

The Climate and Hydrology of the Upper Blue Nile River

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The Upper Blue Nile river basin is the largest in Ethiopia in terms of volume of discharge, second largest in terms of area, and contributes over 50 per cent of the long-term river flow of the Main Nile. This paper provides a review of the nature and variability of the climate and hydrology in the source region of the Blue Nile – the central Ethiopian Highlands. Annual rainfall over the basin decreases from the south-west (>2000 mm) to the north-east (around 1000 mm), with about 70 per cent occurring between June and September. A basin-wide time series of annual rainfall constructed from 11 gauges for the period 1900 to 1998 has a mean of 1421 millimetres, minimum in 1913 (1148 mm) and maximum in 1903 (1757 mm). Rainfall over the basin showed a marked decrease between the mid-1960s and the late 1980s and dry years show a degree of association with low values of the Southern Oscillation Index (SOI). The October to February dry season in 1997/98 was the wettest on record and responsible for widespread flooding across Ethiopia and also parts of Somalia and Kenya. Available river flow records, which are sparse and of limited duration, are presented for the Blue Nile and its tributaries upstream of the border with Sudan. Runoff over the basin amounts to 45.9 cubic kilometres (equivalent to 1456 m³s⁻¹) discharge, or 261 millimetre depth (1961–1990), a runoff ratio of 18 per cent. Between 1900 and 1997 annual river flow has ranged from 20.6 cubic kilometres (1913) to 79.0 cubic kilometres (1909), and the lowest decade-mean flow was 37.9 cubic kilometres from 1978 to 1987. Annual river flow, like rainfall, shows a strong association with the SOI.

KEY WORDS: Ethiopia, Blue Nile, climate, hydrology, water resources.

The Upper Blue Nile basin is the largest river basin in terms of volume of discharge and second largest in terms of area in Ethiopia and is the largest tributary of the Main Nile. It comprises 17 per cent of the area of Ethiopia (176 000 km² out of 1 100 000 km²), where it is known as the Abay, and has a mean annual discharge of 48.5 cubic kilometres (1912–1997; 1536 m³s⁻¹). In spite of this, the Blue Nile within Ethiopia has been the subject of very few studies, is poorly documented in the published literature, and has a very low level of water resources development, so much so that, within the context of the Nile Basin, it has been described as ‘the great unknown’ (Waterbury, 1988: 77). This is in part a reflection of the national level of development in Ethiopia as a whole, but also in part the result of the basin’s remoteness, low population density, mountainous topography and its international significance – which has created a reluctance on the behalf of the Ethiopian authorities to release information about the hydrology of the river. Water resources

development in Ethiopia to date has been mainly concentrated in the more densely populated and flatter areas in the Awash river basin and Ethiopian Rift Valley lakes located along the southern and eastern margins of the Blue Nile basin (Fig. 1).

The basin drains a large portion of the central and south-western Ethiopian Highlands. The river has cut a deep and circuitous course through the central Ethiopian Highlands and in some places its gorge is one kilometre deep. Its course flows 900 kilometres from Lake Tana until it leaves Ethiopia and crosses into the vast plains of Sudan. There is only one significant waterfall, at Tis Isat, roughly 25 kilometres from Lake Tana where the river drops 50 metres into the Blue Nile gorge. Much of the highland plateau is above 1500 metres and consists of rolling ridges and flat grassland meadows with meandering streams that waterfall over vertical sides of canyons. The river basin is composed mainly of volcanic and Pre-Cambrian basement rocks with small areas of sedimentary rocks. The soils generally consist of latosols

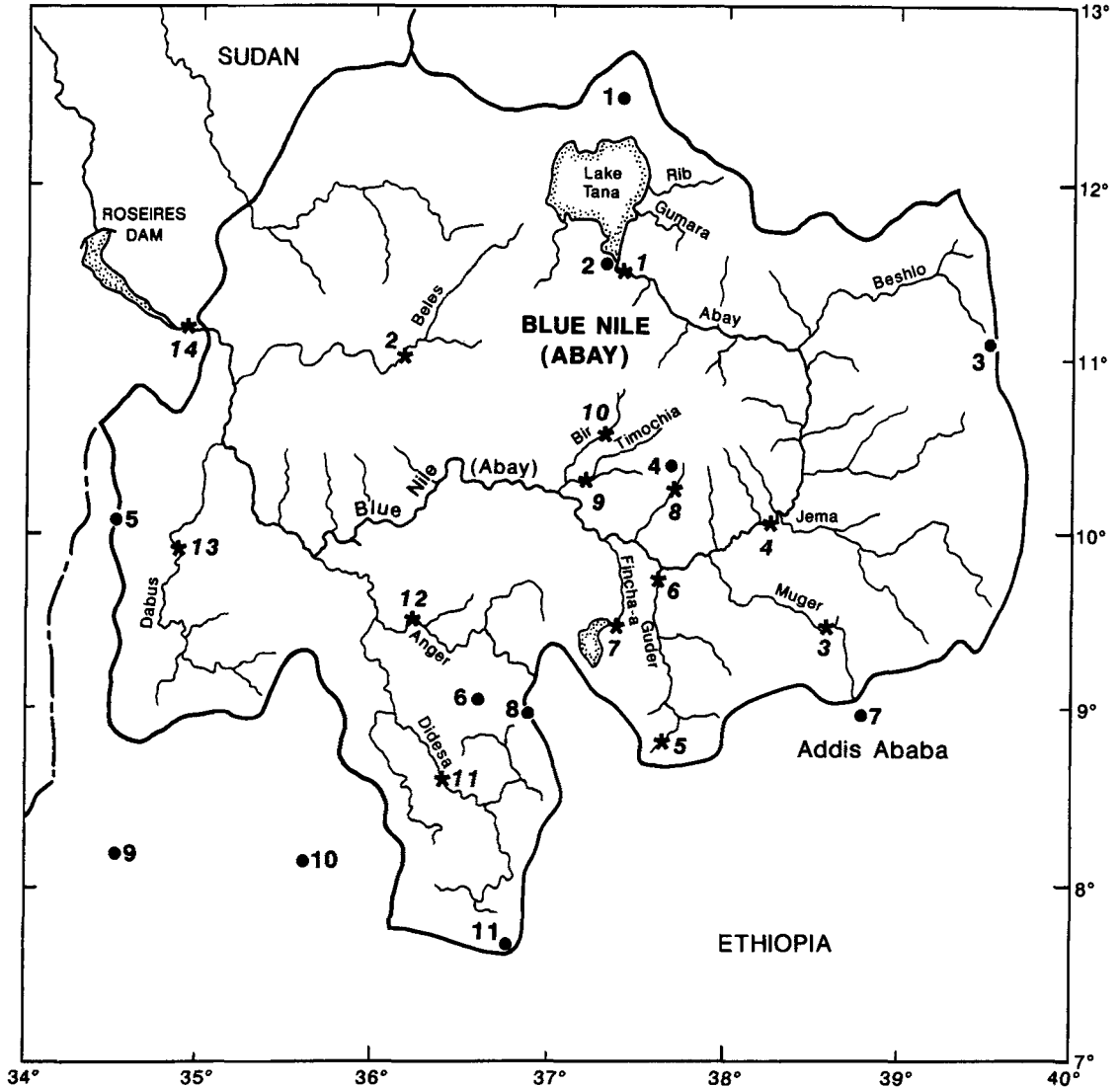


Figure 1 The Upper Blue Nile and location of rain gauges (•) and river gauges (*) used in this study (see Tables 1 and 2 for rain gauge and river gauge keys, respectively)

on gentle slopes and deep vertisols in flatter areas subject to waterlogging.

Ethiopia enjoyed a period of political stability and above average agricultural production and economic growth between 1991 and 1998 after nearly two decades of military conflict, intermittent drought and associated famine during the 1970s and 1980s. During this recent period, the Government commissioned Development Master Plans for most of the major river basins in the country and the Master Plan for the Blue Nile, undertaken by a French consultancy, was due to be completed in 1997 (Anon., 1997). This will update the one and only major study of the Blue Nile in Ethiopia which was undertaken

by the US Bureau of Reclamation between 1958 and 1963 and published in seven volumes (USBR, 1964a–c). It is possible, therefore, that in the near future various water resource projects will be proposed and implemented within the Ethiopian part of the basin (Conway, 1998). The aim of this paper is to present a timely assessment of the climate and hydrology of this important river basin based on the limited amount of data that is currently available.

Climate

Williams and Faure (1980) and Williams and Adamson (1981) edited two major books on

Quaternary environments in the Nile region. Both volumes concentrate on work undertaken in Sudan and Egypt, although there is some work dealing specifically with conditions in the Ethiopian highlands (Messerli and Winiger, 1980). Most other studies of past climates in Ethiopia concern palaeo and historical fluctuations in levels of Ethiopian Rift Valley Lakes such as Gillespie *et al.* (1983) and Street-Perrott (1982). Conway *et al.* (1998) assessed the potential for dendroclimatological research in Ethiopia and identified two tree species with cyclical growth rings from 18 tree species sampled in and around the Blue Nile basin. Nearly all the samples, however, contained areas with unclear ring boundaries and false rings. Attempts to match up cores from the same tree were only successful in one or two cases and it was not possible to achieve the same degree of unequivocal cross-matching between different trees as is routinely possible in other (non-African) regions.

For the instrumental period there are very few long duration rainfall series available in the region and even fewer temperature series. The longest rainfall series is for Addis Ababa (from 1898 onwards) and two gauges (Gore and Gambela) have records extending back to the 1900s. Most series, however, begin during the 1950s and 1960s when the Ethiopian National Meteorological Services Agency (NMSA) was first established. It is highly likely that many of the longer records have been subject to changes in location and instrumentation which is definitely the case with Addis Ababa, but it has not been possible for this study to obtain detailed station histories. Rainfall data are used here from 11 gauges situated within or close to the basin with at least 25 years duration of record (Fig. 1). These incorporate records published by Fantoli (1965) and recent updates from the NMSA. There are even fewer long-duration temperature records available. Again, Addis Ababa is the longest, dating back to 1898, but records are missing between 1912 and 1945. For this paper only the long-term mean temperatures obtained either from the NMSA or from FAO (1984) are presented for a number of key stations.

Seasonal characteristics

The seasonal variation in temperature for six stations representative of the wide range of climatic conditions found within the basin is shown in Figure 2. There is little variation in temperature through the year, roughly between 3 and 6°C from the warmest month to the coolest months (between November and February). In summer, peak temperatures are reduced because rainfall, cloudy conditions and energy use for evapotranspiration rather than sensible heat occur when the highest temperatures would normally be expected (July and August). The hottest period is, therefore, March to May, before the onset of the major rains. This produces a smaller annual

range of temperature than might be expected and in some instances results in two cooler and warmer periods. The range in elevation within the basin (from roughly 500 to 4050m) has a major influence both on the climate and human activities. On average temperatures fall by 5.8°C for every 1000 metres increase in elevation (the lapse rate is greater in the Winter dry season from September to March whereas during the wet season from May to August it falls to roughly 5.3°C per 1000m). The traditional Ethiopian classification of climate is based on elevation and recognizes at least three zones:

- 1 the *Kolla* zone below 1800 metres with mean annual temperatures of 20–28°C;
- 2 the *Woina Dega* zone between 1800 and 2400 metres with mean annual temperatures of 16–20°C;
- 3 the *Dega* zone above 2400 metres with mean annual temperatures of 6–16°C.

Most of the population inhabit the upper two zones which are cooler, healthier and more suitable for agriculture. Mean monthly Penman potential evapotranspiration (FAO, 1984) for the six sites (Fig. 2) varies by only 50 millimetres between its lowest values in July and August and its highest values in April or May. The differences are driven by seasonal variations not only in temperature, but also in radiation, humidity and windspeed.

The causes and characteristics of rainfall in Ethiopia have been described by Griffiths (1972) and Gamachu (1977). Rainfall is influenced by three mechanisms:

- 1 the Summer monsoon (Inter-tropical Convergence Zone, ITCZ);
- 2 tropical upper easterlies; and
- 3 local convergence in the Red Sea coastal region.

During the Winter dry season (traditionally known as *Bega*) the ITCZ lies south of Ethiopia and rainfall occurs only along the Red Sea coast. The Blue Nile region, north-west of the Rift Valley, is affected by north-east continental air controlled by a large Egyptian zone of high pressure. This cool airstream from the desert produces the dry season. From March, the ITCZ returns bringing rain to the southern, central and eastern parts of the country, particularly the high ground in south-western Ethiopia. This short period of rainfall is known as the *Belg* or 'small rains'. In May, the Egyptian High strengthens and checks the northward movement of the ITCZ producing a short dry season before the main wet season, the *Kremt*. Around June, the ITCZ moves further north and the south-west air stream extends over all high ground in Ethiopia to produce the main rainy season, lasting until the north-easterly continental airstream is re-established in Autumn.

The various causes of rainfall in Ethiopia lead to a

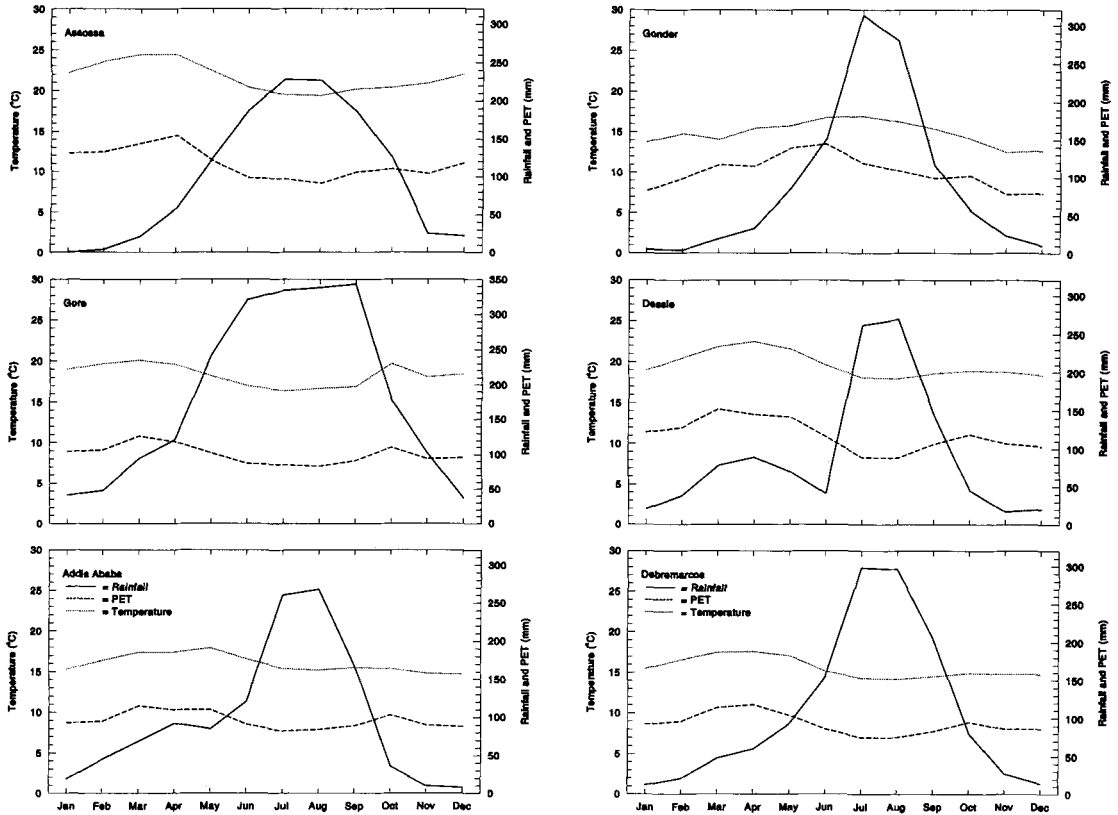


Figure 2 Annual variation in temperature (dotted line), potential evapotranspiration (dashed line) and rainfall (solid line) at six sites in the Upper Blue Nile

wide range in seasonal rainfall distribution (Fig. 2). The Summer months account for a large proportion of mean annual rainfall; roughly 70 per cent occurs between June and September and this proportion generally increases with latitude ranging from 60 per cent at Gore in the south-west, to 73 per cent at Debrebmarcos and 78 per cent at Gonder, north of Lake Tana (Fig. 2). Ethiopia is often divided into regions according to seasonal rainfall patterns and the distinctive characteristics of the three main regions are as follows:

- 1 an extended single wet season in the south-west (e.g. Gore);
- 2 a shorter single wet season further north (e.g. Gonder); and
- 3 a bi-modal pattern in the east with a short wet season in March–May preceding the main wet season (e.g. Dessie).

Interannual variability

Table 1 lists details of the 11 stations with long-duration rainfall records (>25 years) located within or close to the basin. Mean annual rainfall generally

decreases moving south-west to north-east and with decreasing elevation, and ranges from 1077 millimetres at Gonder in the north up to 2208 millimetres at Gore in the south-west. Interannual variability is not particularly high, with the coefficient of variation of annual rainfall in most parts of the basin being generally less than 20 per cent. A basin-wide rainfall series has been constructed as the average of all 11 gauges using the mean of the percentage departures from each station's 1961–1990 mean to take the series back to 1900 because only Addis Ababa extends back to this date, as described in Jones and Conway (1997).

Figure 3a–d shows the annual, March to May, June to September, and October to February rainfall totals, respectively. The station coverage is heavily biased to the southern and south-western parts of the basin (Addis Ababa, Gambela and Gore) until the mid-1950s when more central and northerly located stations start to contribute to the series (Fig. 3e). Notable dry years (<1200mm) were 1902, 1912, 1913 (driest on record, 1148 mm), and 1984 and wet years (>1700mm) were 1903 (wettest on record, 1917, 1947, 1961 and 1964. A slight increasing trend occurred between 1900 and 1964

Table 1. Characteristics of key rain gauge series within or close to the Blue Nile basin with long duration records, a basin-wide (11 gauge) series and Blue Nile river flow

Rain gauge	Lat. (°N)	Long.(°E)	Elev. (m)	Period of record	MAR. 1961–1990 (mm) ⁴	CV % 1961–1990 ⁴	Correlation with time ¹	Correlation with SOI ¹	Correlation with Blue Nile ²
1 Gonder	12.50	37.40	1966	1952–98	1077	19	-0.45	0.41	0.62
2 Bahar Dar	11.60	37.42	1805	1961–98	1460	18	-0.39	0.62	0.45
3 Dessie	11.08	39.67	2460	1962–98	1129	17	0.05	0.14	0.56
4 Debremarcos	10.33	37.67	2440	1954–98	1308	11	-0.21	0.24	0.59
5 Assossa	10.07	34.52	1540	1961–86	1193	21	-0.68	0.30	0.46
6 Nekemte	9.08	36.45	1950	1964–98	2095	13	-0.29	0.38	0.63
7 Addis Ababa	9.03	38.75	2324	1898–98	1186	12	-0.01	-0.13	0.24
8 Sibiu Sire	9.00	36.90	1750	1954–91	1337	14	-0.57	0.10	0.66
9 Gambela	8.25	34.58	450	1905–93	1207	27	-0.17	0.33	0.69
10 Gore	8.15	35.53	1974	1908–98	2208	22	0.05	0.07	0.22
11 Jimma	7.67	36.82	1577	1952–98	1461	11	0.06	-0.02	0.26
Basin-wide series	-	-	-	1900–98	1421	11	-0.04	0.35	0.73
							(-0.65) ³	(0.45) ³	(0.80) ³
Blue Nile discharge	11.23	34.98	467	1912–97	261	21	-0.16	0.43	-
					(45.89 km ³)		(-0.46) ³	(0.55) ³	-

Notes: 1=Calculated over whole length of record

2=Calculated from 1912 or start of record to 1997

3=Calculated from 1961 to 1990

4=1961–1990 or start of record to 1990 where records begin post-1961

MAR=Mean annual rainfall

CV = Coefficient of variation in %

Gauge numbers refer to locations in Figure 1

followed by a prolonged decline which reached its nadir in 1984. Since then totals have steadily increased, with 1996 the wettest year since 1964 (33 years) and 1997 and 1998 the second and third wettest in 30 years, respectively. The changes in the annual series have been dominated by variations in June to September rainfall, and in contrast, the decadal variability in March to May seasonal totals has been very low. Since 1990, however, March to May rainfall has increased substantially with 1996 the third wettest on record. Shanko and Camberlain (1998) found that years with consecutive occurrence of several tropical depressions over the south-west Indian Ocean coincided with drought years in Ethiopia. In their analysis, March to May rainfall was much more influenced by cyclonic activity than June to September rainfall, and on interannual time-scales an increased (reduced) frequency of tropical depressions during November to January tended to be followed by unusually low (high) March to May rainfall. The October to February dry season in 1997/98 was the wettest on record (>400mm) owing to unseasonally high rainfall particularly in October and November, responsible for widespread flooding across Ethiopia and also parts of Somalia and Kenya. This event was associated with a widespread warming across the western equatorial Indian Ocean with persistent anomalous low and mid-tropospheric easterly flow leading to the advection of anomalously moist and highly unstable air over the Indian Ocean into East Africa. The event is described in more detail

by Birkett *et al.*, (1999), Kousky *et al.* (1998) and Webster *et al.* (1999). Using satellite altimetry data, Birkett *et al.* (1999) have identified large increases in lake levels across East Africa as a result of the heavy rainfall, for instance Lake Victoria has risen by ~1.7 metres, Lake Tanganyika by ~2.1 metres and Lake Malawi by ~1.8 metres. Such hydrological impacts are similar in magnitude to those which occurred after a previous heavy rainfall event that occurred over East Africa in 1961.

All gauges show strong correlations between annual rainfall and Blue Nile flow except three gauges located to the south and south-west (Addis Ababa, Jimma and Gore) and the basin-wide series is very strongly correlated (q.v. Figs 3a and 6a). Annual rainfall at the two most northerly gauges (Gonder and Bahar Dar) has fallen over their period of record (from 1952 and 1961 to 1998, respectively), whilst the whole basin-wide rainfall series shows no overall change. Two gauges (Assossa and Sibiu Sire) show much stronger declining trends primarily because their records end in 1986 and 1991 and so do not incorporate the higher rainfall amounts seen during the late 1980s and through the 1990s (over the period 1961–1990 the basin-wide series also showed a strong negative correlation with time, $r = -0.65$).

Yilma Seleshi and Demareé (1995) found significant negative correlations between monthly Darwin sea-level pressure (a component of the Southern Oscillation Index, SOI) and regional rainfall series

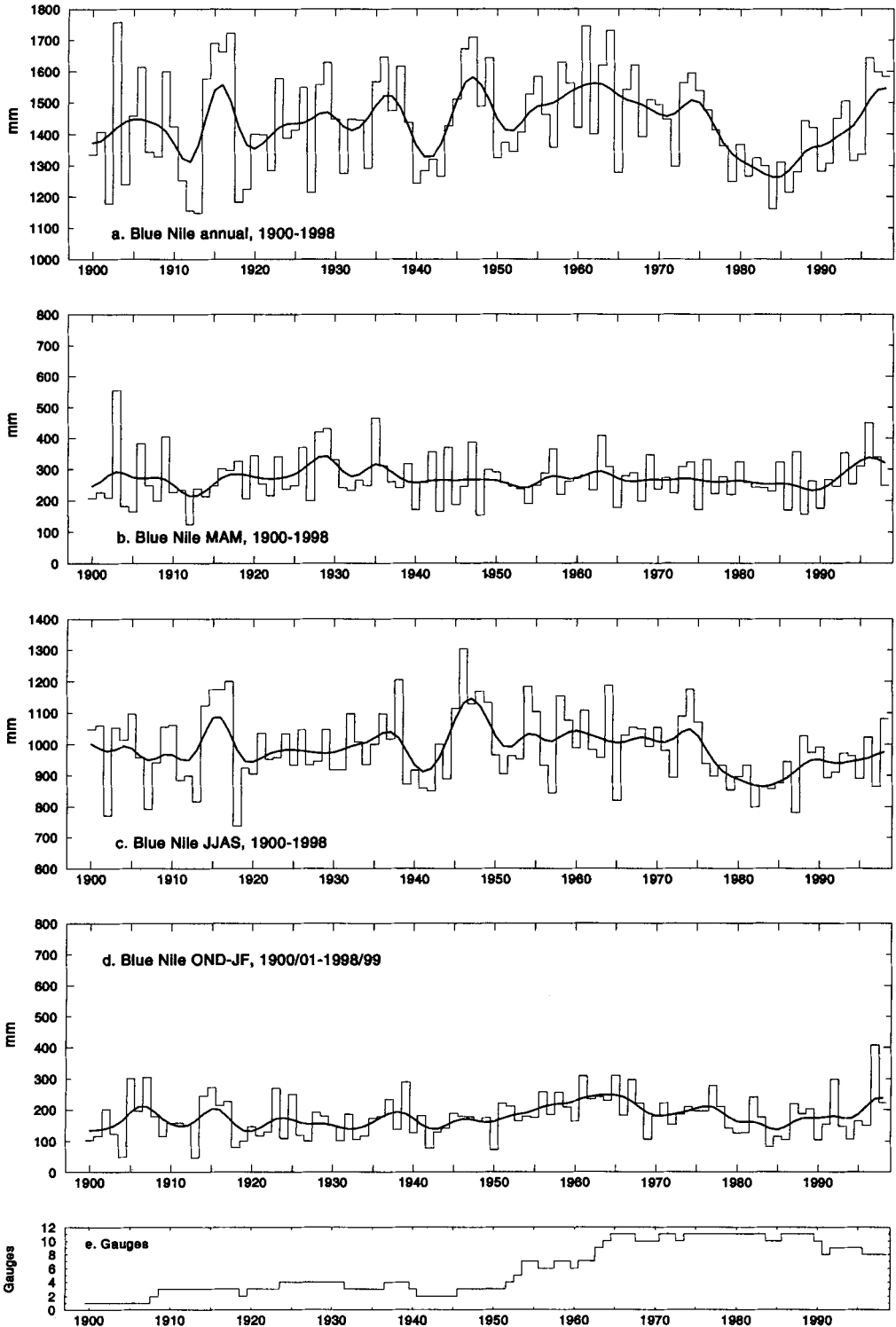


Figure 3a-d Time series of rainfall averaged over the Upper Blue Nile, 1900-1998. a) Annual b) March to May *Belg* season c) June to September *Krempf* season d) October to February *Bega* season (1900/01-1998/99) e) Number of gauges with data contributing to the series. The smooth curves were obtained using a 10-year Gaussian filter

for North Central Ethiopia (in June, September and March, positive correlation). Table I lists the annual correlation coefficients between the SOI and annual rainfall totals. There are strong positive correlations for the basin-wide series and five of the 11 individual rain gauge series. There appears to be a weak spatial pattern in the relationship with the SOI. The more easterly and southerly stations, in particular those close to the rift valley (Jimma, Gore and Addis Ababa) and along the eastern escarpment (Dessie) show much weaker association with the SOI. This may reflect differences in circulation and influences from the Atlantic and Indian Oceans. The western, central and northern highlands are more affected by south-westerly flow advecting moisture from the Congo Basin, while the Ethiopian Rift Valley and Eastern Escarpment are more affected by southerly flow in the Somali Jet advecting moisture from the Indian Ocean (unfortunately there are no radiosonde or air balloon data available for the Ethiopian Highlands to explore these upper air characteristics in more detail). Camberlain (1995; 1997) has investigated the nature of rainfall anomalies in the region and their association with the SOI and in particular with the Indian Summer Monsoon. He found a strong association between Summer (July–September) rainfall variations in East Africa (including the Blue Nile region) and India and an even stronger association with Bombay pressure. Negative pressure anomalies over Bombay were associated with increased rainfall over East Africa. This relationship is stronger than, more stable over time and independent of, the relationship with the SOI. Camberlain (1997) concludes that active monsoon conditions enhance the west–east pressure gradient near the Equator and produce stronger westerly winds that advect moisture from the Congo Basin to Ethiopia and other parts of East Africa.

Hydrology

Although good quality long-duration records exist for the Blue Nile at a number of sites in Sudan (see for example, Shahin, 1985; Evans, 1990; Walsh *et al.*, 1994; and Sutcliffe and Parks, 1999), there is very little published hydrologic data for the Blue Nile and its tributaries in Ethiopia upstream of the El Deim gauge (just upstream of Roseires, Fig. 1). River flow data are limited because of the remoteness of many of the catchments, the lack of economic resources and infrastructure to build and maintain monitoring sites, and the concentration of urban development and population south and east of the Blue Nile basin and, consequently, less need for data on the Blue Nile itself. Longer duration river flow series than the ones presented here are held by the Ministry of Water Resources in Ethiopia, but these are currently unavailable.

Volume IV of *The Nile Basin* contains Lake Tana levels and outflows from August 1920 through

February 1926 and from January 1928 through December 1933 which are the earliest records for the Blue Nile in Ethiopia (Hurst and Phillips, 1933). According to USBR (1964b) a staff gauge was installed on the Blue Nile near Kese during the 1935–1941 Italian occupation, but no records were available for that period. A new staff gauge was installed at this site in July 1953 and runoff records are available from July 1953 to September 1954. There is a gap in the records until 1956, when a recorder was installed, but from January 1956 until 1992 and probably up to the present time (but unavailable), the record is almost complete (1969, 1970 and 1991 missing, Fig. 6b). A concerted programme of river flow data collection was first initiated in Ethiopia in 1956 with the establishment of the Water Resources Department (Abate, 1994). Between 1958 and 1963 a total of 59 gauging stations were established, including 14 stations with both automatic stage recorders and cableways, and ranging down to simple staff gauges read visually. At the non-automated sites measurements were taken at least once a month during the dry season and more often during the wet season. The records collected at the time were considered to be fair to good in terms of quality. The daily flows up to 1962 were published in the 1961 and 1962 Abbay Basin Hydrologic Summary (USBR, 1964b). According to Admasu Gebeyehu (1996) a total of 102 gauges have been installed on tributaries in the basin at some time, but he estimates that at least 25 per cent of the gauging network has now been abandoned or is non-operational.

Table 2 lists the characteristics of runoff for tributaries with available data and annual discharge of at least 0.18 cubic kilometres (Fig. 1 shows the location of some of the river gauges). Four sources of data were used. The main source is the USBR (1964b) report which contains monthly river flow data recorded between late 1959 and early 1963. For most gauges, however, this report only contains data for at most one or two years. Short series of runoff data were also obtained from Gamachu (1977), the Global Runoff Data Centre (GRDC, Germany), along with Lake Tana outflows between 1921 and 1933 (Hurst and Phillips, 1933; the outflows were later updated in Hurst *et al.*, 1953). The quality of all these data is unknown, although cross-referencing allows limited verification. For instance, the GRDC records for Lake Tana between 1974 and 1975 appeared to be much too high when compared with other periods and are not used here.

Seasonal characteristics

The seasonal distribution of runoff varies considerably owing to differences in the seasonality of rainfall and catchment physiography. Figure 4 shows the monthly runoff patterns for eight tributaries. The smaller rivers have more rapid 'flashy' responses

Table 2. Characteristics of the river gauge series for tributaries of the Blue Nile with annual discharge over 0.18 km³

	Lat. (°N)	Long. (°E)	Gauged area (km ²)	Discharge (km ³)*	Period of record	Source	Runoff depth (mm)**	Contrib. to Blue Nile (%)*	Area of basin (%)	
1 Lake Tana	11.60	37.42	16 750	3.85	1921–33	Hurst	230	–	–	
	–	–	15 240	5.06	1961–62	USBRb	332	8.2	8.7	
	–	–	–	3.40	1969–73	GRDC	223	–	–	
	–	–	–	12.80	1974–75	GRDC	837	–	–	
2 Beles	11.20	36.33	3520	1.10	1962	USBRb	313	1.7	2.0	
	–	–	3520	1.14	1965–67	Gamachu	322	–	2.0	
Andassa	11.50	37.48	660	0.25	1960–62	USBRb	377	–	0.4	
3 Muger	9.30	38.73	606	0.18	1959–62	USBRb	297	0.4	0.3	
4 Blue Nile (at Kесе)	10.07	38.20	65 000	18.58	1956–62	USBRb	286	29.1	36.9	
	–	–	–	13.72	1963–92	GRDC	211	–	–	
5 Guder (upstream)	8.67	37.35	499	0.46	1961	USBRb	881	0.7	0.3	
	–	–	–	0.18	1978–80	GRDC	360	–	–	
6 Guder	9.90	37.82	6690	2.12	1961/62	USBRb	316	3.3	3.8	
7 Finchaa	9.67	37.35	1390	0.46	1960–62	USBRb	330	0.8	0.8	
8 Chemoga	10.30	37.77	320	0.22	1961–62	USBRb	687	0.4	0.2	
	–	–	320	0.18	1965–69	Gamachu	560	–	0.2	
Jedeb	10.40	37.57	250	0.28	1960–62	USBRb	1120	0.6	0.1	
9 Timochia	10.53	37.50	350	0.45	1961–62	USBRb	1291	0.9	0.2	
	Fettam	10.85	37.02	200	0.35	1960–62	USBRb	1750	0.5	0.1
	Kechem	10.63	37.42	183	0.20	1961	USBRb	1092	0.3	0.1
10 Birr	10.65	37.38	813	0.54	1960–62	USBRb	665	0.9	0.5	
	Dura	10.98	36.48	550	0.82	1961–62	USBRb	1490	1.5	0.3
	Lah	10.68	37.27	273	0.21	1960–62	USBRb	769	0.3	0.2
	Gudla	10.55	37.50	360	0.29	1960–62	USBRb	806	0.5	0.2
11 Didessa	8.68	36.41	9486	6.86	1961	USBRb	723	10.7	5.4	
12 Angar	9.43	36.51	4350	3.36	1961	USBRb	772	5.3	2.5	
	–	–	4349	2.06	1965–69	Gamachu	473	–	2.5	
13 Dabus	9.87	34.90	10 100	4.67	1961/62	USBRb	462	7.3	5.7	
14 Blue Nile Roseires +El Deim	11.23	34.98	176 000	48.60	1912–97	Hurst	276	100	100	
						World Bank				

Notes: Hurst=Hurst and Phillips (1933) and Hurst *et al.* (1953)

USBRb=USBR (1964b)

Gamachu=Gamachu (1977)

World Bank=World Bank (1989)

* represent 1961 values, ** represent average of whole period of record

1 km³=1 milliard=10⁹ m³=31.7 m³s⁻¹

Gauge numbers refer to locations in Figure 1

with less baseflow and many dry out after the wet season (e.g. Birr). The rivers in the south and south-west region tend to have longer flood periods and larger dry season flows (e.g. Angar, Didessa). Peak flows usually occur in August, one month after the rainfall maximum. These runoff patterns reflect the variation in rainfall distribution in the basin:

- longer wet seasons and flood periods and higher baseflow in the south-west; and
- shorter wet seasons and flood periods and lower baseflow in the north and north-east.

The Didessa is the largest tributary of the Blue Nile and has fairly high dry-season flows although it has no large expanses of swamps; dry season flows here probably result from lags within the large catchment (9486 km²), smaller headwater wetlands, groundwater contributions and the longer wet season in the

south-west. Three tributaries possess particularly distinctive seasonal regimes as a result of their physical characteristics:

- 1 Lake Tana: because of the lake's large storage capacity (surface area is roughly 3000 km²) and the restriction at its outlet, outflow from the lake peaks two months after maximum rainfall and one month after maximum flows at Roseires.
- 2 The Dabus river: located in the river's headwaters is an area of wetlands of approximately 900 square kilometres which has a considerable smoothing effect on the runoff distribution, as peak flows occur in September and flows remain quite high through to the following April.
- 3 The Finchaa river: located in the headwaters of the Finchaa river there is a small dam which impounds an area of 500–600 square kilometres which used to be an area of natural wetlands

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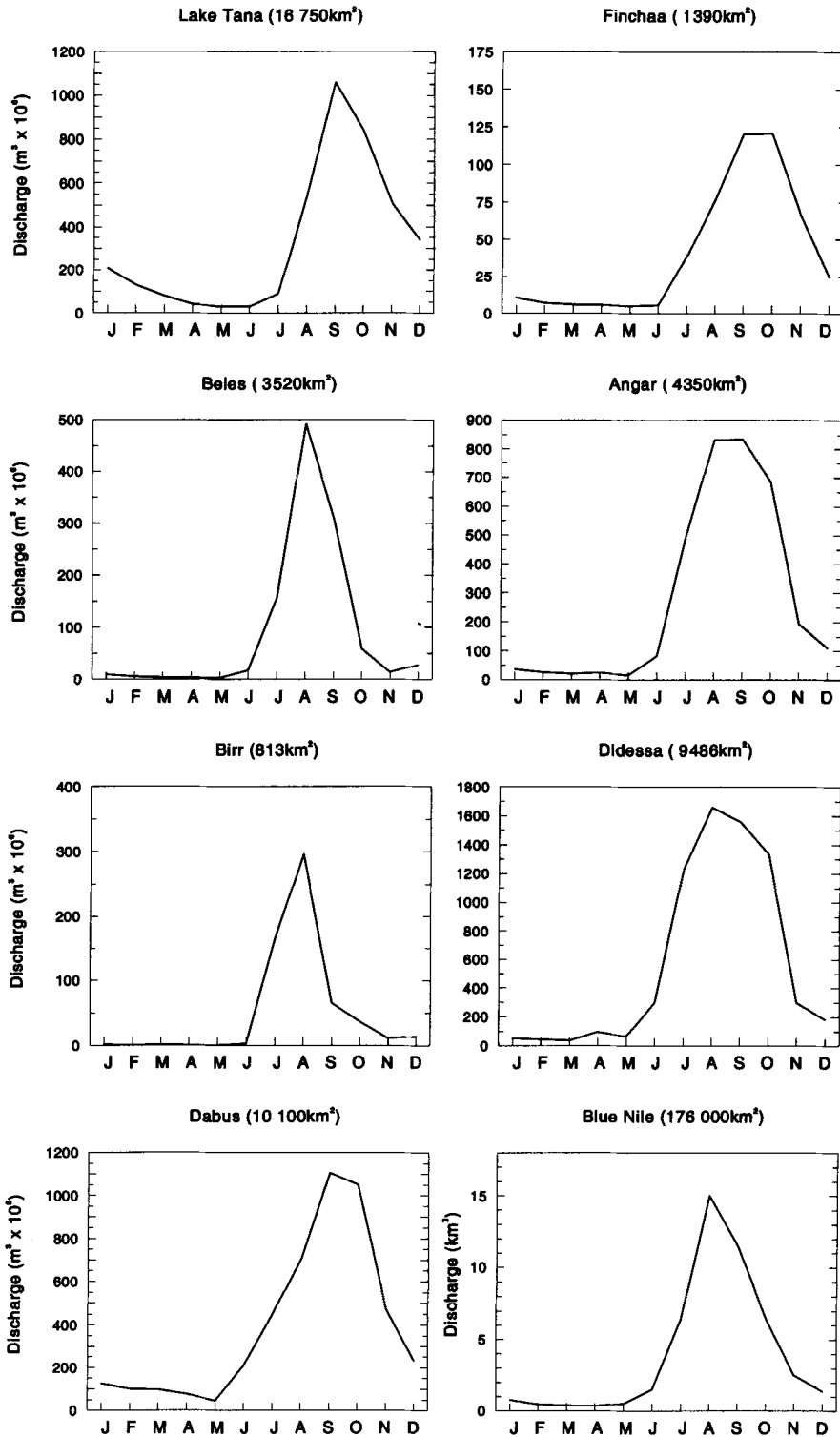


Figure 4 Annual variation in streamflow for eight catchments within the Upper Blue Nile. Values based on means for whole period of record, see Table 2. (Note different vertical scales)

known as the Chomen Swamps. Both features have a controlling effect in storing peak season water and releasing it in the following months.

The mean annual discharge for the period between 1961 and 1990 expressed as millimetre depth over the basin is 261 millimetres. Basin-wide mean annual rainfall for the same period was 1421 millimetres, so the long-term runoff ratio is 18 per cent. Runoff over the basin ranges considerably from 211 millimetres at Kese to over 1000 millimetres in some of the smaller catchments, although the very large runoff depths in Table 2 may result from measurement errors, particularly in the delineation of catchment areas. The second from last column in Table 2 shows the tributary runoffs in 1961 expressed as a percentage of the flow at Roseires in the same year (1961 was chosen as it was the year with data at the largest number of sites). These figures may be compared with each tributary's area expressed as a percentage of the total Blue Nile basin area (last column in Table 2) to highlight spatial differences in the amount of runoff produced across the basin. For instance in 1961, Lake Tana outflows made up 8.1 per cent of the total Blue Nile flow at Roseires and were generated from 8.7 per cent of the total catchment area. The area drained between Lake Tana and the gauge at Kese (see Fig. 1) produces fairly low runoff owing to its lower rainfall, so that 36.9 per cent of the catchment area contributes only 29.1 per cent of the total runoff. Further downstream, river flows from the Didessa and the Angar rivers which drain the wetter south-west region amount to roughly twice that expected given their catchment areas. The Dabus, downstream of the swamp outlet, also contributes a high proportion of runoff, even after losses to evaporation in the swamp areas.

Figure 5 shows, for 1961, the cumulative monthly river flows of some of the larger Blue Nile tributaries expressed as a percentage of the monthly flows at Roseires. This highlights the seasonal variation in the contributions of different tributaries to overall Blue Nile river flow. Lake Tana, the Finchaa river and the Dabus river contribute relatively little to the peak August flows of the Blue Nile and much higher proportions during the low-flow season given their catchment areas. Together these three tributaries make up 30–50 per cent of the overall Blue Nile river flow during the dry season (between November and April) from only 15.2 per cent of the total basin area. The more northern and smaller catchments tend to contribute mainly in the wet season (e.g. Beles and Birr). The Didessa also generates a large proportion of the runoff between February and July owing to the higher rainfall over the south-west of the basin. However, it should be noted that a significant and prolonged rainfall anomaly occurred in East Africa from October 1961 through to 1964 which also extended over the south-western area of the basin (particularly high annual rainfalls were

recorded at Gambela and Gore in 1961 [Figs 3a and d; Conway, 1997]) and for the whole basin it was the second wettest year and fifth wettest dry season on record. The Blue Nile annual flow at Roseires was high in 1961 (63.8 km³ compared to the long-term mean of 45.9 km³). It is, therefore, unlikely that many of the riverflow records contained in USBR are representative of the long-term mean conditions, and they may be biased to over-estimate river flows, particularly in the south-west of the basin.

Interannual variability

Figure 6a shows annual and 10-year Gaussian filtered Blue Nile river flow from 1900 to 1997, measured at Khartoum (1900–1933), Roseires (1912–1963) and El Deim (1964–1997). Comparison with the annual rainfall series shows close agreement ($r=0.73$), particularly between the filtered series. There is an increasing trend up to 1964 followed by a prolonged decline until 1984 since when flows have generally increased, but not to quite the same extent as the recovery in annual rainfall (Fig. 3a). High flow years (>65 km³) occurred in 1909 (highest, 79.1 km³), 1917, 1929, 1946, 1964 and 1988 and low flow years (<32 km³) in 1913 (lowest, 20.7 km³), 1972 and 1984. Fluctuations in Blue Nile flows have been the main cause of fluctuations in Main Nile discharge of up to ± 20 per cent which have had important consequences for water resource management in the downstream riparians Egypt and Sudan (Fig. 6c; Conway and Hulme, 1993; 1996). As a result of the recovery in Blue Nile flows, recent Main Nile flows have returned to nearer the long-term mean. The flood level of 1994 was higher than average and the High Aswan Dam (HAD) reservoir levels surpassed the level of 173 metres for the first time since 1978 (Anon, 1994). In 1996, the Blue Nile was extremely high and so was the Main Nile, so much so that for the first time since construction of the HAD, it was thought that the Toshka overspill canal would need to be used as reservoir storage levels reached their maximum point. Figure 6b shows annual series for the only two sites upstream of the border with Sudan with more than a couple of years of readings available; Lake Tana outflows and river flows at Kese. The records at both sites show good agreement with the downstream flows during their periods of overlap (Lake Tana, 1926 and 1927 missing, estimated by regression with Roseires, $r^2=0.57$; Kese 1969, 1970 and 1991 missing, estimated by regression with Roseires, $r^2=0.73$). Lake Tana outflows show low interannual variability and the river flows at Kese show much greater interannual variability and highlight the marked decline in flows that occurred from 1975 to 1984.

A number of studies have analysed the relationship between the El Niño-Southern Oscillation (ENSO) and Nile river flows. On the basis of an established relationship, Quinn (1992) used the

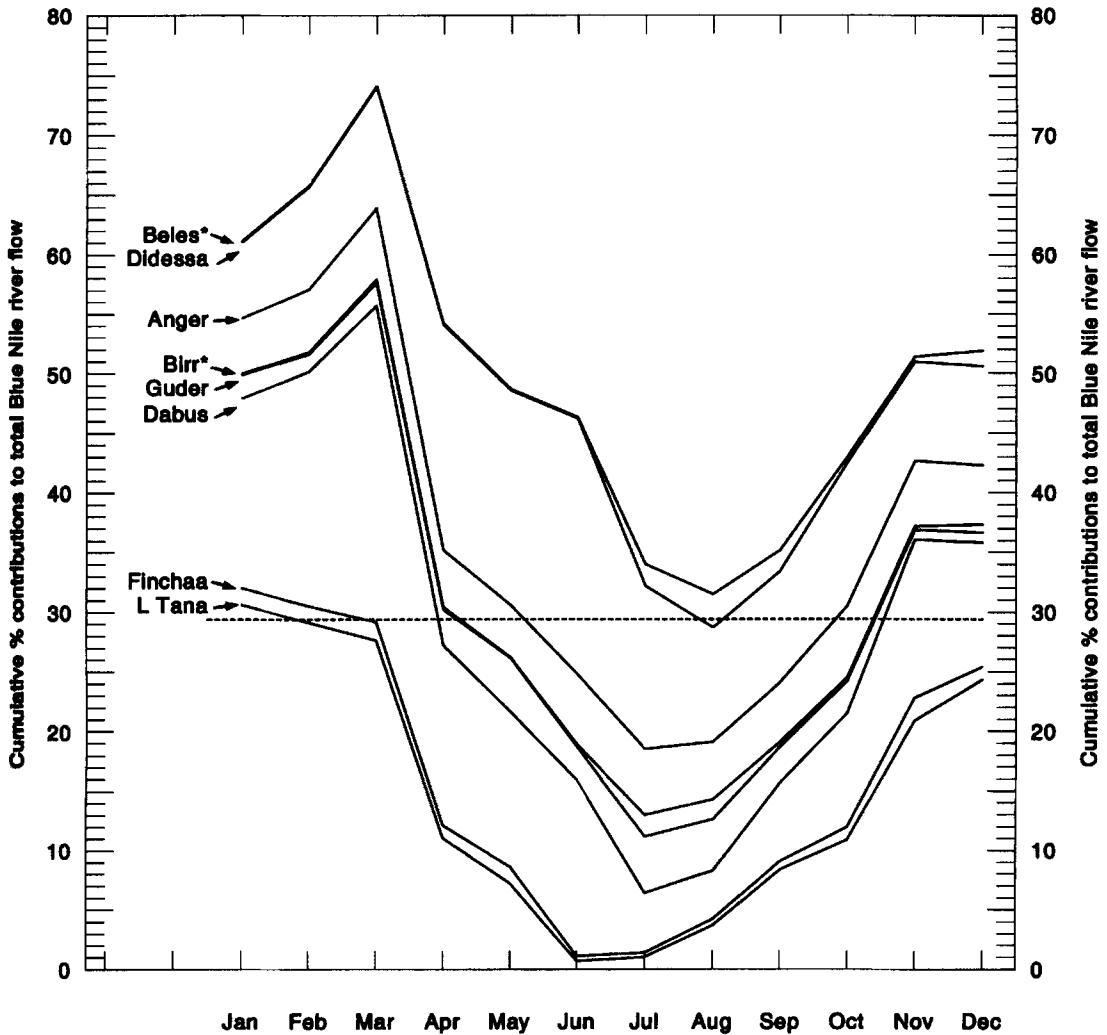


Figure 5 Cumulative percentage contributions from eight Blue Nile tributaries to overall Blue Nile discharge by month in 1961. The dashed line represents the percentage area of the Blue Nile covered by the eight tributaries (29.4 per cent). No allowance is made for transmission losses. *The contributions of the Birr and the Beles are negligible throughout the dry season and only become apparent from June onwards

long-duration series of annual maximum Nile flood levels from the Roda gauge (the famous Nilometer in Cairo) extending back to the early seventh century to reconstruct the record of low SOI behaviour (related to below normal flood levels at Cairo). When the SOI is positive, a large low pressure system extending over India and the Arabian Sea is well developed and Summer monsoon rainfall is likely to be heavy; when the SOI is negative, the large low pressure system is not well developed and/or is displaced to the east and the summer monsoon rainfall is likely to be low (Quinn, 1992). Whetton and Rutherford (1994) used the series back to 1587 to analyse changes in the relationship between ENSO and Nile flood levels over time. They found Nile floods were significantly lower than average in all El Niño years, but that the

strong relationship develops only after about 1830 and continues up to the 1980s. Eltahir (1996) obtained correlation coefficients of about 0.5 between Nile flows at Aswan and an ENSO index averaged over the months of September to November (1872 to 1972). There is a similar level of association between Blue Nile flows and the SOI during the period 1961–1990 and slightly weaker association over the whole record (Table 1).

Conclusions

The spatial and temporal characteristics of climate in the region of central Ethiopia that comprises the Upper Blue Nile basin have been presented. Rainfall is highly seasonal, with roughly 70 per cent of

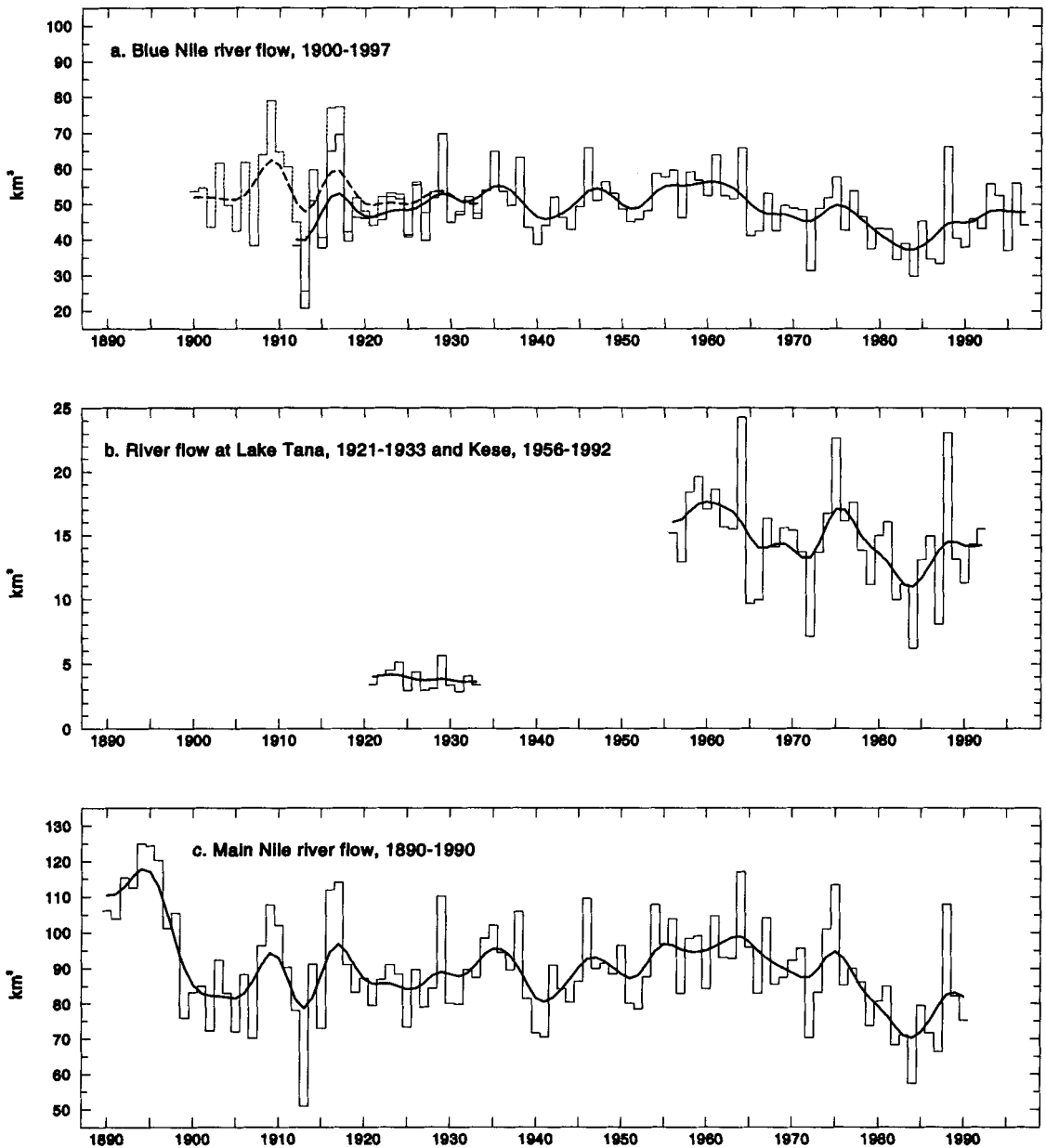


Figure 6 Time series of annual riverflow of **a)** Blue Nile, 1900–1933 Khartoum (dashed line), and 1912–1963 Roseires and 1964–1997 El Deim (both bold line) **b)** Lake Tana (1926 and 1927 missing, estimated by regression with Roseires, $r^2=0.57$) and Kese (1969, 1970 and 1991 missing, estimated by regression with Roseires, $r^2=0.73$) **c)** Main Nile at Dongola naturalized (upstream of the High Aswan Dam reservoir). The smooth curves were obtained using a 10-year Gaussian filter

annual rainfall occurring between June and September. Annual rainfall generally declines from over 2000 millimetres in the south-west to less than 1000 millimetres in the north-east, although the effects of the extremely mountainous topography, rain shadow effects and local moisture sources complicate this pattern. A 99-year basin-wide area aver-

age time series of rainfall (1900–1998) was constructed using records from 11 gauges each with over 25 years length of record (only three gauges have continuous records back to pre-1910 and these are likely to have experienced changes in location and site conditions). Basin-wide mean annual rainfall from 1961 to 1990 is 1421 millimetres and has

ranged from 1148 millimetres in 1913 to 1757 millimetres in 1903. The driest decade in the whole record is centred on 1984 and since then rainfall has increased gradually. The basin-wide series shows association with the SOI; this association is strongest in the central and northern parts of the basin, but is not present in the Ethiopian Rift Valley or along the Eastern Escarpment. There are inter-seasonal differences in interannual variability with rainfall during March to May showing less association with the SOI and little decadal-scale variability. Rainfall over the southern margins of the basin (along the Ethiopian Rift Valley) shows little association with rainfall over the Central Highlands nor with the SOI.

A review of the limited amount of hydrologic data available for the Upper Blue Nile highlights the strongly seasonal nature of runoff as a result of the rainfall regime, with many tributaries drying out in the dry season. During 1961 (the year with data at the largest number of sites) roughly 40 per cent of Blue Nile discharge originated from Lake Tana, the Finchaa Reservoir and Dabus wetlands during the dry season (November to April) owing to their storage effects. There is strong correlation between the basin-wide rainfall series and Blue Nile river flow. The river flow of the Blue Nile is, therefore, influenced by the same factors as rainfall over the region, namely association with the strength of the Indian Monsoon and the behaviour of the SOI. Attempts to understand past interannual variability in Blue Nile and hence Main Nile river flows should, therefore, consider these factors. Furthermore, attempts to produce seasonal forecasts for Nile river flows should concentrate upon predictor variables traditionally used for the Indian Monsoon (as suggested and used for rainfall over the region by Camberlain [1997]) and incorporate the Blue Nile association with the ENSO.

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