CHAPTER 12

THE NILE AND HYDROLOGICAL ASPECTS OF WATER USE

INTRODUCTION

With the long-term record of inflows to Aswan, the hydrological information on the Nile basin is complete. This presents an opportunity to describe the contributions of the different tributaries over the years, and to derive a correlation matrix to illustrate the links between them. A comparison is made of key sites throughout the basin, to help understanding of the hydrological complexity of the system. A brief discussion of rainfall and runoff over the basin is followed by a reminder of the importance of wetlands.

The development of water resources in the various countries of the Nile basin must be to a large extent dependent on the hydrology of the different tributaries. Because upstream developments could affect the availability of water downstream, there may be choices in some cases between developments upstream and water use downstream. It seems appropriate to present a brief review of some of the needs and problems of water resources development in the countries of the Nile basin in order to round off a discussion of the hydrology.

SUMMARY OF FLOW SERIES

The contributions of the different Nile tributaries have been described in previous chapters. Before discussing the way in which the available water has been used, this is a convenient point at which to compare the annual flow records at key sites over the basin. In order to compare flows on a common basis, the flows at downstream sites have been naturalized by adding the upstream abstractions to the measured flows. This has been necessary for the White Nile at Mogren, the Blue Nile at Khartoum, the Atbara, and the main Nile at Tamaniat, Hassanab, Dongola and Aswan.

The upstream sites are illustrated by annual flow series in Fig. 12.1, where common time scales have been used from 1890 to 1997, and also common volume scales. The sites in the lake basin above Mongalla all show the increase of flows after 1961, though the pattern of flows of the Semliki is less clear. By comparison with Jinja, the flows at Kamdini and Mongalla show enhanced responses to the 1961/62 event, which was not limited to the Lake Victoria basin. The Sudd outflows are very damped, but also reflect the rise in inflows at Mongalla. The flows of the Jur at Wau, the Baro at Gambeila and the Sobat at Doleib Hill do not show an increase.

The downstream sites are shown in Fig. 12.2 from 1870 to 1997, with a different volume scale. The White Nile at Malakal reflects the rise after 1962 in Sudd outflows, but these have increased less than the upstream inflows. The flows of the Blue Nile and Atbara are variable and show a decline in the 1970s and 1980s. The Tamaniat flows combine the joint flows of the White and Blue Niles, while the records at Dongola, which have been extended back to 1870 using Kajnarty, Wadi Halfa and Aswan, show the high flow period up to 1900, the variable flows until 1970, and the lower flows since 1970.

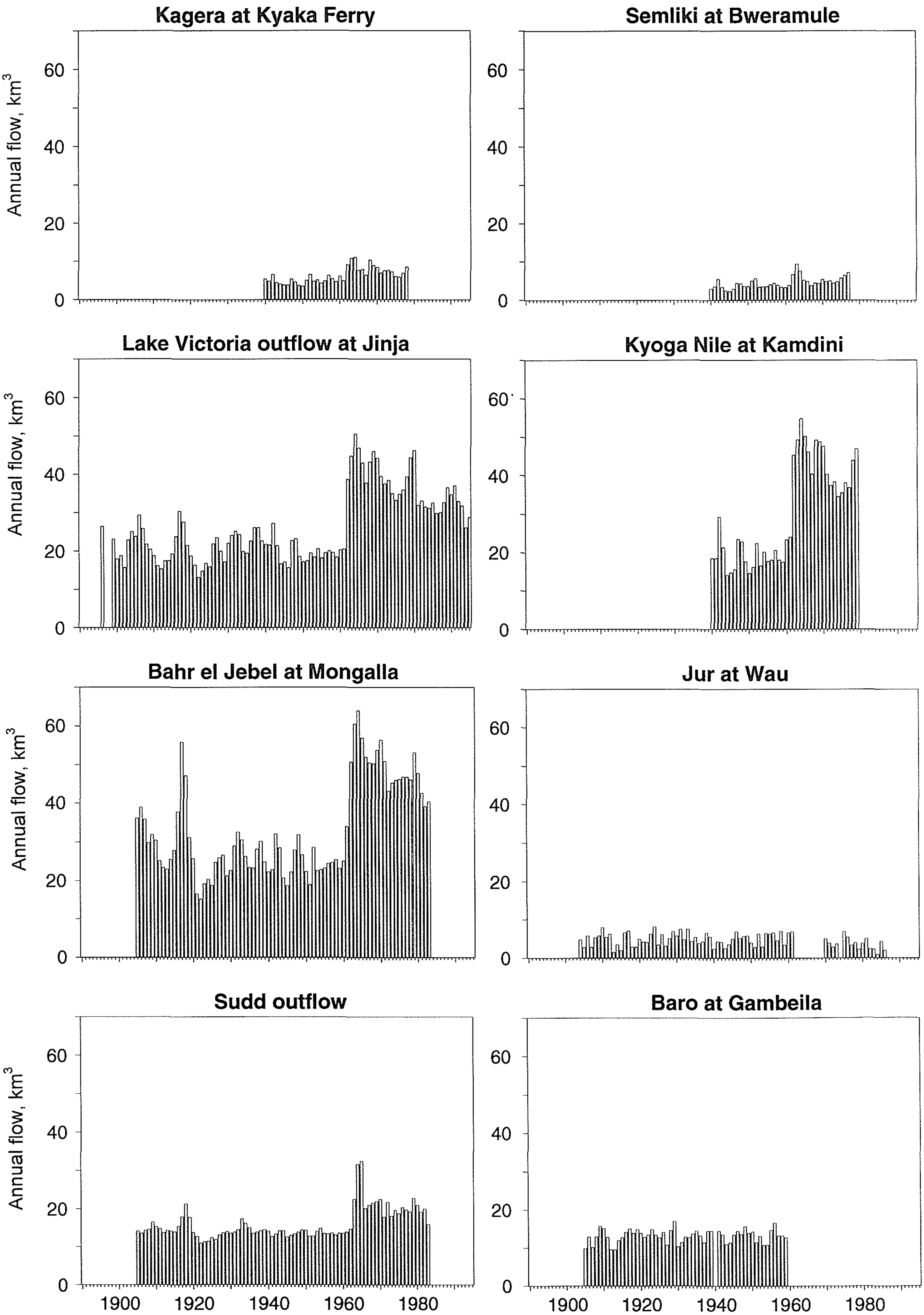

Fig. 12.1 Annual flows at upstream sites, 1890–1997.

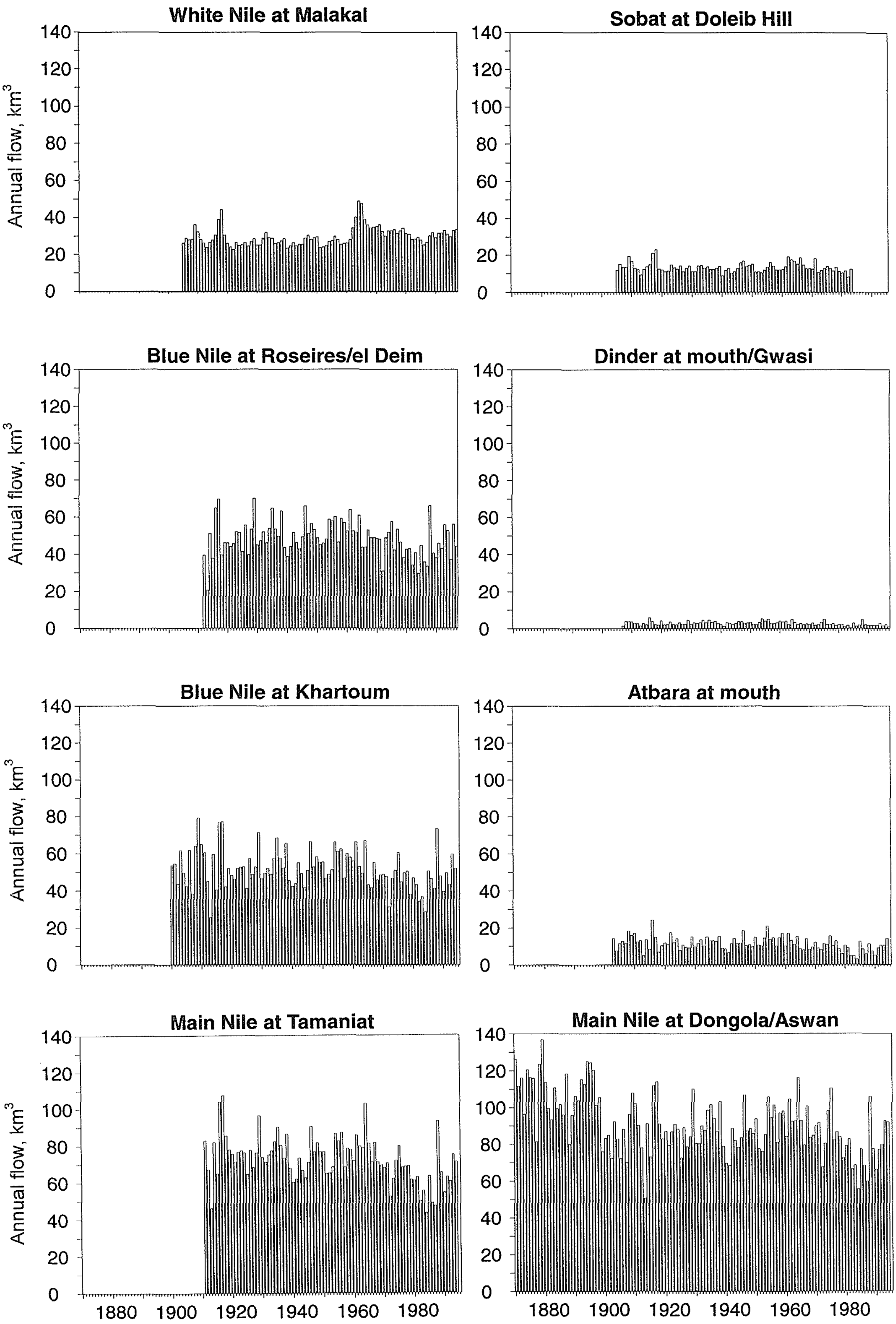

Fig. 12.2 Annual flows at downstream sites, 1870–1997.

Table 12.1 Correlation matrix of annual flows (R^2).

	Khartoum, Mogren, Tamaniat, Atbara, Dongola naturalized																				
	Kagera Kyaka A	Vict N Jinja B	Kyog N Kamd. C	Semliki Bwer. D	L Alb. Outfl. E	B el J Mong. F	Torr. Mong. G	Jur Wau H	Baro Gamb. I	Sobat at Dol. H J	Whi N Malak. K	Whi N Mogren L	Blue N Ros/Dm P	Dinder mouth N	Rahad mouth O	Blue Nile Khar. M	Nile Taman. Q	Nile Hassan. R	Atbara mouth S	Nile Dongola T	W Arr Aswan U
A	1.000	0.805	0.838	0.548	0.724	0.753	0.002	0.030	0.013	0.102	0.532	0.475	0.020	0.014	0.002	0.054	0.043	0.006	0.099	0.003	0.039
B		1.000	0.981	0.446	0.903	0.888	0.002	0.066	0.000	0.031	0.520	0.488	0.019	0.039	0.027	0.046	0.008	0.017	0.106	0.001	0.111
C			1.000	0.484	0.953	0.963	0.000	0.043	0.008	0.128	0.731	0.722	0.038	0.023	0.006	0.079	0.066	0.012	0.119	0.006	0.080
D				1.000	0.485	0.523	0.017	0.000	0.014	0.149	0.375	0.317	0.000	0.001	0.000	0.006	0.075	0.040	0.019	0.027	0.005
E					1.000	0.964	0.000	0.024	0.002	0.115	0.677	0.666	0.008	0.023	0.018	0.033	0.044	0.001	0.075	0.006	0.069
F						1.000	0.023	0.014	0.008	0.132	0.705	0.653	0.000	0.007	0.013	0.009	0.081	0.008	0.035	0.022	0.030
G							1.000	0.174	0.073	0.095	0.008	0.001	0.306	0.131	0.055	0.315	0.281	0.235	0.272	0.248	0.248
H								1.000	0.216	0.150	0.007	0.000	0.500	0.418	0.274	0.473	0.443	0.472	0.312	0.479	0.453
I									1.000	0.329	0.188	0.108	0.382	0.162	0.094	0.353	0.352	0.413	0.034	0.359	0.320
J										1.000	0.433	0.382	0.167	0.124	0.069	0.187	0.386	0.399	0.038	0.308	0.276
K											1.000	0.916	0.016	0.012	0.003	0.011	0.211	0.110	0.003	0.131	0.021
L												1.000	0.000	0.001	0.001	0.003	0.147	0.075	0.024	0.074	0.004
M													1.000	0.569	0.327	0.902	0.795	0.797	0.558	0.840	0.726
N														1.000	0.405	0.600	0.563	0.611	0.532	0.667	0.646
O															1.000	0.489	0.372	0.382	0.331	0.380	0.319
P																1.000	0.786	0.777	0.619	0.802	0.747
Q																	1.000	0.849	0.454	0.902	0.689
R																		1.000	0.519	0.889	0.840
S																			1.000	0.618	0.657
T																				1.000	0.825
U																					1.000

These links between key stations have been confirmed by the correlation matrix given in Table 12.1. The correlations between the Lake Victoria outflows and the sites down to Mongalla are naturally close, as shown by the R^2 values. The Kagera and the Semliki are less closely related. The flows of the torrents above Mongalla have no link with other sites, though this may reflect the method of estimation. The flows of the Baro at Gambeila, and more surprisingly the Jur at Wau, appear to be linked with the Blue Nile and Dinder; they have in common a single rainfall season. The Sobat has lower correlation with other tributaries. The Blue Nile naturally has links with the Atbara and the sites on the main Nile.

The seasonal distribution of flows has been similarly illustrated by collating the monthly mean flows for as long a period as possible in Table 12.2 and Fig. 12.3. The Kagera and Semliki are also damped by swamps and lakes. The peak month is delayed from Jinja downstream, though Mongalla shows the effect of the torrents. The halving of flows in the Sudd is clearly shown. The seasonal character of the Baro and Jur, and the attenuation on the lower Sobat, are clear, while the White Nile at Malakal combines the Sudd outflow and the Sobat. The comparison between the White Nile at Malakal and Mogren is affected by Jebel Aulia reservoir. The seasonal similarity and relative sizes of the Blue Nile tributaries and the Atbara are evident, and the attenuation between Roseires/el Deim and Khartoum is suggested. The similarities between Tamaniat and Hassanab, and between Dongola and Aswan, are to be expected, while the difference reflects the Atbara contribution.

The concept of water balance has been used throughout the book to describe individual tributaries. A regional picture can be indicated by the relation between average rainfall and runoff depth over the whole basin given in Fig. 12.4. Runoff has varied dramatically on some tributaries since records began, but periods of records vary and a concurrent series would be short; estimates have been made for the whole period of records at each site. The information is dominated by the Lake Victoria basin, but includes a few Ethiopian tributaries, where the rainfall is not known with any precision. Some conclusions can be drawn. The runoff from the Bahr el Ghazal tributaries is low by comparison with the other areas, and this reflects the low gradients of this region. Apart from these rivers, the relation between rainfall and runoff is reasonably defined, and the wide variation of both over the basin is clear. The major flow contributions are confined to mountainous areas with high rainfall.

The role of wetlands in reducing river flows is a feature of the White Nile basin. The flows of the Bahr el Jebel, Bahr el Ghazal, and the Sobat, are all affected by spill into wetlands and subsequent evaporation. The role of hydrological conditions, and in particular duration, maximum depth and level range of flooding has been shown to control the vegetation type and species. Conversely, it has also been demonstrated that the evidence of wetland distribution, and especially the evidence of key vegetation species, provides valuable information on the hydrology of a basin.

Although the Nile basin is extremely heterogeneous in terms of topography, climate, vegetation and river flows, it is nevertheless interdependent in the sense that each tributary impinges on the river basins downstream. It is hoped that this book has highlighted the links between the different parts of the basin.

WATER USE IN THE NILE BASIN

The following discussion of water use in the Nile basin is limited to hydrological aspects; there is clearly also a need for negotiations and agreements, which are matters for individual governments. This review is classified by countries for simplicity, though some of the issues have also been discussed in the chapters dealing with specific tributaries. In particular, the proposals to store water in the East African lakes in order to supplement the flows of the Blue

Nile during periods of shortage, while reducing transmission losses in the Sudd by the Jonglei Canal, were known collectively as the Equatorial Nile Project; these were described in Chapter 5. Only the Owen Falls dam, which combined hydroelectric production with the potential for outflow control, has been completed, while the construction of a modified Jonglei Canal was suspended in 1983. The alternative planning of the Aswan High Dam, to provide overyear storage, was discussed in Chapter 11.

Table 12.2 Mean monthly flows at key sites ($m^3 \times 10^6$).

Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Kagera at Kyaka Ferry (1940–1978)												
452	420	491	518	617	627	647	603	531	499	460	467	6 332
Other Lake Victoria tributaries (1956–1978)												
819	578	972	2103	2474	1342	1201	1 387	1 332	999	1151	1207	15 565
Victoria Nile at Jinja (1896–1997)												
2162	1973	2204	2212	2412	2369	2372	2 277	2 143	2 160	2057	2160	26 501
Kyoga Nile at Kamdini (1940–1980)												
2511	2200	2372	2301	2526	2550	2679	2 695	2 660	2 733	2609	2657	30 493
Semliki at Bweramule (1940–1978)												
359	292	327	363	415	371	392	417	409	423	435	419	4 622
Bahr el Jebel at Mongalla (1905–1983)												
2534	2180	2327	2360	2767	2663	2920	3 317	3 295	3 244	2975	2751	33 332
Jur at Wau (1904–1986)												
45	17	10	19	98	212	450	818	1 115	1 149	623	176	4 730
Sudd outflow (1905–1983)												
1515	1318	1392	1280	1262	1188	1227	1 284	1 328	1 444	1379	1473	16 091
Baro at Gambeila (1905–1959)												
257	169	163	202	454	1154	1946	2 590	2 971	2 022	816	440	13 184
Sobat at Doleib Hill (1905–1983)												
967	431	273	232	413	851	1301	1 608	1 780	1 992	1964	1718	13 530
White Nile at Malakal (1905–1997)												
2479	1756	1675	1528	1696	2042	2556	2 914	3 117	3 434	3340	3178	29 714
White Nile at Mogren (1911–1995)												
2469	1905	2014	2225	2026	1792	1368	1 435	2 236	3 024	2786	2747	26 026
Blue Nile at Roseires/el Deim (1912–1997)												
762	446	364	324	612	1659	6763	15 228	12 111	6 484	2559	1348	48 658
Dinder at Mouth (1907–1997)												
0	0	0	0	0	16	318	1 005	1 009	392	51	6	2 797
Rahad at Mouth (1908–1997)												
0	0	0	0	0	2	119	346	378	228	27	2	1 102
Blue Nile at Khartoum (1900–1995)												
724	448	406	427	503	1084	4989	15 237	13 625	7 130	2451	1257	48 279
Main Nile at Tamaniat (1911–1995)												
3099	2302	2378	2555	2490	2860	6398	16 151	15 584	9 996	5067	3810	72 691
Main Nile at Hassanab (1909–1995)												
3146	2320	2286	2428	2359	2690	5937	15 607	15 859	10 460	5351	3894	72 337
Atbara at Mouth (1903–1994)												
17	6	1	3	8	88	1536	5 126	3 306	770	145	46	11 052
Main Nile at Dongola (1890–1995)												
3577	2547	2268	2239	2175	2169	5268	18 701	20 554	13 337	6767	4538	84 138
Main Nile at Aswan (Water Arriving) (1869–1992)												
3738	2651	2257	2011	1980	1943	4754	18 207	21 189	14 318	7478	4849	85 376
Main Nile at Aswan/Dongala (1869–1995)												
3831	2715	2379	2220	2127	2178	5529	19 341	21 385	14 151	7295	4298	88 079

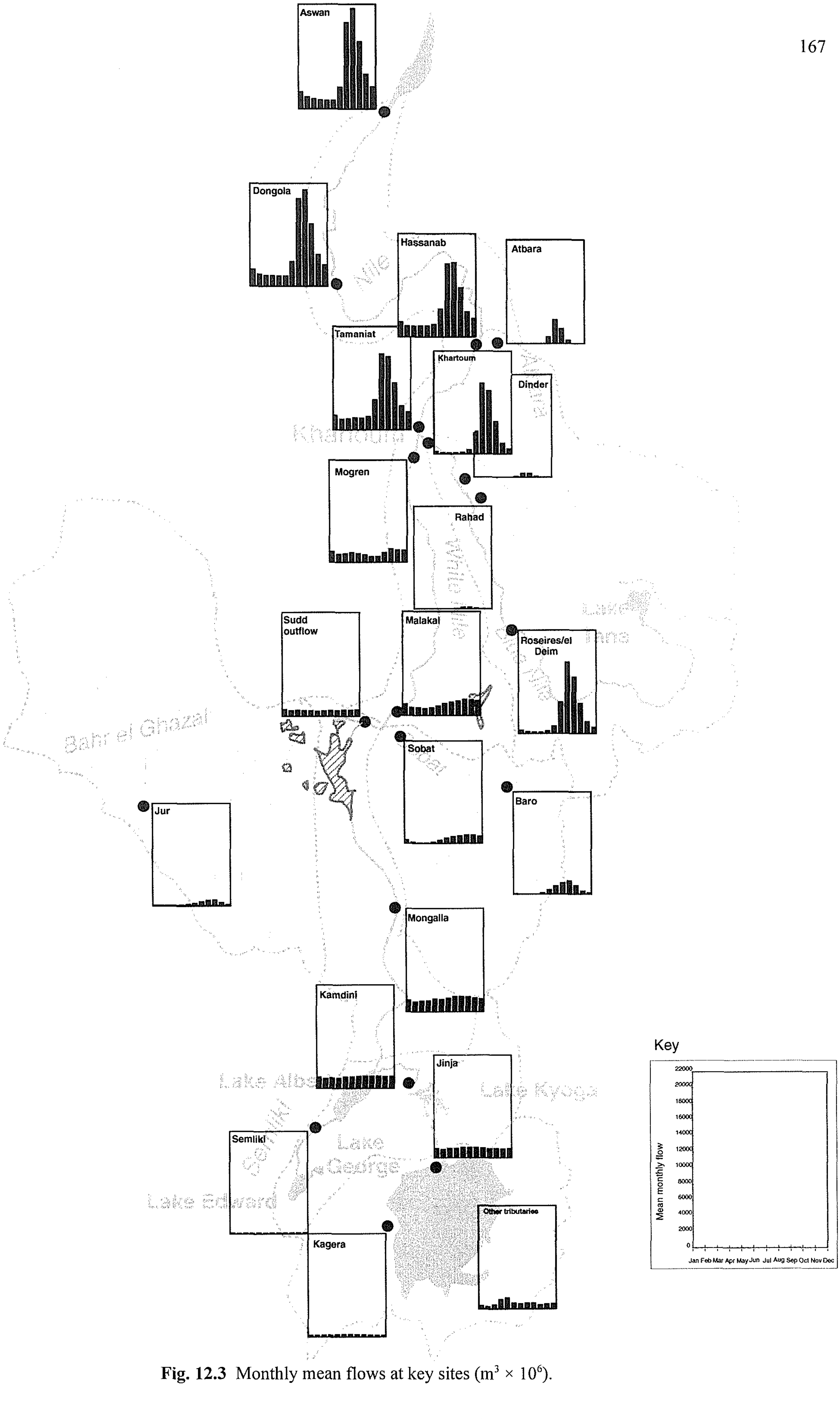

Fig. 12.3 Monthly mean flows at key sites ($m^3 \times 10^6$).

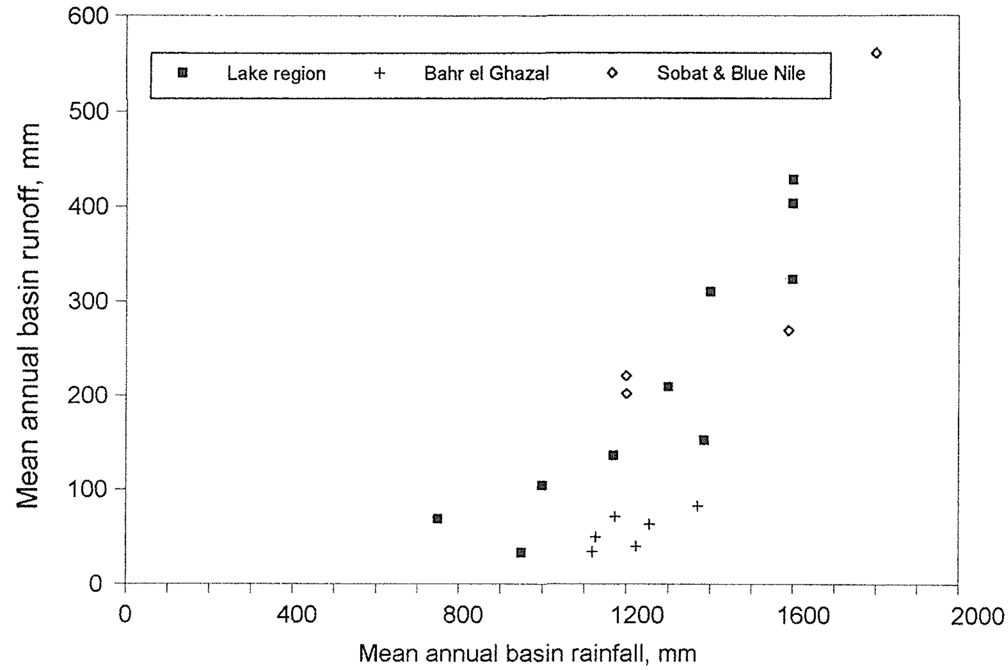

Fig. 12.4 Mean rainfall and runoff depth of Nile tributaries.

EAST AFRICA

Within the upper basin of the White Nile, the areas belonging to the various East African countries have in common a climate with two rainfall seasons and a requirement in some locations for supplementary irrigation for perennial crops. Because of their location, remote from fuel supplies, they also have a need for hydroelectric power. Thus the problems of water requirements have certain similarities over the region.

RWANDA, BURUNDI AND CONGO

Rwanda and Burundi comprise much of the catchment of the Kagera and its tributaries. The runoff of the Kagera is high, and at Rusumo Falls the annual total averages 7 km^3 from 30 000 km^2 or a depth of 230 mm. The domestic and industrial supplies to the towns of Rwanda and Burundi are unlikely to be significant in the context of this amount of water. There are projects for developing rice irrigation in the valleys of various tributaries, largely in swamps which are inundated seasonally or permanently. The irrigation demand, compared with the natural evaporation from these swamps, is unlikely to result in greatly reduced runoff as these developments occur. One major project which has been investigated for the Kagera river has been the hydroelectric scheme at the Rusumo Falls on the border between Rwanda and Tanzania. The evaporation from the storage reservoir above Rusumo Falls would not be greatly different from the lakes and wetlands which cover the area at present. Thus the effect of this project would be to alter the distribution rather than the total amount of Kagera runoff, and this change would have little effect below Owen Falls because of the storage of Lake Victoria.

The Congo interest is limited to Lake Edward and the upper Semliki, where irrigation could be useful, and the western shore of Lake Albert, which would be affected by a dam below the lake.

UGANDA, KENYA AND TANZANIA

These countries need to supplement rainfall to grow some perennial crops like sugarcane. In preparation for early negotiations over Nile waters, investigations were carried out by 1955 to identify the potentially irrigable areas for Uganda. The irrigation requirements were estimated on a 25-year time scale (Howell, 1994, pp. 82 and 88). The conclusions were that some 110 000 acres (45 000 ha) were suitable for irrigation, mainly for sugarcane and paddy rice, and the water requirement was estimated at 0.535 km^3. Similar surveys were also made for Kenya and Tanzania; irrigation needs were estimated as 0.297 and 0.478 km^3 respectively. The total requirements for the three East African countries were provisionally estimated as 1.77 km^3, of which 1.385 km^3 would be required above Owen Falls. This is 5% of the long-term mean outflow. Any irrigation abstractions, except those offset by swamp reclamation, would reduce the inflow to Lake Victoria and the outflow down the Victoria Nile by a similar amount.

A later estimate of water demand was made by WMO (1982) for the years 1980 and 2000. This was based on population statistics and information supplied by governments on irrigated schemes and industrial demand, rather than detailed surveys. The 1980 total water consumption for the five countries, including Rwanda and Burundi, was estimated as 19.0 $m^3 s^{-1}$ or 0.600 km^3 $year^{-1}$; the equivalent estimate for the year 2000 was 185 $m^3 s^{-1}$ or 5.834 km^3 $year^{-1}$. The range of these estimates points to the need for more detailed studies.

At one stage the possibility for diverting water from Lake Victoria or its tributaries towards the south had been investigated (Hurst, 1952). Such diversions, for instance for irrigation, would also directly reduce the inflow to Lake Victoria and the outflow at Owen Falls.

The suggestion has been made that the growth of water hyacinth around the shores of Lake Victoria could affect the outflow by increasing the evaporation. This possibility would need experimental evidence of evaporation from an area of water hyacinth, but it seems likely that the growth will be confined to the borders of the lake and not greatly affect the water balance.

The operation of the Owen Falls dam is at present constrained by agreement to reproduce natural lake outflows by following, at least on a monthly basis, the so-called "Agreed Curve" derived from the natural relation between lake level and outflow. However, the maximization of firm hydroelectric power could give Uganda the incentive to use Lake Victoria storage to maintain outflows at a higher level than historic low flows. Reservoir trials have been carried out by a number of investigators, including WMO (Bakhiet, 1996) and FAO (Georgakakos & Klohn, 1997). The firm flow could be improved by storage; however, the range of lake levels would be increased, and this could affect installations around the lake.

In addition, any alteration of the natural flow would affect the regime of the Bahr el Jebel and the Sudd. It has been shown that the pastoral economy of the Sudd is dependent on the rhythm of flooding and uncovering of the seasonal flood plain. This pattern depends on relatively steady outflows from Lakes Victoria and Albert and the seasonal flows of the torrents above Mongalla. Any random disturbance of lake outflows would disrupt the economy of the area, but it should be possible to ensure that outflows retain a fairly natural pattern after passing through Lakes Kyoga and Albert.

Proposals have been made for a dam below Lake Albert, together with a regulator to control Lake Kyoga. These have been investigated as a part of the Equatorial Nile Project specifically to control the inflow to the Sudd to maximize the diversion down the Jonglei Canal. It would be possible to use such a reservoir in Lake Albert to balance the flows below Lake Victoria and maintain the natural flows into the Bahr el Jebel. The reservoir could provide flood protection to an economy in the southern Sudan which had adapted to the completion of the Jonglei Canal.

By contrast, a simulation study (Georgakakos & Klohn, 1997) to combine energy generation while reducing Sudd losses with the Jonglei Canal relies on curtailing releases from Lake Albert to minimize losses. This implies that water would be released during the dry season when torrent flows are minimal, and when grazing is required. In other words, losses would be reduced by eliminating the natural fluctuations. This would have a dramatically adverse effect on the local economy.

It is essential to include an understanding of the ecology of the Sudd in modelling studies. The vegetation of the regional wetlands is controlled by the hydrology, and in particular by the flooding regime. The nature of these controls has been deduced from hydrological analysis, following collaborative investigations with ecologists. In turn the hydrological study of an area can be supported by a knowledge of the vegetation and the ecological links with flooding. Joint investigations are required.

ETHIOPIA AND ERITREA

Ethiopia is the source of a high proportion of the Nile flow. The Baro, Blue Nile, Rahad, Dinder and Atbara together provide an average 73 km^3 annual inflow to Sudan, while the Bahr el Jebel contributes 33 km^3 as measured at Mongalla (1905–1983). However, the flow records within Ethiopia have not been published except for early flows of the Blue Nile below Lake Tana and the Baro at Gambeila. The Eritrean contribution to the Nile is limited to a portion of the Setit tributary of the Atbara. The Gash and Baraka do not drain to the Nile.

The water balance study of runoff by Gamachu (1977) compared average rainfall with transpiration to estimate potential runoff over the country. This showed that the highest rainfall is in the mountains to the west of the central Rift Valley. Here the rainfall is concentrated in a single season and the runoff is disproportionately high. Thus the bulk of the outflow from Ethiopia is towards the Nile tributaries as opposed to the eastern and southern rivers like the Awash, Shebbeli, Juba and Omo. It has been estimated (Said, 1993) that about 70 km^3 flow to the Nile compared with about 20 km^3 to the Indian Ocean.

The flows of these tributaries are considered as a major resource for Ethiopia (Woudeneh, 1997). The US Bureau of Reclamation studied the Blue Nile basin on behalf of the Ethiopian Government between 1959 and 1964 (Said, 1993). This study concluded that there were no lands along the Blue Nile itself which could be irrigated. However, they located potential irrigation projects totalling 0.53 million ha near Lake Tana and along various tributaries, including the Dinder and Rahad. The potential water requirement totalled 6.4 km^3. A number of major hydroelectric projects were suggested along the Blue Nile and its tributaries, including Lake Tana itself. These would involve in total over 20 dams with capacities of over 100 km^3. To date projects have been constructed at the outlet of Lake Tana to generate power, and on the Finchaa with a capacity of 0.4 km^3 to generate hydropower and to irrigate sugarcane downstream of a swamp.

Further studies have recently been carried out for the Baro-Akobo, Abbay (Blue Nile), and Tekeze (Atbara) basins (Amanuel, 1997). The Baro-Akobo basin is subject to considerable spillage after reaching the plains below Gambeila. This spill occurs both within Ethiopia and into the Machar marshes. There are plans to irrigate the plains and a dam is under consideration on the Baro near Gambeila with a capacity of 1.5 km^3 (Said, 1993) in order to irrigate some 315 000 ha. This is an area where there have been in the past Egyptian plans to reduce spillage from the Baro-Sobat by means either of storage or channel construction. It is possible that a joint study on the Baro might show that benefits could accrue to both Ethiopia and the downstream users.

It has been argued (Guariso & Whittington, 1987) that the construction of reservoirs in the Blue Nile basin and their management in coordination with the Roseires and Aswan reservoirs need not reduce the water available to Sudan and Egypt because evaporation in the

Ethiopian reservoirs would be less than the saving of evaporation downstream. It seems that exchange of hydrological information could be of benefit to all countries.

SUDAN

As a result of negotiations between Egypt and Sudan preceding the construction of the Aswan High Dam, the two countries agreed in 1959 that the mean natural flow at Aswan, estimated as 84 km^3 less 10 km^3 reservoir evaporation, should be divided with 55.5 km^3 to Egypt and 18.5 km^3 to Sudan, which Shahin (1985) notes was in proportion to the population of the countries at that time.

The main water demand in Sudan is for irrigation, though the hydroelectric power production from existing reservoirs is an important contribution to the economy. The relative importance of the irrigation demand is illustrated by Sutcliffe & Lazenby (1990). The annual water supply demand for the Khartoum complex is only 0.07 km^3 compared with an irrigation demand of 14 km^3. The evaporation from Roseires, Sennar and Khashm el Girba reservoirs is 0.5 km^3. These reservoirs are used primarily for irrigation but also for hydroelectric power.

On the Blue Nile the Sennar dam was built in 1925 to provide water to the Gezira and has a current capacity of about 0.5 km^3. The Roseires dam was completed in 1966 to provide further water for irrigation and from 1973 also provided hydroelectric power (capacity now 275 MW). After significant siltation of the dead storage in the early years of operation, the storage volume has largely stabilized at some 2.4 km^3. The problem of operating these reservoirs is that the sediment load of the Blue Nile is high, especially on the rising flood. The storage capacity is relatively low, compared with the mean annual flow of 49 km^3. The sediment concentration at the flood peak is some 10 times that on the falling flood. The policy has been to draw down the reservoirs during the rising flood season, which has a major impact on hydropower operation. Operating rules have been developed to optimize hydropower production in terms of water availability and irrigation demand. Similar problems arise in the case of the Khashm el Girba reservoir. This was constructed on the Atbara in 1960–1964 with an initial capacity of 1.3 km^3. This reservoir was designed to provide an alternative livelihood to those displaced from the Sudan reach of the Aswan reservoir; it has suffered from sediment problems and alternative sites are being investigated. The Roseires dam, on the other hand, is being raised to provide increased storage capacity.

The Jebel Aulia dam on the White Nile was constructed in 1934–1937 with a capacity of 3.5 km^3. It was built to store the flows of the White Nile for release to Egypt during the "timely season" when Blue Nile flows are low. Since the construction of the Aswan High Dam this role is no longer vital; on the other hand it is responsible for a significant evaporation loss. However, the development of irrigation along the White Nile has been facilitated by the higher levels of the reservoir, which also provide recession agriculture and grazing at some cost in evaporation.

Potential hydropower development along the relatively steep course of the main Nile between Khartoum and the Aswan reservoir has been investigated, with possible sites including Merowe (Knott & Hewett, 1994).

EGYPT

The history of water resources development in Egypt, and the change from basin to perennial irrigation, cannot be treated fully here, but has been discussed elsewhere (e.g. Said, 1993). A dam at Aswan was first completed in 1902 and heightened in 1912 and 1933. The reservoir capacities (1–5 km^3) were sufficient only for annual storage, to retain part of the main Nile flow, supplemented by Jebel Aulia storage, for release during the irrigation season.

Hurst *et al.* (1946) carried out research on the storage volume required to maintain a draft equal to or near the long-term mean flow. At that time the search for overyear storage was concentrated on the East African lakes and to a lesser extent on Lake Tana, where rainfall could reduce or eliminate the effect of reservoir evaporation. This basinwide planning involved the use of storage in Lakes Albert or Victoria to overcome flow variations of the Ethiopian tributaries. It necessarily led to the inclusion of a proposed Jonglei Canal to route the flows from the lakes through the Sudd, where the flows would otherwise have been much reduced. This so-called Equatorial Nile Project required the concentration of flows through the canal during periods when "timely flow" was required in Egypt and this meant the reversal of seasonal flows in the Sudd. The insistence of the Jonglei Investigation Team (1954) that this was unacceptable, and the move towards political independence of the countries of the White Nile basin, led towards the alternative solution of the Aswan High Dam. This has provided overyear storage and an assured supply of water during periods of drought on the Blue Nile, though the annual cost in increased evaporation has been estimated as about 10 km^3.

A series of barrages along the Nile below Aswan has been constructed over the years to facilitate the distribution of water for irrigation. Flows at these sites provide estimates of the water diverted along the course of the river. The construction of the Aswan High Dam by 1964 has made it possible to equalize the water available from year to year, and has allowed the water diverted above the Delta barrage to be increased over the years.

Irrigated agriculture could be increased further by improving the efficiency of existing irrigation. An alternative is increasing the available water by reducing the evaporation losses in the White Nile basin, mainly in the southern Sudan. The scope for agricultural improvement has been described as large (Stoner, 1994); increases in crop yields could be substantial while the choice of area for development, improvement in distribution systems, and drainage re-use could all contribute. As part of a project to improve water-use efficiency, a network of over 800 sites is at present being developed as part of a system of monitoring and telemetering water levels and flows along the Nile and distribution systems.

PROJECTS TO INCREASE RIVER FLOWS

The background to the various projects to increase the yield of the White Nile by reducing evaporation in the wetlands of the Bahr el Jebel, Bahr el Ghazal and Sobat basins has been described in Chapters 5, 6 and 7. These projects have been investigated over many years since the Jonglei Canal was first suggested in 1904. However, the project known as Jonglei I, which was two-thirds completed by 1983 before suspension, was quite different from the earlier project which was examined by the Jonglei Investigation Team (1954). The recent project was based on a canal to pass a steady flow of 20 $m^3 \times 10^6$ day^{-1} without control of the inflows. This project was estimated to increase White Nile flows by 4 km^3 $year^{-1}$, and its effect has been estimated to reduce the area of permanent swamp by 35% and the important area of seasonal swamp by 22% over the historic period 1905–1980. More importantly, the seasonal cycle of inundation would not have been affected. However, this effect would have been proportionally higher during the low flow period 1905–1961 than the high flow period 1961–1980. It would be possible to reduce the adverse effects of this project by varying the flow down the canal between seasons and thus alter the residual flow down the Bahr el Jebel. Initial estimates have suggested that amending the constant flow of 20 $m^3 \times 10^6$ day^{-1} to a flow of 25 $m^3 \times 10^6$ day^{-1} during November–April and 15 $m^3 \times 10^6$ day^{-1} during May–October would result in a decrease of only 11% in the seasonal swamp and a decrease of 38% in the permanent swamp. This would also have the advantage that the level range of seasonal flooding, due to the uncontrolled flows of the torrents above Mongalla, would be increased by this mode of operation. This would favour grassland rather than papyrus.

The scheme known as Jonglei II would include the use of storage in Lake Victoria or Lake Albert to regulate the flows of the Bahr el Jebel. Variations of inflows to the Sudd would be reduced and flows down the canal would be doubled to provide a capacity of $50\ m^3 \times 10^6\ day^{-1}$. The control of inflows to the Sudd would clearly have a major effect on the seasonal fluctuations of inundation. At present these provide the dry season grazing on which the pastoral economy depends. However, it is the torrents between Lake Albert and Mongalla which provide most of the seasonal inundation. Provided no attempt were made to store these virtually in Lake Albert, this seasonal pattern would continue. Alternatively, the operation of any Lake Albert reservoir might reproduce the present pattern of inundation. Further study of detailed proposals would be necessary.

Another project is known as the Bahr el Ghazal conservation scheme, but details do not appear to have been formulated. The inflows of the Bahr el Ghazal tributaries are highly seasonal and average about 11 km^3. Three other tributaries contribute 2.6 km^3 towards the Bahr el Jebel. The flows are spilled into the flood plains and evaporation accounts for virtually all the inflow. The proposals include storage on the tributaries, for example on the Jur and Busseri above Wau (*The Nile Basin*, vol. XI, pp. 66–89). It would be necessary to construct canals to divert the stored water to the Bahr el Jebel for transmission by the Jonglei Canal or directly to the White Nile. The upper reaches of the Bahr el Ghazal flood plains provide grazing to the inhabitants of the area, as illustrated by Maps A and B of the Southern Development Investigation Team report (1955). The effect of storage and diversion of the tributary flows would clearly affect the vegetation of the flood plains. There would presumably be scope to pass sufficient of the flood flows to provide seasonal inundation and grazing at the expense of permanent swamp. Ecological input to the planning of these projects is essential.

The high flows of the Baro and other Sobat tributaries are spilled into adjacent wetlands and towards the Machar marshes. The losses have not been estimated with precision, as the area has not been investigated in detail because of access problems. Schemes to reduce these losses have only been planned in general terms. Alternative proposals have included a storage reservoir on the Baro, and a channel to carry excess flows from the Baro through the Machar marshes. However, any developments would need collaboration with Ethiopia, and there are also proposals for development of the Baro and other tributaries within Ethiopia itself.

Although the area of the lower Baro and adjacent tributaries was sparsely occupied by 50 000 Anuak up to 1984, the population had quadrupled by 1996. To support this increase, projects are being studied for a dam on the Mekoy (Woube, 1997) and for a dam at Gambeila (Said, 1993). It is doubtful that the construction of these dams for local irrigation would have sufficient capacity to prevent some continued losses to the Machar marshes. A larger dam on the Baro might both provide water for local irrigation and also control flows on the lower Baro sufficiently to reduce spilling and thus increase downstream contributions. It is possible that this area could provide a fruitful topic for collaborative investigation, leading to a project to benefit both upstream and downstream users.

CONCLUSION

This book has treated each major tributary or reach of the Nile as a separate entity, and has described its hydrological character. However, the unique feature of the Nile is that a number of disparate tributaries have, by geological accident, combined into one long river system. Thus the whole river has developed a complex joint character of its own.

The overall impression is of a persistent baseflow, reflecting the outflow from the Lake Victoria basin, but modified by other lake systems and wetlands as the river flows downstream. The influence of each reach is very different, depending on topography and local water balance; this is expressed by an increase or decrease in the baseflow, and the addition of seasonal variations.

The importance of seasonal variation changes dramatically below the Sudd, because the local inflow is then derived from the Ethiopian tributaries. These have limited rainfall seasons and steep upland catchments, and thus relatively fast response. In addition the rainfall season becomes shorter as one moves north, and consequently the runoff season becomes progressively shorter and the flow more seasonal in character.

The Nile waters are at present used mainly well below the sources of inflow. The cumulative effect of all these influences on the series of annual flows and their seasonal distribution has been the source of hydrological interest in the Nile over many centuries and will remain so.

It is promising to note that the series of Nile 2002 conferences being held annually are leading to an atmosphere in which information is being shared, and it is to be hoped that this will lead to collaborative studies throughout the Nile basin. This has already been achieved between Egypt and Sudan through the PJTC, and in the East African basin through the Hydrometeorological Survey and Tecconile. It could be argued that local studies would be practicable, dealing for example with the Baro basin and the conveyance losses, or the possible role of Lake Albert in reconciling the hydroelectric benefits of equalizing the flows of the Nile below Lake Victoria with the concerns of downstream countries.

It is now over 40 years since H. A. W. Morrice, as Irrigation Adviser to the Republic of the Sudan, prepared a Nile Valley Plan (Morrice, 1956, with tables published by the Ministry of Irrigation and Hydroelectric Power). This considered the role which reservoirs in Lake Victoria and Lake Albert, together with a Jonglei Canal designed to pass much of the lake outflow past the Sudd, could play in increasing the water available for irrigation. Reservoirs on Lake Tana and on the Baro near Gambeila were included in the modelling, and the hydroelectric potential of the Ethiopian tributaries, and the irrigation requirements of East Africa, were acknowledged but not quantified. The transmission losses in the Sudd, and the flow requirements of the area, as expressed by the Jonglei Investigation Team (1954), were included. An account of this first modelling exercise was published by IAHS (Morrice, 1957) under the title "The use of electronic computing machines to plan the Nile Valley as a whole". The modelling was based on flow records from 1905 to 1952, but the dramatic changes which have occurred in the subsequent period make it desirable to make another trial with longer records and wider objectives.