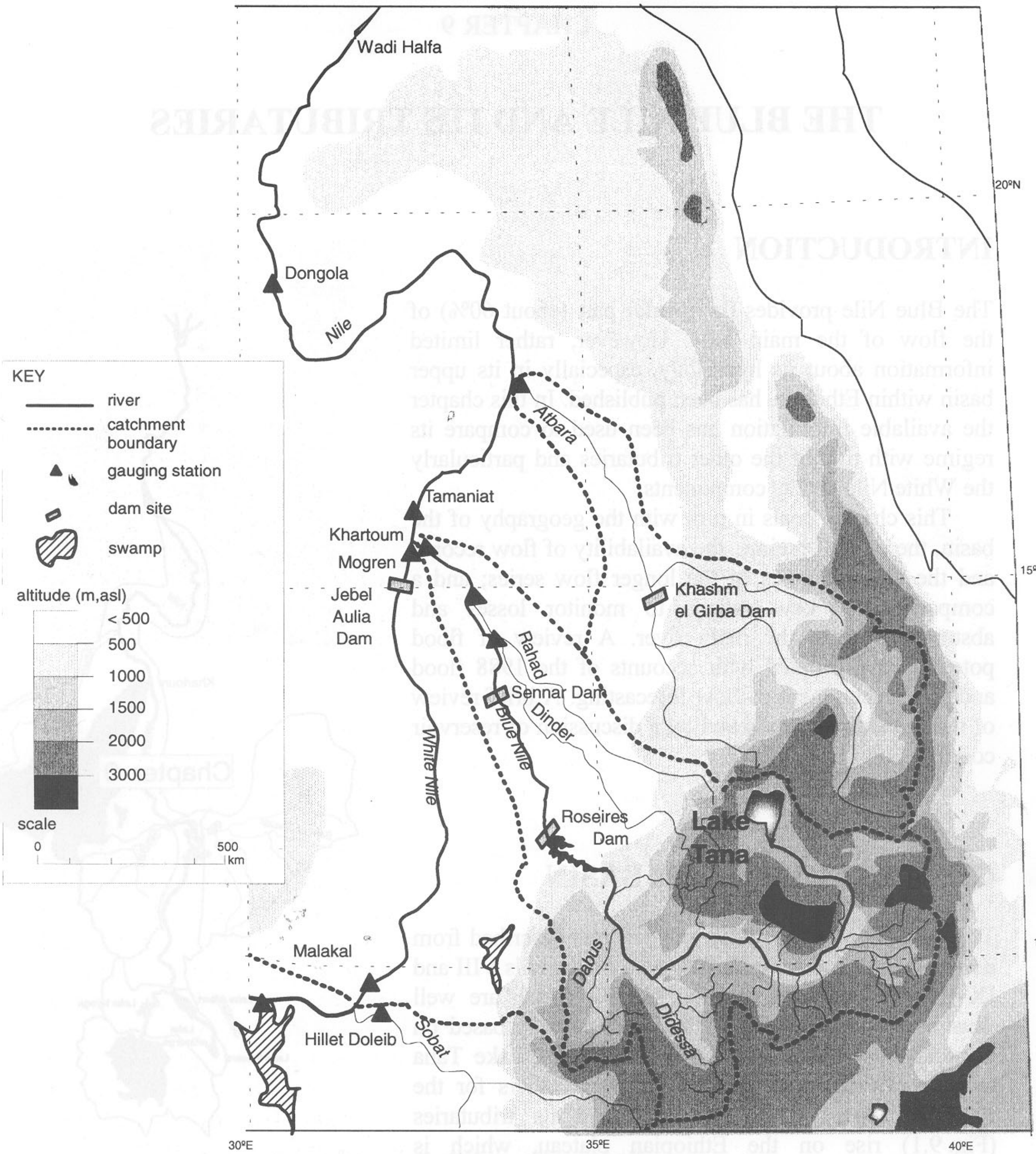


Fig. 9.1 Map of the Blue Nile, Atbara and main Nile.

slopes west from an elevation of about 700 m, is largely covered with thin savannah or thorn scrub.

Lake Tana is a feature of the upper basin which was studied (Grabham & Black, 1925) as a possible site for storage. The lake, at an elevation of about 1800 m, has a surface area of about 3000 km^2. Little of the 13 750 km^2 basin draining to the lake is above 2400 m, though it rises to nearly 4000 m to the northeast. The lake has many tributaries, like the Gilgel Abbay or Little Abbai with high and perennial, but highly seasonal, runoff. The level range of the lake between 1920 and 1933 was about 2 m, and the shoreline contains a number of swamps dominated by *Cyperus papyrus*; *Echinochloa pyramidalis* and *Echinochloa stagnina* provide grazing in areas flooded annually by the lake.

Plate 9 The Blue Nile below Roseires dam during the dry season.

The Blue Nile leaves the lake, which was formed by a relatively recent lava flow, through a series of cataracts. The Tissisat Falls has a drop of 50 m. It then enters the Blue Nile ravine or canyon; the river profile is illustrated in Fig. 1.2. The vegetation is mainly thin savannah with small trees of acacia, Dom palms (*Hyphaene thebaica*) and Tebeldi (*adansonia*). The main river is joined by a large number of tributaries in steep valleys which are oversized by comparison with the present streams. The relative importance of the tributaries is indicated by the graph of contributions given by Rushdi Said (Said, 1993, p. 284) after the US Bureau of Reclamation (1964) study. The Didessa and Dabus, draining the southwestern and humid portion of the Ethiopian basin adjacent to the Baro, contribute significant fractions (over a third) of the total flow, especially at the start and the end of the runoff season. Other tributaries joining the main river from the east drain a wide area north of Addis Ababa. A number of tributaries drain an area of high rainfall in Gojjam in the loop of the river below Lake Tana. A feature of the Dabus tributary, the wetlands with an area of about 900 km^2 (Conway, 1997), has an effect in delaying runoff. There are smaller swamps in the Didessa and Finchaa basins, which are also in the south of the basin where the longer rainfall season allows wetlands to develop. There is a weir on the Blue Nile below Lake Tana for hydroelectric power and a regulator on the lake outlet. A dam was built on the Finchaa in 1972 with a capacity of 0.4 km^3.

Below the Damazin rapids at Roseires, where the main reservoir storing Blue Nile waters for irrigation within Sudan was built in 1961–1966, the character of the Blue Nile (Plate 9) changes in response to its change of profile (Fig. 1.2). The river is little below the level of the surrounding plain, and some areas are inundated during the flood season. The country near the river is covered with thin acacia woodland, though much of the Gezira plain has been irrigated since the construction of the Sennar dam in 1925. The recent capacity of the Roseires reservoir is 2.4 km^3 and that of Sennar is about 0.5 km^3.

The Blue Nile receives two major tributaries from the north, the Dinder between Sennar and Wad Medani and the Rahad below Wad Medani. These drain country which is similar to the lower Blue Nile basin within Ethiopia; both streams are highly seasonal. When they reached the plains in their natural condition they meandered and overflowed their banks to form basin lakes; they were reduced in the dry season (January–May) to a series of pools and a dry sandy bed.

RAINFALL AND EVAPORATION

The average annual rainfall over the Blue Nile basin above Roseires is about 1600 mm. It increases (Gamachu, 1977) from about 1000 mm near the Sudan border to about 1400–1800 mm over parts of the upper basin, in particular in the loop of the Blue Nile below Lake Tana, and above 1800 mm in the south within the Didessa basin. This high rainfall extends into the upper Baro basin (Chapter 7), with a value of 2400 mm at Gore. The seasonal rainfall distribution is governed by the migration of the ITCZ from south to north and back, so that the duration of the rainfall season decreases from south to north. In the south, in the upper basins of the Didessa and Baro, there is a tendency towards two rainfall maxima at some stations, especially in individual years. Gamachu (1977) compared rainfall with potential evapotranspiration, estimated by the Thornthwaite method, to give water budgets for selected stations. This revealed that the two main areas of high annual water surplus in Ethiopia are within the Nile basin in the Didessa and Baro basins and near Lake Tana.

In fact the runoff in Ethiopia is concentrated to the west of the Rift Valley. This corresponds broadly with the areas draining towards the Nile, where the rainfall in general occurs within a single season.

Figure 9.2 shows monthly mean rainfall totals at a number of stations in the Blue Nile and Sobat basins (Gamachu, 1977), with their relative positions maintained. This illustrates the tendency for rainfall to be concentrated within a shorter season from south to north. This is reflected in the river flows of the different tributaries. Conway (1997) has shown that it is possible to reproduce the 1951–1987 Blue Nile flow series near the Sudan border from distributed rainfall and potential transpiration estimates. He used a simple water balance approach in which runoff is generated by net rainfall after the soil moisture deficit has been satisfied, with a small component for direct runoff. Separate components were used for the outflows from Lake Tana and the Dabus swamps. The model was tested on short periods of flow records for other tributaries. The mean annual runoff for the 1951–1987 period was 47.37 km^3 or 269 mm over the basin of 176 000 km^2, compared with an estimated mean annual rainfall of 1590 mm. This corresponds to a runoff coefficient of 17%; this reflects the relatively short rainfall season.

AVAILABILITY OF FLOW RECORDS

The assessment of the water balance of the Blue Nile is more dependent on downstream measurements than elsewhere in the Nile basin, as available information on the rainfall and water balance within Ethiopia is limited. Although some 100 gauging stations have been established within the basin in Ethiopia and flows are being processed using the HYDATA system (Asefa, 1997), only limited data have been published. Increased availability of hydrological information could only increase scientific understanding of the Nile system.

Gamachu (1977) has summarized the flows of four stations within the basin: the Angar (4349 km^2); the Beles (3520 km^2); the Chemoga (320 km^2); the Gilgel Abbay (1600 km^2). The mean flows from the five years 1965–1969 are summarized in Table 9.1. The runoff coefficients vary from 27% to 70%, though the latter figure is surprisingly high for a natural

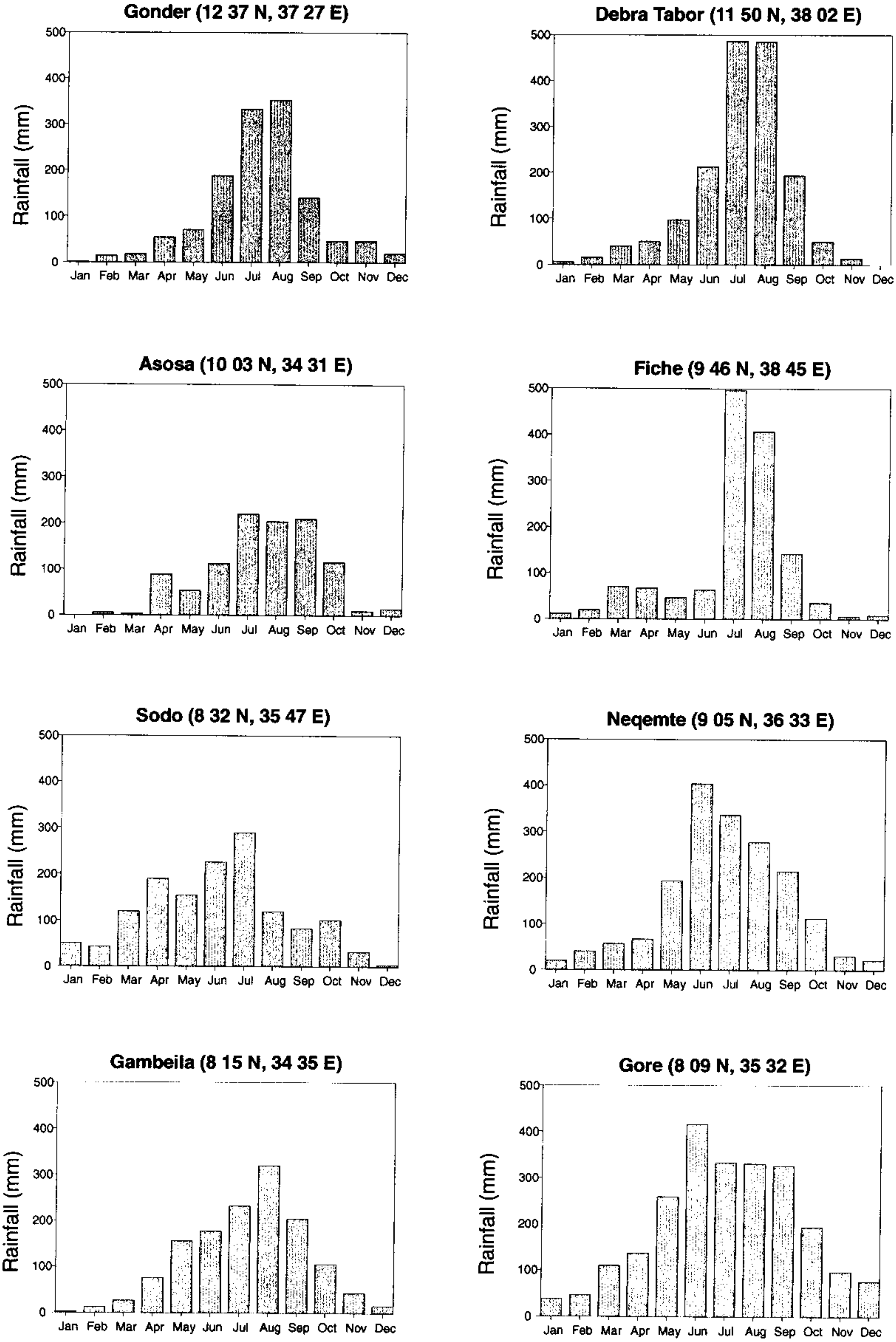


Fig. 9.2 Average monthly rainfall at Ethiopian stations (after Gamachu, 1977).

Table 9.1 Mean tributary flows in Blue Nile basin (1965–1969).

River	Lat. N	Long. E	Area (km²)	Runoff: (km³)	(mm)	Rain (mm)	Runoff coefficient (%)
Angar	9°26′	36°33′	4349	2.043	470	1500	31
Beles	11°10′	36°20′	3520	1.135	322	1200	27
Chemoga	10°18′	37°46′	320	0.179	559	1600	35
Gilgel Abbay	11°22′	37°01′	1600	1.681	1051	1500	70

basin. These tributaries have similar seasonal distributions, with about 90% of the runoff occurring in the four months July–October. Figure 9.3 (after Johnson & Curtis, 1994) shows monthly rainfall and runoff for the Chemoga basin, and illustrates the course of the runoff process. It shows that the early rainfall is required to replenish the soil moisture storage after the dry season, followed by the runoff of most of the later rainfall. This results in a lag of about a month between rainfall and runoff, even on a small tributary.

On the Blue Nile itself, flow records are available at the outlet from Lake Tana for the period 1920–1933 (with some gaps), at el Deim about 85 km above Roseires from 1962, at Roseires/Wad el Aies from 1912, and at Khartoum/Soba from 1900. There was an earlier level record at Khartoum from 1869 to 1883 during the flood period, but this was not supported by gauging; this record provides a comparison with flood levels recorded at Aswan during this period of high flows (Walsh *et al.*, 1994). The Dinder has been measured at Hillet Idris, near its mouth, from 1907 to 1951, with a record at Gwasi upstream from 1972; the Rahad has been measured at Abu Haraz near its mouth from 1908 to 1951, with a record at el Hawata from 1972. The gaps in the record between 1951 and 1972 were filled by means of a statistical model (Institute of Hydrology, 1978) based on the earlier concurrent series of monthly flows of the Blue Nile at Roseires and the Dinder and Rahad at their mouths. Months of low flow were grouped into seasons and a logarithmic transformation was used before analysis. Cross-correlations between the three flow series, and lag-one serial correlations within each series, were preserved in the flow generation, and a random element was introduced and a typical series selected. Monthly flow series are illustrated in Figs 9.4 and 9.5.

The records at el Deim and Roseires at the upstream end of the main channel of the Blue Nile within Sudan, and at Khartoum above its confluence with the White Nile (Plate 10), provide a comparison of flows. These indicate the balance between inflows, losses, abstractions and outflows within the reach.

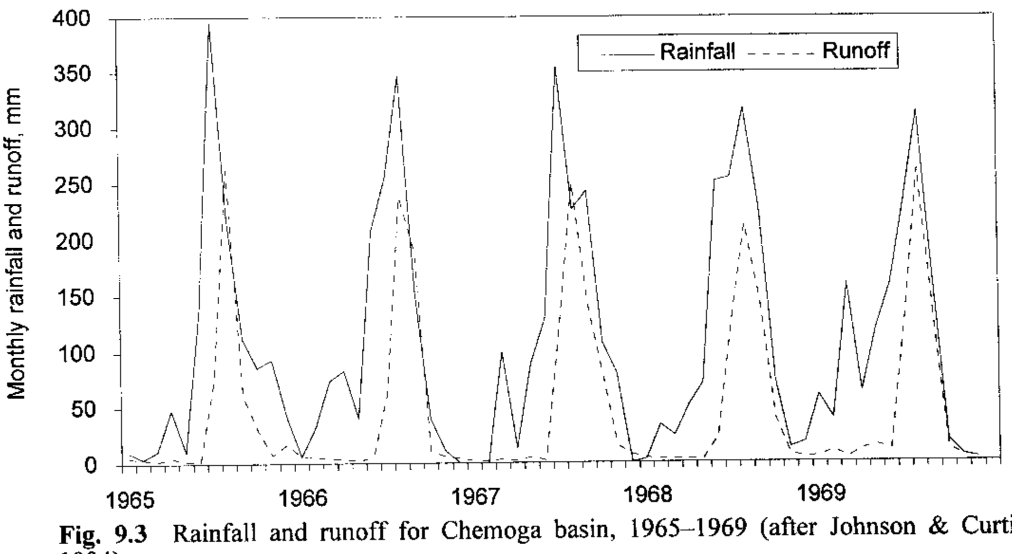


Fig. 9.3 Rainfall and runoff for Chemoga basin, 1965–1969 (after Johnson & Curtis, 1994).

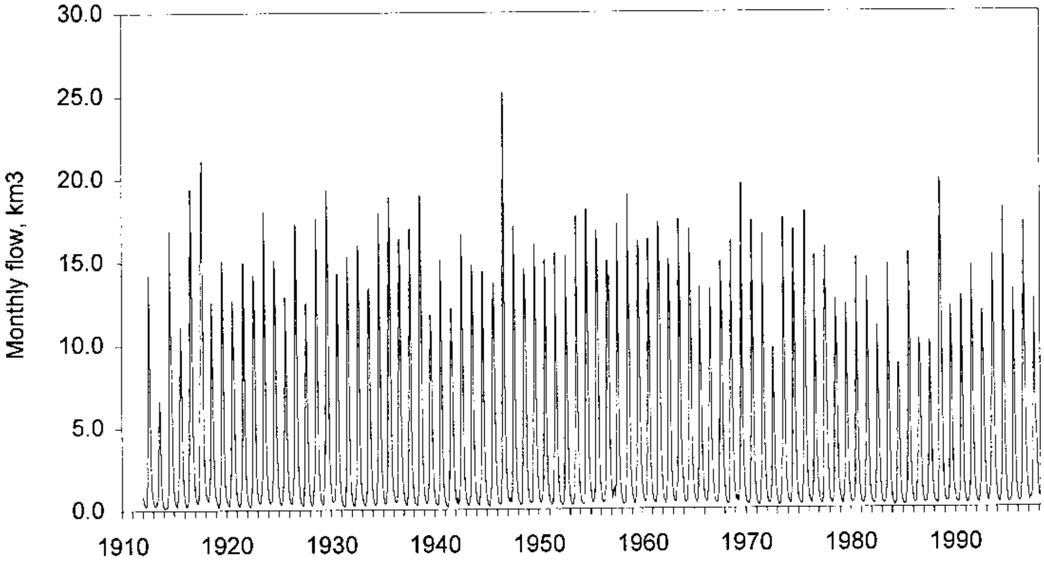


Fig. 9.4 Blue Nile at Roseires/el Deim: monthly flows, 1912–1997.

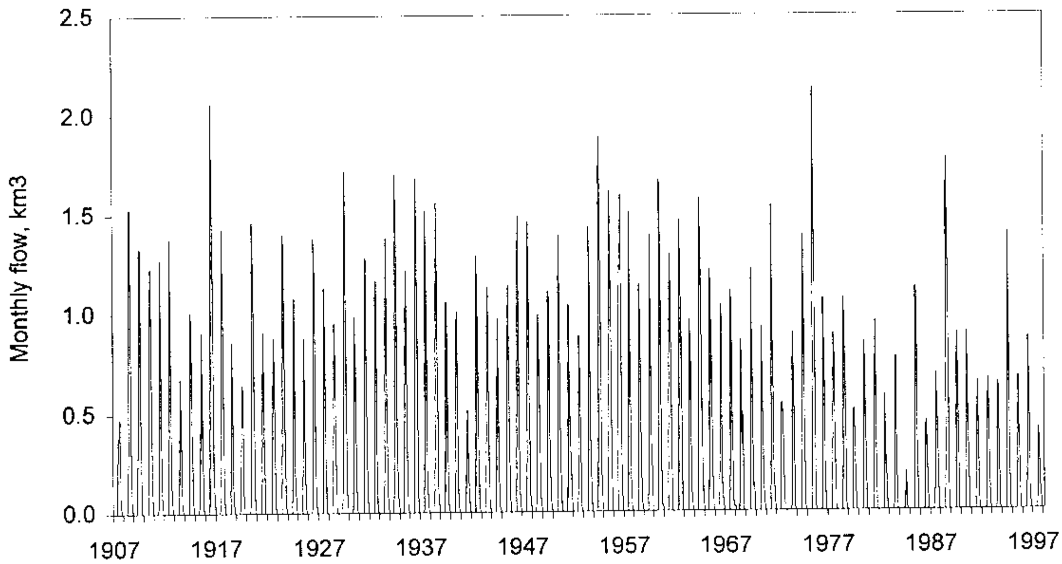


Fig. 9.5 Dinder at mouth/Gwasi: monthly flows, 1907–1997.

The key to the precision of the flow records is the number of gaugings carried out at each site during the period of records. Regular gaugings have been made at or near Khartoum (Table 2.1) since 1902, with about 40 a year at Soba for low flows and 30 at Khartoum for high flows. Levels have been recorded at Roseires since 1912; gaugings have been made at Roseires since 1918 for low flows and since 1922 at Wad el Aies for high flows, with up to 100 gaugings a year at Roseires and 30 a year at Wad el Aies. Thus the published flow record from 1912 to 1922 was based on general rating curves and may be considered less reliable than the later record. Gaugings were carried out on the River Dinder near its mouth from 1911, with more frequent measurements from 1922; about 30–100 gaugings were made annually. After the upstream site was established at Gwasi, frequent gaugings were carried out and the ratings were well defined. The same is true of the River Rahad, though there have been changes in bed levels at el Hawata at the upper site. The gaugings at el Deim started in 1962 and many measurements (over 200) were carried out in some years; the site is stable and the rating is reliable and precise.

The existence of flow records at Khartoum on the Blue Nile, at Mogren or Jebel Aulia dam on the White Nile, and at Tamaniat on the main Nile below the confluence, allows a

Plate 10 Confluence of the Blue Nile and White Nile, Khartoum. Note the lighter shade of the White Nile flowing from the far left.

check to be made by comparison. This (Fig. 9.6) showed annual differences with a fair amount of scatter in the early years from 1914 to 1930. After 1980 the apparent error increased again, with errors in 1986 and 1988 exceeding 10 km^3. It is clear that some of the flows recorded for recent years have not been accurate; it was not possible to gauge the river at Khartoum or Tamaniat between mid-July and the beginning of October in 1988. In order to minimize the corrections to the published record, the Khartoum flows for August and September 1988 have been replaced in Fig. 9.8 and subsequent calculations by the differences between the flows at Tamaniat and those at Jebel Aulia dam.

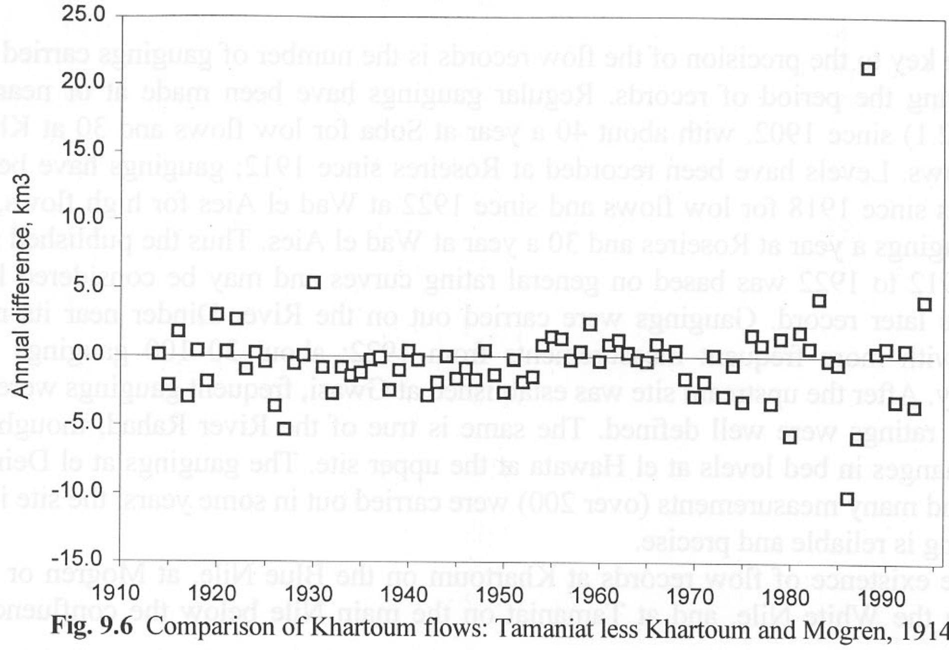


Fig. 9.6 Comparison of Khartoum flows: Tamaniat less Khartoum and Mogren, 1914–1994.

FLOWS AT VARIOUS SITES ON THE BLUE NILE

The flow records at the main sites are summarized in Table 9.2, and show the progress of the flow down the river system. Flows for different periods are summarized to illustrate declines since 1961, together with the overall mean. The outflow from Lake Tana is only available for the relatively short period 1920–1933. Over this period the total runoff average is 3.810 km^3, with a range between 5.6 km^3 in 1929 and 1.9 km^3 in 1925 and 1930. The total outflow is about 230 mm from the lake area of 3000 km^2 and its basin of 13 750 km^2, but its seasonal distribution is not greatly damped by the lake storage. The peak outflow occurs in September–October, with a long low flow recession from January to June. The average flow of 3.81 km^3 during the years of record compares with an average of 49.564 km^3 during the equivalent years at Roseires; thus the lake outflow is only some 7.7% of the flow at Roseires.

The annual measured flows at Roseires/el Deim and Khartoum are illustrated in Figs 9.7 and 9.8. The long-term mean annual flow of 48.658 km^3 at Roseires/el Deim from 1912 masks a variation from low annual totals of 20.69 km^3 in 1913 and 29.65 km^3 in 1984, to high totals of 69.67 km^3 in 1917 and 69.85 km^3 in 1929. The seasonal distribution of flows is very marked, with maximum monthly flows averaging 15.23 km^3 in August contrasting with 0.32 km^3 in April. The bulk of the runoff (84% on average) occurs between June and October. Since 1960 the average has declined because of the relatively low flows of 1979–1987, from 50.36 km^3 in 1912–1960 to 46.47 km^3 in 1961–1997. The difference between the peak month in August at Roseires/el Deim and in September at the outfall of Lake Tana shows the relatively slight effect of lake storage.

The Dinder (Fig. 9.9) and Rahad records also illustrate the reduction of flows in recent years. The average flow recorded at the mouth of the Dinder (1907–1960) is 3.086 km^3,

Table 9.2 Mean flows at key sites on Blue Nile ($m^3 \times 10^6$).

Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Blue Nile (Abbay) at outlet of Lake Tana						**(1920–1933)**						
208	124	83	43	28	26	97	503	995	841	519	344	3 810
Blue Nile at Roseires/el Deim						**(1912–1960)**						
796	468	376	331	621	1648	6651	15 647	12 859	6889	2684	1385	50 355
						(1961–1997)						
716	417	348	315	600	1672	6911	14 672	11 119	5946	2394	1299	46 411
						(1912–1997)						
762	446	364	324	612	1659	6763	15 228	12 111	6484	2559	1348	48 658
Blue Nile at Khartoum						**(1900–1960)**						
852	509	437	367	490	1210	5401	15 963	14 931	8245	2889	1497	52 791
						(1961–1995)						
501	342	352	532	526	865	4248	13 933	11 280	5128	1665	826	40 199
						(1900–1995)						
724	448	406	427	503	1084	4989	15 237	13 625	7130	2451	1257	48 279
Dinder at mouth/Gwasi						**(1907–1960)**						
0	0	0	0	0	17	355	1 085	1 123	433	64	8	3 086
						(1961–1997)						
1	0	0	0	0	15	265	887	841	333	31	2	2 374
						(1907–1997)						
0	0	0	0	0	16	318	1 005	1 009	392	51	6	2 797
Rahad at mouth/el Hawata						**(1908–1960)**						
0	0	0	0	0	2	106	350	396	259	29	3	1 145
						(1961–1997)						
0	0	0	0	0	2	137	342	353	185	25	1	1 044
						(1908–1997)						
0	0	0	0	0	2	119	346	378	228	27	2	1 102

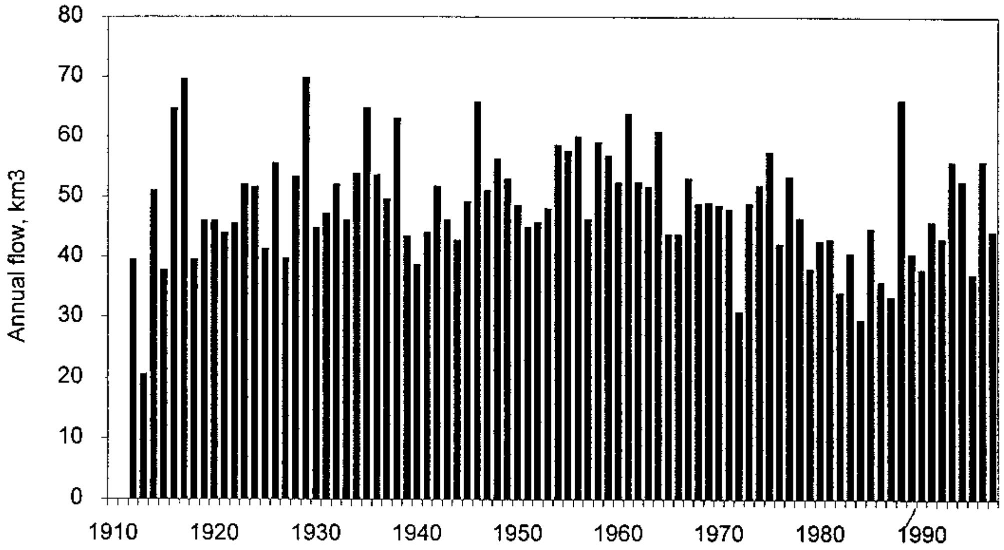


Fig. 9.7 Blue Nile at Roseires/el Deim: annual flows, 1912–1997.

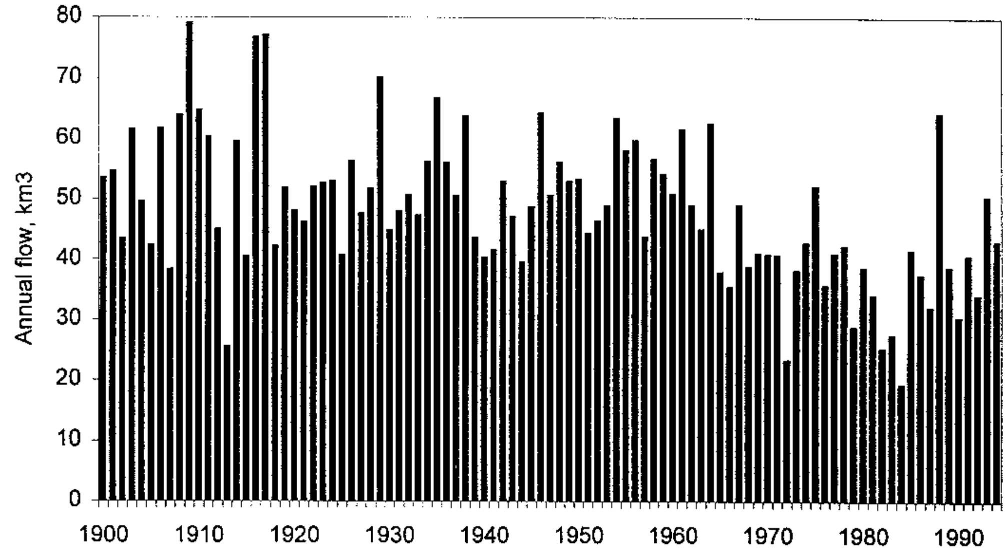


Fig. 9.8 Blue Nile at Khartoum: annual flows, 1900–1994.

compared with the later upstream record (1961–1997) of 2.374 km^3. The corresponding average flows for the Rahad are 1.145 km^3 (1908–1960) and 1.044 km^3 (1961–1997). These comparisons underestimate the real decline because channel losses between the upper and lower sites are neglected. The range of annual flows is great in both cases; the maximum recorded in the early years was 5.65 km^3 in 1916 for the Dinder and 1.96 km^3 in 1909 for the Rahad, compared with low flows in 1941 of 1.24 and 0.53 km^3 respectively. These low flows have been superseded in 1984 by flows of 0.31 km^3 on the Dinder and of 0.34 km^3 on the Rahad. In each case the average peak flow occurs in September, marginally above the average for August; there is an extended period from January to May or June in most years when there is no flow recorded.

The flows of the Blue Nile recorded at Khartoum and Soba reflect the inflows of the Dinder and Rahad to the Blue Nile, the natural channel losses between Roseires and Khartoum and significantly the abstractions for irrigation and to a lesser extent for urban supply. The annual flows at Khartoum (Fig. 9.8), compared with Roseires (Fig. 9.7), show the effect of these factors. Together with the recent decline in runoff from the Blue Nile basin, these are responsible for the marked decline in Khartoum flows since about 1965.

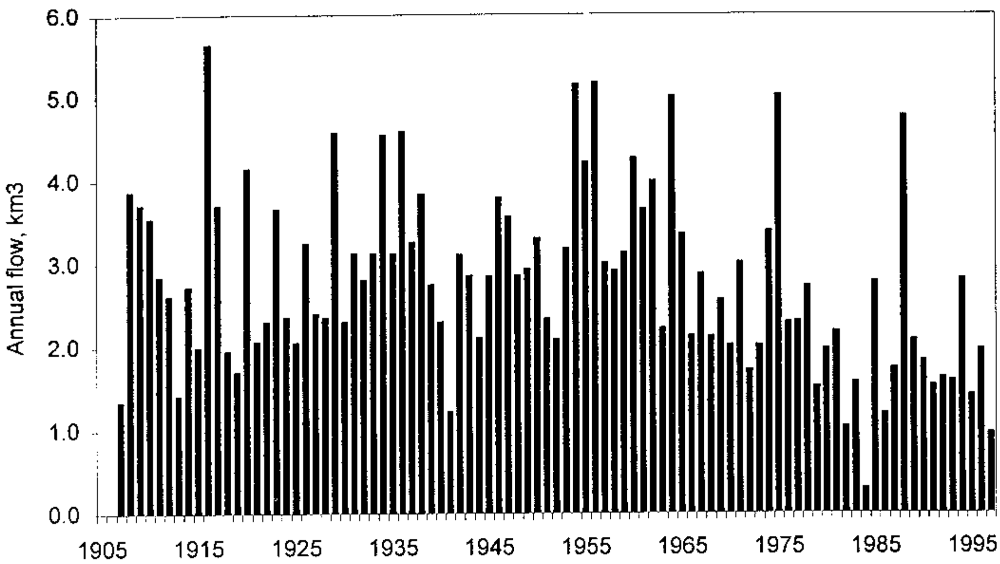


Fig. 9.9 Dinder at mouth/Gwasi: annual flows, 1907–1997.

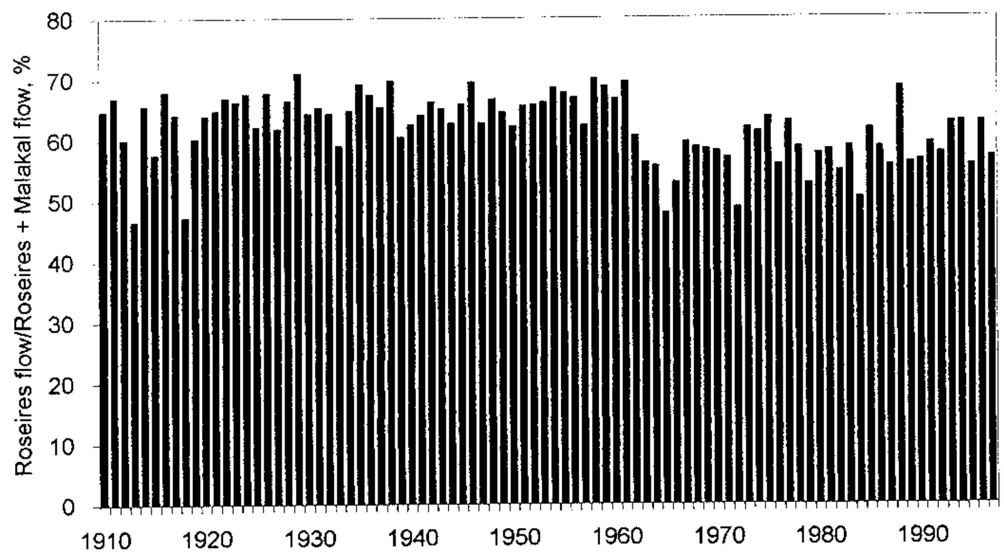


Fig. 9.10 Blue Nile contribution to total flow: Roseires flow as percentage of Roseires + Malakal, 1912–1995.

There has been a marked contrast between the annual series of contributions of the White Nile and the Blue Nile to the total resources of the Nile. Because of abstractions it is preferable to compare the flows at Roseires or el Deim with those at Malakal; the latter include the losses in the Sudd. The change over the years is illustrated by Fig. 9.10, where the annual flows at Roseires/el Deim are expressed as a percentage of the sum of the flows at Roseires and at Malakal. It is clear that the contributions of the Blue Nile, though still the major part of the joint flow, have decreased in importance from about 65% to about 55% over the course of the century. This is due to a combination of the rise in Lake Victoria after 1961 and the more recent decline in Blue Nile flows. It would, however, be unwise to predict future trends.

LOSSES BETWEEN ROSEIRES AND KHARTOUM

Evidence of channel losses and abstractions is given by the differences over the years between the sum of Roseires/el Deim, Dinder and Rahad, and those at Khartoum, which are shown in

Fig. 9.11. There is evidence of a steady increase over the years, but this is to some extent obscured by scatter caused largely by random errors. The apparent losses must be affected by the comparatively poor flow records at Roseires before 1922, when a general rating curve was used due to lack of gaugings. The recent scatter can be attributed largely to data uncertainties.

The main abstractions from the Blue Nile, the discharges of the Gezira main canal from 1925 and the discharges of the Managil main canal from 1959, have been published in *The Nile Basin*, vol. IV and supplements. The total abstractions over the period are included in Fig. 9.11. The net loss, indicated by the difference between apparent loss and abstractions, has averaged about 2 km^3. This is not unreasonable for net evaporation from a main river length of 624 km between Roseires and Khartoum, with an average width of about 300 m. Reservoir evaporation, which includes Sennar from 1925 and increased after 1966 with the completion of Roseires dam, has been estimated as about 0.5 km^3.

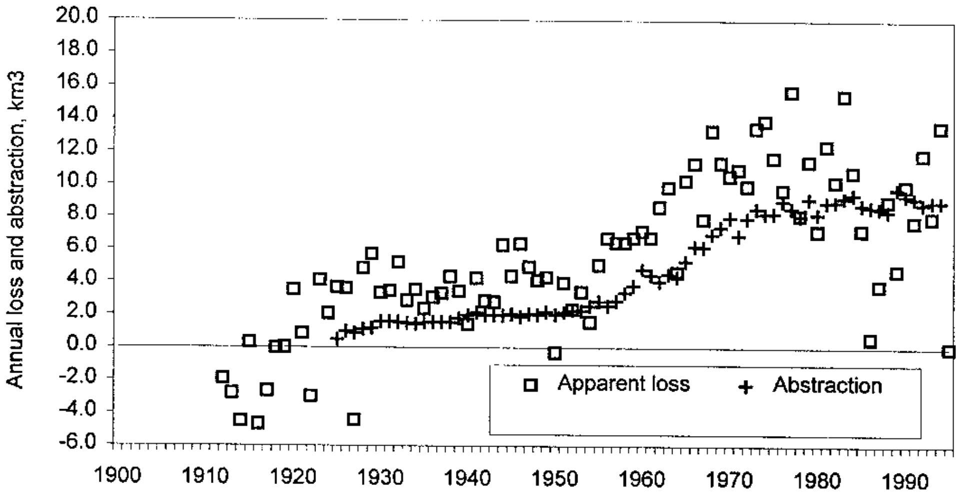


Fig. 9.11 Blue Nile: annual losses from Roseires (including Rahad and Dinder) to Khartoum, 1912–1994.

FLOOD REGIME

The Blue Nile at Khartoum has greater flood potential than the White Nile as flood peaks are experienced without attenuation by major lake storage or wetland spilling. This was illustrated during 1988, when heavy rainfall over Khartoum and to the north was compounded by floods on the Blue Nile and Atbara (Sutcliffe *et al.*, 1989). These together caused severe damage along the river. The main immediate damage in the Khartoum area was caused by a severe storm on the night of 4/5 August 1988 which recorded daily rainfall of 200 mm or more at sites in the city. An approximate estimate of 500 years (Hulme & Trilsbach, 1989) was made for the return period of the storm. The river flood was also significant, with a peak level reached on 27 August 1988 which was second only in this century to the flood of 1946. There was at the time concern in Khartoum about the possibility of inundation, and information on cold cloud cover over the Ethiopian basins of the Blue Nile and Atbara was derived at Reading University and passed to Khartoum, providing assurance that further rises were not imminent.

The 1988 floods can be put into perspective by flood frequency analyses at gauging sites. The peak flows were not published, so the highest discharge measurement in each year was taken as the annual maximum flow. Linear flood frequency relations were fitted at a number of sites. An example (Fig. 9.12) for the Blue Nile at Khartoum shows that the 1988 peak flow (estimated at 8500 $m^3 s^{-1}$) had a return period of about 10 years. Analysis at other sites

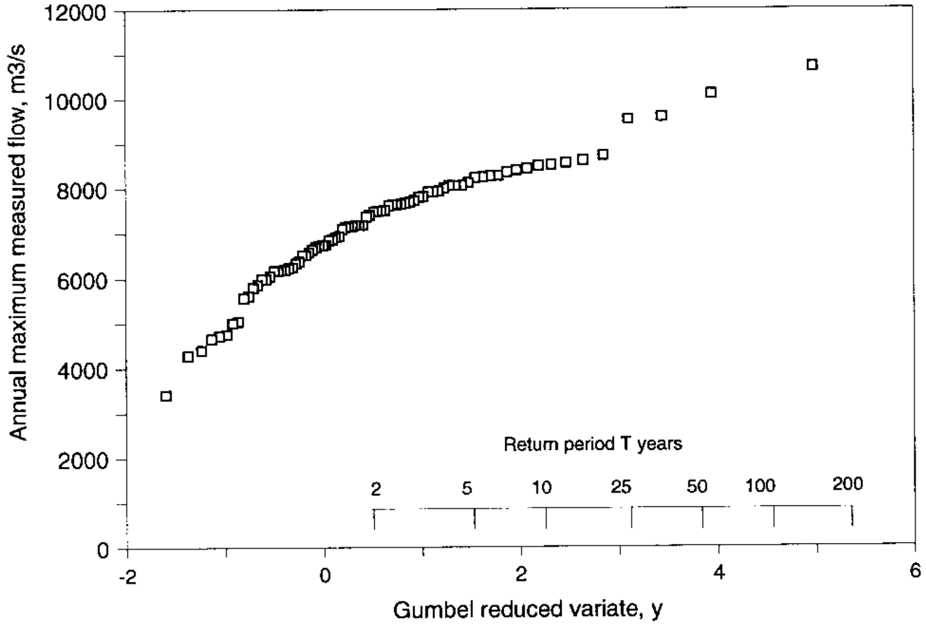


Fig. 9.12 Blue Nile at Khartoum: flood frequency, 1902–1992.

(Sutcliffe *et al.*, 1989) showed that the flow had a return period of about 10 years from Roseires to Tamaniat, but a higher return period of 50–100 years on the main Nile below the Atbara confluence.

However, a similar study of historical peak levels at Khartoum suggested that the 1988 peak level corresponded to a return period of about 50 years, exceeding the 10-year estimate for flows. A comparison of annual maximum measured flows and corresponding levels for the period 1902–1982 suggested that the level at Khartoum gauge had risen by about 0.5 m over this period for a typical flood flow. Similar trends were found at Tamaniat below the confluence and suggested that channel change or aggradation might have occurred. This would account for the apparent discrepancy between the return periods of flows and levels.

The record length at Khartoum has been extended by research on historic level records. Walsh *et al.* (1994) made use of the levels observed between 1869 and 1883, which Hurst & Phillips (1932) in *The Nile Basin*, vol. III had related to the zero of the later gauge. They (Walsh *et al.*) also estimated annual flood levels at Khartoum for the period 1884–1898 by regression from peak levels at Aswan. They concluded that the 1946 peak had been exceeded at least three times between 1869 and 1900. Inclusion of these floods would reduce the return period of the floods recorded in this century; floods of this magnitude could occur more frequently than recent records suggest.

The floods of the Blue Nile are less variable than those of rivers in many parts of the world (Meigh *et al.*, 1997). Consequently, floods of high return period are unlikely to reach high multiples of the mean annual flood. This is a common feature of rivers relying on a single well-defined rainfall season, as opposed to rivers in semiarid areas. For example, the daily peak of the probable maximum inflow flood at Roseires has been estimated (Snyder *et al.*, 1961) as about 19 000 $m^3 s^{-1}$ compared with the 1946 daily peak of about 11 000 $m^3 s^{-1}$.

FLOW FORECASTING SYSTEMS

It was shown during the 1988 flood that cold cloud data from satellite imagery could provide useful information on rainfall amounts, from which flow forecasts could be made. This procedure has the advantage, in areas of difficult access, that it does not depend on direct rainfall measurement and data transmission in real time. This was developed in the River Senegal (Hardy *et al.*, 1989) and was used to provide a flow forecasting system for the Blue Nile and the River Atbara.

The three main components of the forecasting system (Grijsen *et al.*, 1992) are: the collection of cold cloud duration data and their conversion to rainfall estimates in real time; the conversion of rainfall estimates to river flow forecasts at key sites; the modelling of flood transmission down the main channels to forecast levels and flows at key points. These components are supported by a data collection and transmission system.

Rainfall estimation is based on cold cloud duration (CCD) below a temperature threshold, and linear regression with rainfall records by calendar months and sub-catchments. The conversion of rainfall estimates to river inflows was based on development of the Sacramento conceptual model, which is quasiphysical and allows limits to be set for certain parameters. Daily actual flows are used to update the model parameters, and this procedure was extended to operate on the CCD-rainfall conversion within the model. The combination of rainfall estimation and a rainfall–runoff model allows river flows to be forecast up to three days ahead on the Blue Nile and thus increases the forecast lead at Khartoum from three to six days. The forecasts for the Dinder and Rahad are based on regression. The transmission of the inflow flood hydrograph down the channel and reservoir system is analysed by a one-dimensional dynamic flow model, based on the equations of continuity and momentum; this model takes account of abstractions and tributary inflows. Although the system is geared to forecasting flows during the flood season, there is the prospect that it could be used to forecast the start of runoff on the various Blue Nile tributaries.

SEDIMENTATION

The Blue Nile is the first of the Nile tributaries where the sediment load is of critical importance. The White Nile tributaries on the whole are lake-fed or lose much of their sediment load by spilling and deposition over flood plains. The Blue Nile, by contrast, has a highly seasonal flow regime and carries a significant sediment load during the flood period. The basin is steep and the vegetation is relatively sparse because of the short rainfall season. The seasonal distribution of sediment is important. The storage available in Roseires and Sennar reservoirs is fairly limited and it is vital to minimize the sedimentation by reservoir operation during the period of filling. According to El Moushid *et al.* (1997), the suspended sediment load of the Blue Nile at el Deim is estimated as 140 million tonnes per year during the flood season. The sediment concentration reaches a peak of nearly 6000 ppm in early August, before the peak discharge is reached, and decreases until the end of the flood. After nearly 30 years, the capacity of Roseires reservoir had been reduced by 0.9 km^3 by 1995, when the capacity was estimated from satellite imagery at 2.4 km^3. The dam is currently being raised. The strategy for the Blue Nile reservoirs is to delay the filling until the peak of the flood has passed through the reservoir, as the sediment load is greatest on the rising limb of the hydrograph. Forecasting of future flows could provide a means of minimizing the risk of the reservoir not being filled while postponing the filling as late as possible in order to reduce sedimentation.

OPERATION OF BLUE NILE RESERVOIRS

Because the dry season flows of the Blue Nile and its tributaries are limited, the water stored from the previous flood season in Roseires and Sennar reservoirs is essential to the irrigated agriculture of the Gezira and associated schemes. A second important function of the reservoirs is to provide hydroelectric power, and the joint operation of the reservoirs needs careful planning.

Within the limits on inflows and storage, and on abstraction permitted by the Egypt–Sudan agreement of 1959, the aim of the Sudan authorities (Sutcliffe & Widgery, 1997) is to maximize irrigation, hydropower and water supply while minimizing sedimentation. The policy has been to draw down Roseires and Sennar reservoirs during the flood season. This drawdown, which coincides with high tail water levels, has a major impact on hydropower operation. Reservoir filling rules have been based on flow statistics to minimize sedimentation while ensuring filling. During the flood recession, when the future inflow may be estimated, the area to be planted with wheat must be decided; other crops like cotton will already have been planted. Operating rules have been developed to optimize hydropower production at Roseires (capacity 275 MW) and Sennar (15 MW) in terms of water availability and irrigation demand; the problem is complex because energy demand increases during the hot season and does not coincide with irrigation releases.

In the past the dry season recession flow of the Blue Nile, which forms a useful supplement to the stored water, was forecast using either a "similar year" method or a recession constant linking successive 10-day flows. A recent case study by Osman Eltom Hamad (Hamad, 1993) was designed to provide an improved method of operating the reservoirs during the dry season. To model the inflows he proposed the use of a nonlinear reservoir system, whose parameters are derived from the flow records for individual years. It was found that the flow series for each dry season could be forecast from the flow in October, using a single slope parameter related to the preceding flood and the previous year's flow. This forecast method provided generally better results than previous methods.

In some years flows rise in March–May because of equatorial spring rains on the southern tributaries. A forecast of these flows might be used to plan the area of irrigable crops to be planted each season, and also to plan the operation of the reservoir system: to provide irrigation requirements, to provide minimum releases downstream and to generate hydropower while taking into account channel losses. The model includes a water balance of the reservoir, which takes account of changes of storage, rainfall and evaporation, river inflow, abstractions, releases and transmission losses. The simulation of hydropower generation takes account not only of turbine flow but also head differences and efficiency; it has to take account of the relation of reservoir storage to level, which again varies over time with sedimentation. Comparison of hydropower generation with the reservoir operated according to this model, with results obtained earlier, showed that there would have been significant improvement.

CONCLUSIONS

The Blue Nile contributes a large proportion of the total flow of the Nile, but its regime differs markedly from the White Nile tributaries because of pronounced seasonal and annual variations. The decrease in flows over the years, influenced to some extent by increasing irrigation abtractions, contrasts with the outflows from Lake Victoria and thus the flows of the White Nile which have shown considerable increases after 1961–1964. The management of water resources systems can be improved by better forecasting of flood flows, and a review of flood potential is needed. It is possible that the extension of rainfall monitoring to the early rains, which result in the inflow to Roseires reservoir during April/May, could also improve the operation of the joint reservoirs. An exchange of hydrological information between Ethiopia and Sudan could lead to improved operation of the reservoir system.