The Influence of Climate Change and Climatic Variability on the Hydrologic Regime and Water Resources (Proceedings of the Vancouver Symposium, August 1987). IAHS Publ. no. 168, 1987.

Historical variations in African water resources

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ABSTRACT The variability of African water resources is studied through historic flow records. Spatial variability is linked to rainfall distribution and areas of high runoff are limited in extent. Annual runoff is sensitive to rainfall variations and seven year moving averages on a number of rivers are presented and compared. The implications for water resources planning are discussed.

Variations historiques des ressources en eau en Afrique

RESUME La variabilité des ressources en eau en Afrique est étudiée à partir d'un historique des rélevés hydrométriques. La variabilité spatiale dépend de la distribution de la pluviométrie et les sources d'écoulements importants sont limitées en étendue. L'écoulement annuel est sensible aux variations de la pluviométrie, et les moyennes mobiles sur sept ans des débits moyens sont preséntées et comparées pour des fleuves divers. Les implications sur la gestion des ressources en eau sont discutées.

Introduction

A number of studies have dealt with recent and historical droughts in Africa (Farmer and Wigley, 1985), their meteorologic background and predictions of the future. Most of these studies have been based on rainfall records (Bunting et al, 1976), but use has also been made of river flows and lake records (Faure and Gac, 1981; Nicholson, 1980; Sircoulon, 1985; Beran and Rodier, 1985).

The aim of this paper is to concentrate on certain aspects of African water resources as a contribution to the wider study of hydrologic variations; it is based on historic river flow records.

A series of graphs linking average annual runoff with rainfall in different regions is compared with others showing interannual variations of runoff with rainfall. Runoff records provide a sensitive indicator of variations in rainfall. Historical variations in river flow show similar patterns over wide areas of Africa, when expressed as seven year moving averages. Even in terms of these averages, which could be related to the yield of over-year reservoirs, variations in river flow have been very wide and this should be taken into account when the water resources of an area are considered.

The medium term fluctuations of available water can only be smoothed out by large reservoirs and suitable sites may not always be available on the scale required. There is a case for accepting moving targets for irrigation or hydro-electric power production in these circumstances.

Spatial variability

Although the spatial variability of African water resources is well known, it is normally illustrated by means of annual isohyetal maps. These illustrate broadly the total available water and show, for example, rainfall decreasing from 2000 mm near the coast at Abidjan to 200 mm near Tombouctou some 1300 km to the north (Figure 1(a)).

If one considers water resources as equivalent to river flows which are available for storage and use in irrigation or hydroelectric power production, then the variability of average rainfall is only a first indication of the uneven distribution of water resources. Because runoff is the residual process in the hydrologic cycle, i.e. the difference between rainfall and evaporation, it is much more variable than rainfall itself, especially in Africa where potential evaporation is high.

This sensitivity is illustrated by the series of graphs in Figure 2, in which mean annual runoff is compared with rainfall for gauging stations on tributaries within a number of basins in different parts of Africa. These comparisons, taken from recent water resources studies, confirm that spatial variations in rainfall are amplified

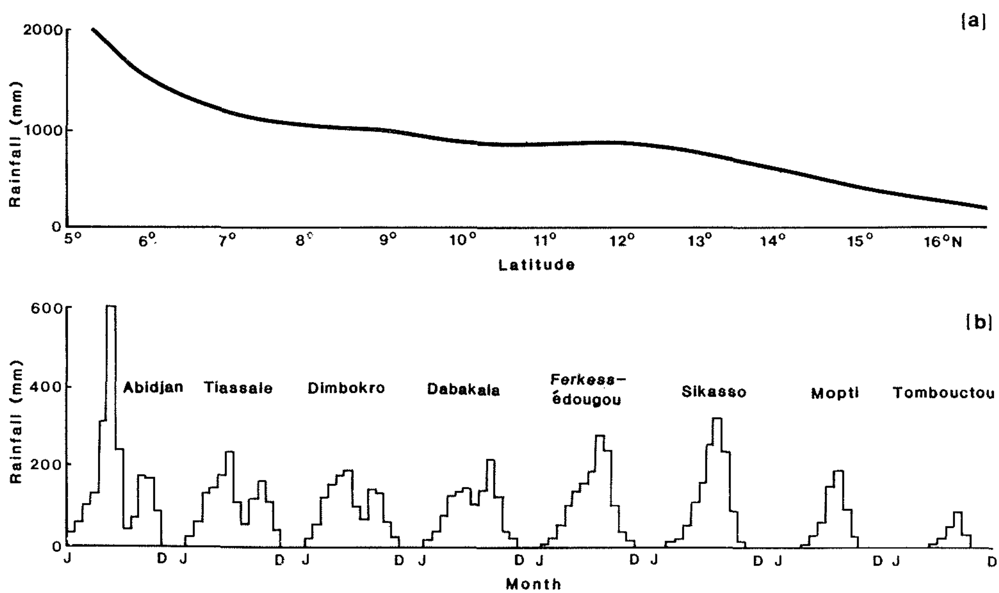

Figure 1 (a) Mean annual rainfall and (b) seasonal rainfall along 4°W longitude.

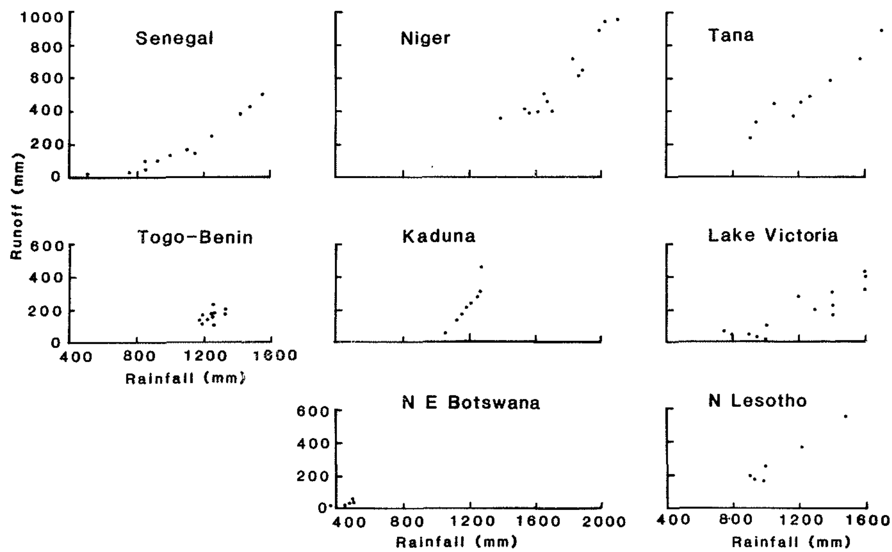

Figure 2 Mean rainfall and runoff of tributaries in different basins (each point represents the period mean rainfall and runoff of an individual tributary).

when runoff is expressed as depth over the basin.

The comparison of annual rainfall with runoff depth oversimplifies the relationship, which depends also on seasonal distribution of rainfall. Where the excess of rainfall over potential transpiration is concentrated into a single season, this excess first fills up the depleted soil moisture storage and then gives rise to runoff. Where the rainfall is spread over two seasons, transpiration losses occur over longer periods and there are two occasions for soil moisture replenishment. Therefore the runoff for a bimodal rainfall distribution is lower than the equivalent for the same gross rainfall occurring in a single season.

Figure 1(b) illustrates such a change in the seasonal rainfall distribution associated with the migration of the ITCZ, with the single rainfall season in the north and the bimodal distribution near the coast. Potential transpiration may be subtracted from rainfall to give maps of net rainfall, which have been used in Guinea and in Togo/Benin to estimate runoff at ungauged sites (Sutcliffe and Piper 1986). However, maps of net rainfall are available only for small areas of Africa, and it is therefore necessary to use maps of gross rainfall, accepting that local relations between mean rainfall and runoff can only be empirical because of the effect of seasonal distribution.

The comparisons of Figure 2 from many different parts of Africa confirm that areas with rainfall less than 1000mm provide low runoff below 100mm, while disproportionately higher runoff occurs from areas with rainfall above 1500mm or 2000mm where runoff generally exceeds

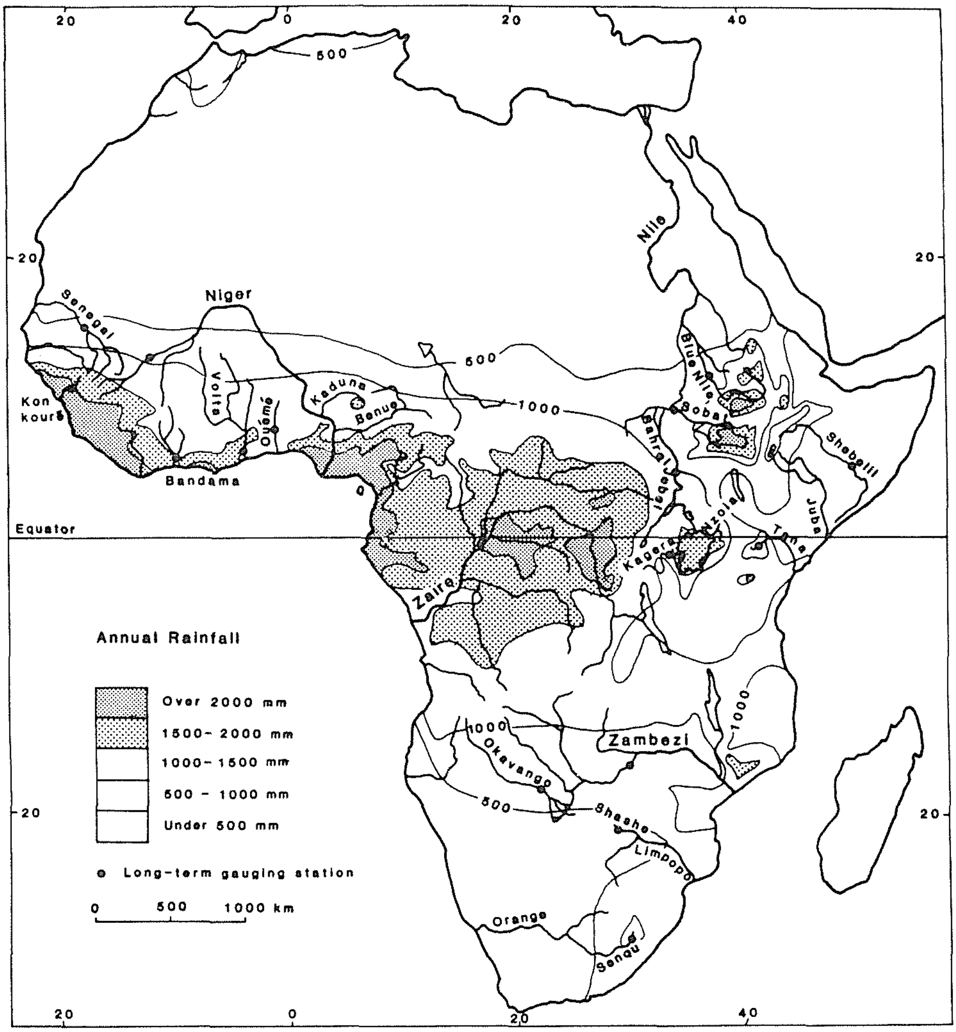

Figure 3 Mean rainfall and drainage in Africa (isohyets after Leroux, 1983).

400mm or 1000mm. The areas of central Africa with average rainfall above these amounts are illustrated in Figure 3.

It follows that the areas of high runoff on the African continent are extremely limited in geographical extent, if one excepts the Zaire and adjacent basins, where large water resources exist but development has not been commensurate. In the Atlas mountains of the Maghreb, winter rainfall of the Mediterranean type gives rise to locally important water resources, but these are not discussed further in this paper.

Many of the high rainfall areas naturally coincide with mountainous areas, which in turn provide the headwaters of a number of major rivers. The sources of a number of West African rivers, like the Senegal, Gambia, Niger, Konkouré and Bandama, coincide with the high ground running east from the Fouta Djalon in Guinea which experiences a single rainfall season. The areas of high runoff in Togo coincide with the high ground between Palimé and Lama-Kara, the river Kaduna draws much of its flow from the Jos Plateau, and the Benue depends on the Cameroon mountains.

In eastern Africa, the Blue Nile, Sobat, Juba, Shebelli and other rivers have their sources in the Ethiopian highlands, while the Tana derives from Mount Kenya and the Aberdares. The Lake Victoria tributaries and thus the Nile outflow depend on the mountains of Rwanda and Burundi drained by the Kagera, and the area to the northeast of the lake below the Mau escarpment.

In southern Africa, the Okavango and Zambezi, with other rivers, have their farthest sources in the mountains of Angola, while the Lesotho highlands give rise to the Orange river.

Thus the variability of a number of rivers, whose contribution to African water resources is important, depends on rainfall in limited areas of the continent.

Annual variability of river flows

Just as the sensitivity of runoff to variations in rainfall, illustrated by Figure 2, is responsible for the concentration of runoff generation in limited areas of high rainfall, this same sensitivity explains the marked annual variations of river flow in response to annual variations in rainfall and especially to the drought of recent years. Where rainfall is highly seasonal, annual runoff is the residual surplus after soil moisture replenishment and evaporation during the wet season have been satisfied. In the same way as mean runoff varies widely according to mean rainfall from basin to basin, so the runoff from a specific basin varies widely from year to year according to annual rainfall. This sensitivity may be deduced from flow records or by modelling (Němec and Schaake, 1982).

In an area where seasonal rainfall distribution and physiography are reasonably homogeneous the relationship between mean rainfall and mean runoff (Figure 2) provides an initial prediction of the response of river flow to variations in annual rainfall. However, annual rainfall and runoff series are compared for a selection of basins in Figure 4. In some cases, like the Shashe and Ouémé, the spread of rainfall and runoff in different years is greater than the spread between the averages of different basins. Nevertheless the similarities with the relationships of Figure 2 are clear, and interannual variations in river flow can be said to mirror interbasin variations in an area.

Thus long-term records provide a measure of water resources which is also a sensitive indicator of fluctuations in rainfall. As they represent net rainfall over a basin rather than at a point, they smooth the effect of random variations from point to point and provide a valuable indication of climatic fluctuations.

The variability of annual flows for the largest rivers is illustrated in Figure 5 where the available records are presented in

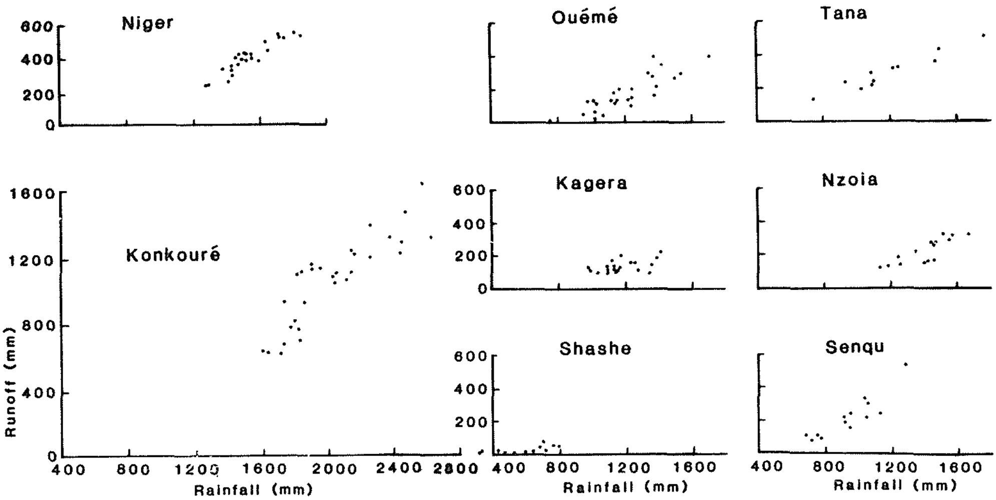

Figure 4 Annual rainfall and runoff from different basins (each point represents annual rainfall and runoff totals for individual years).

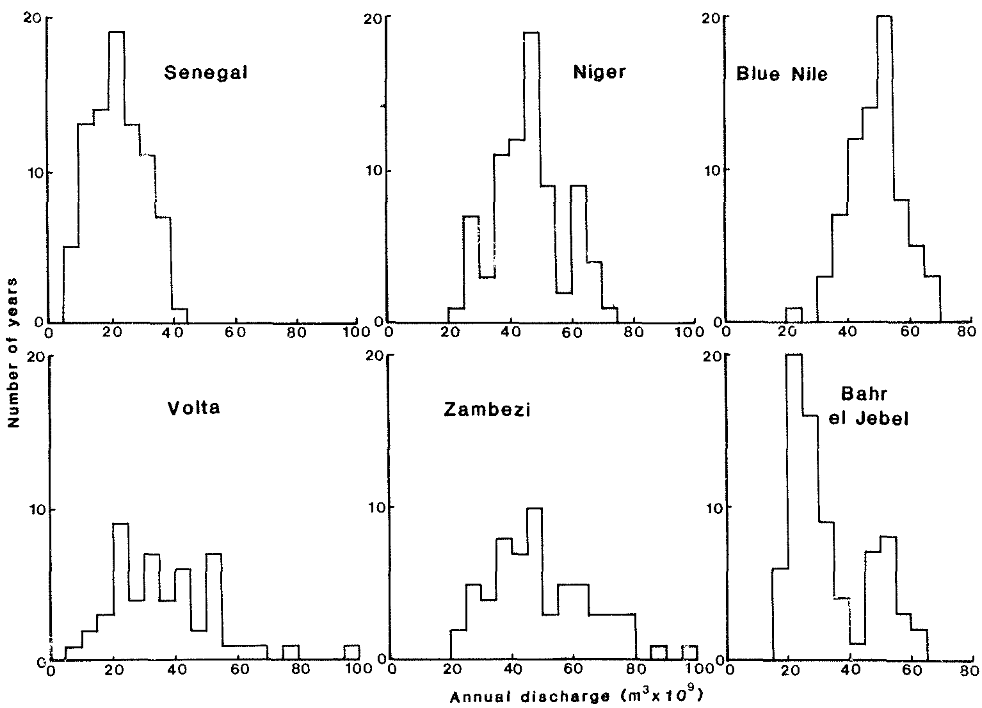

Figure 5 Histograms of annual discharges.

histogram form. The range of annual flows is very wide even on these large rivers; the ratio between highest and lowest years varies from 3.4:1 to 10:1.

Annual flow series for several large rivers are presented in Figure 6, where the scatter tends to obscure the pattern of high and low years which seems to be present in some cases. Moreover, the flow sequence is as important as the overall spread. Hurst (1965) had demonstrated in his study of Nile flows that sequences of high and low years increase the size of the reservoir required to equalize flows beyond that required for an uncorrelated series.

The flow series for a number of African rivers (listed in Table 1) are presented in Figure 7 in the form of seven year moving averages, covering as far as possible the areas which have been noted as the main sources of runoff.

There are certain striking similarities but also a number of contrasts among these series. The flows of the Senegal and Niger are very similar, which would be expected as they derive from adjacent areas of surplus rainfall. The range of seven year mean flows is itself very wide, particularly for the Senegal where the recent mean is only a third of earlier peaks and the recent drought has been much more severe than previous droughts in 1910-1915 and 1940-1945.

The pattern of flows in other west African rivers like the Volta, the Konkouré in Guinea, the Bandama in Côte d'Ivoire, and the Ouémé

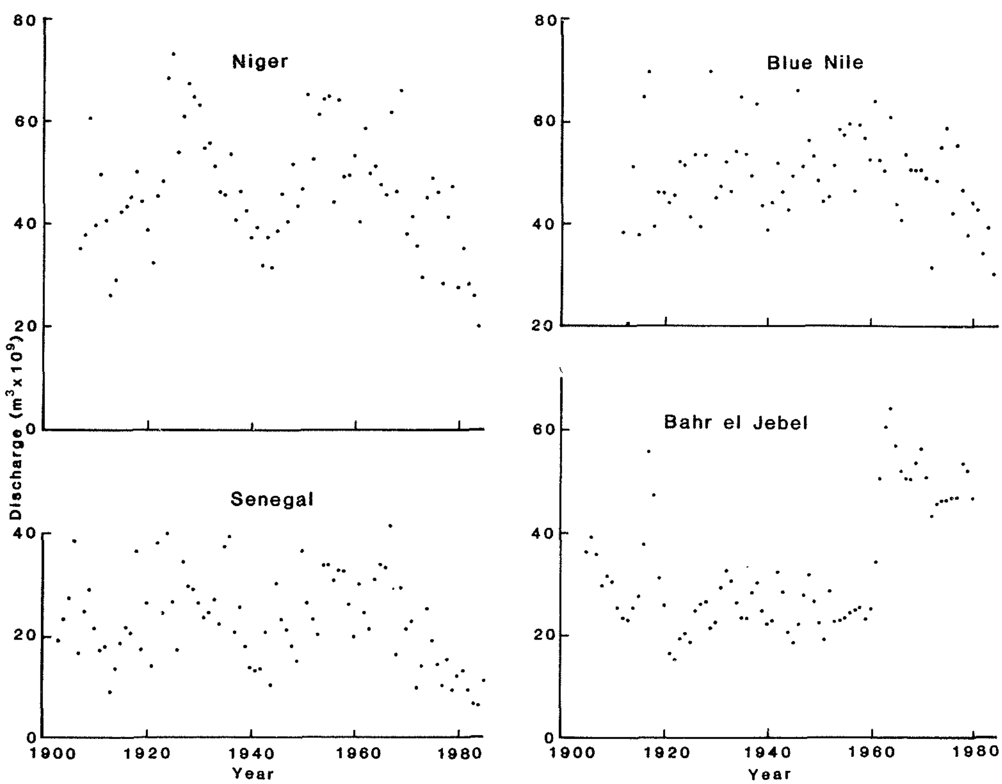

Figure 6 Annual discharges of selected rivers.

Table 1 Long-term river flow records

River	Station	Lat.	Long.	Area $km^2 \times 10^3$	Period	Mean $m^3 \times 10^9$	Runoff mm
Senegal	Bakel	14°54'N	12°27'W	218	1903-85	22.9	105
Niger	Koulikoro	12°51'N	7°33'W	120	1907-84	46.4	386
Konkouré	Teliméle	10°30'N	12°54'W	10.2	1951-80	10.8	1058
Bandama	Tiassale	5°54'N	4°49'W	95.5	1928-85+	9.58	100
Volta	Senchi	6°12'N	0°06'E	394	1936-85	37.2	94
Ouémé	Savé	8°00'N	2°25'E	23.6	1932-83+	3.77	160
Blue Nile	Roseires	11°52'N	34°23'E	210	1912-84	49.3	235
Shebelli	Belet Uen	4°44'N	45°12'E	212	1951-85	2.21	10
Sobat	Doleib	9°20'N	31°38'E	22.5	1905-80	13.6	60
B. el Jebel	Mongalla	5°12'N	31°46'E	450	1905-80	33.0	73
Kagera	Nyakanyasi	1°12'S	31°15'E	55.8	1940-79	6.38	114
Tana	Kamburu	0°49'S	37°41'E	9.30	1908-77+	2.99	321
Okavango	Mohembo	18°13'S	21°49'E	180	1932-76	10.6	59
Zambezi	Kariba	16°31'S	28°50'E	664	1924-85	50.3	76
Shashe	Shashe dam	21°22'S	27°26'E	3.65	1922-85+	0.074	20
Senqu	Koma Koma	29°36'S	28°41'E	7.95	1921-83+	1.88	237

+ Extended using rainfall records

in Benin, have been similar to the Niger and Senegal. It is more surprising that the flows of the Blue Nile, though less variable than the Niger, have also reflected droughts in the early 1940's and more recently.

The flows of the Bahr el Jebel or White Nile at Mongalla present a completely different pattern from the Blue Nile and reflect the rise in Lake Victoria in 1961-64. It is interesting to note that other rivers in East Africa, like the Kagera and Tana, present a similar pattern without the effect of lake storage. The flows of the Sobat which are attenuated by spill to the Machar marshes, show some similarity but the Shebelli does not do so.

The flows of the Zambezi present a quite different pattern, with increased runoff between 1950 and 1980. However, there seems to be little similarity with the other flow records from southern Africa, which are the inflows to the Okavango Swamp and the Shashe in Botswana and the Senqu in Lesotho.

Proxy series

Long term homogeneous river flow series are not available in all parts of Africa. In general, the francophone countries appear to be better provided with long-term river flow records, while the anglophone countries have shorter flow records but a number of long-term rainfall records.

The Nile basin is an exception to this generalization, as the evident importance of river flow records led the Physical Department of the Egyptian Government to establish river gauges throughout the basin at an early date, so that key records are available from about 1905.

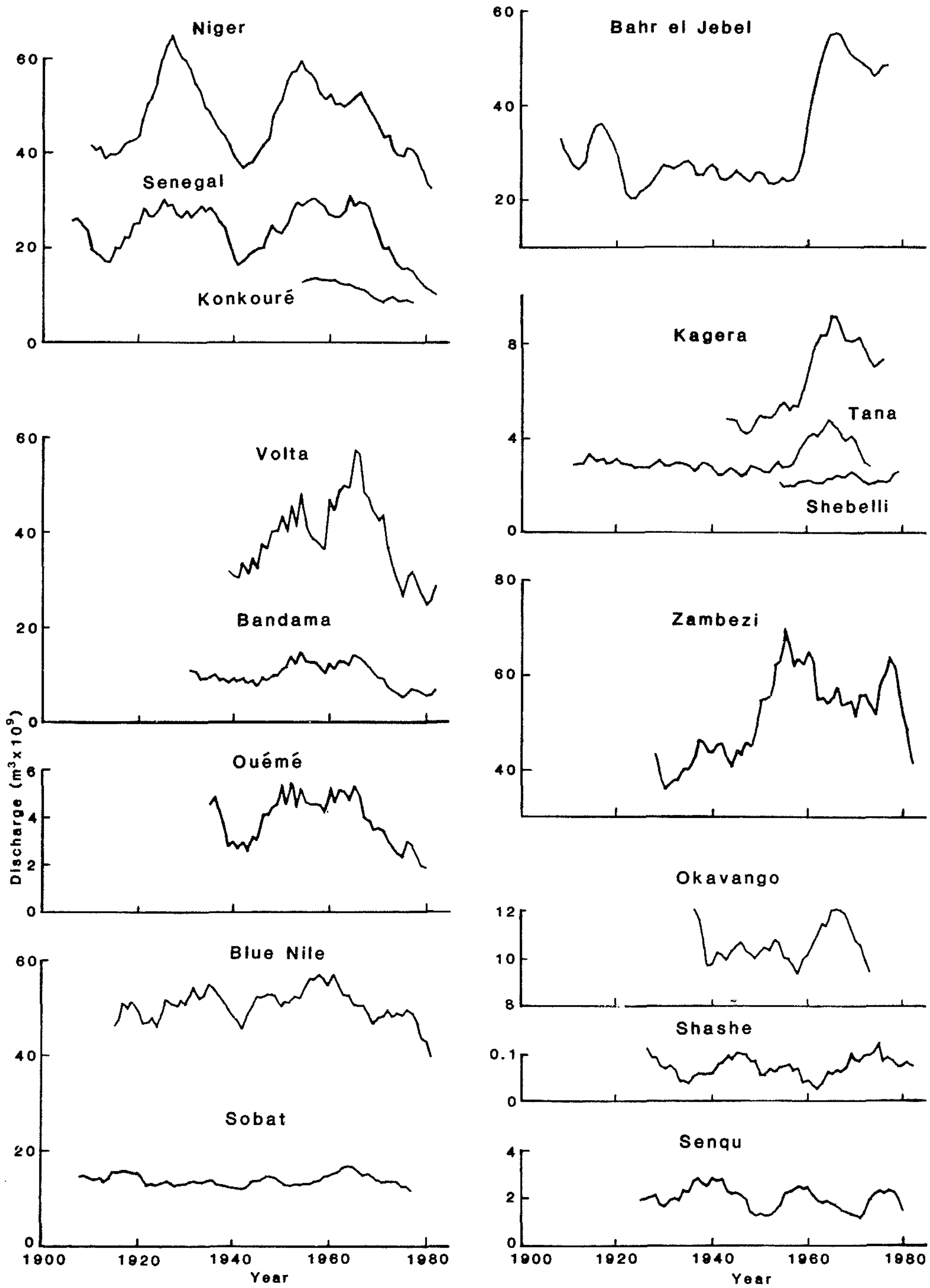

Figure 7 Seven year moving average discharges at long-term gauging stations.

However, long-term rainfall series can be used to estimate basin rainfall series which can be converted to runoff series either by statistical methods or conceptual models calibrated by recent flow records. Some of these extended series have been included in the runoff series of Figure 6.

Where a river basin includes a lake for which the outflow is related to level by a fixed control, as at Lake Victoria and the Ripon Falls, or where there is no outflow and evaporation over the lake area provides the control, then a long-term series of lake levels can be used as a proxy record for a river flow series.

Such lake series are useful as historical levels are often available before the start of regular readings and these can be used to infer hydrologic conditions before river flows are generally available. For example, early accounts of Lake Victoria indicate a period of high levels and high Nile outflows for the period 1875-1895, which is supported by other evidence (Piper et al., 1986).

The rise in Lake Victoria levels in 1961-1964, which was reflected in the flows of the Kagera and Tana rivers as well as the Bahr el Jebel, has been shown to be similar to a contemporary rise in Lake Tanganyika (Kite, 1981). Zaire river levels at Kinshasa were also exceptionally high in 1961-1963 (Hirst and Hastenrath, 1983). Rises also occurred at this time in Lake Turkana (Rudolf) where previous high levels before 1895 have been deduced by reconstructing a lake level series by comparison of early maps and other evidence (Butzer 1971). Similar rises have occurred in Lakes Abaya/Chamo/Chew Bahir in the Ethiopian rift valley (Kingham, 1975).

Similar historical evidence, including such records as the Nile level series from 600 A.D. has been used to extend our knowledge of wet and dry periods over a much longer time scale (Nicholson, 1980).

Water resources planning

These characteristics of the climatology and hydrology have important implications for water resources planning.

(a) They lead to greater emphasis on overyear storage as a means of optimizing the use of water resources. The seven year moving average provides a useful target for the yields that might be provided by overyear storage. It is relevant to water resources planning that these moving averages fluctuate widely in Africa. In general the available resource indicated by the seven year moving average has varied by a ratio of 1:2 over this century. The importance attached to overyear storage capable of providing adequate regulation is reflected in the capacity of such projects as the Aswan High Dam and the Kariba hydro-electric project.

(b) The comparative concentration of the sources of runoff imposes a high degree of interdependence between those countries which control the resource and those which depend on it for their supply of water. The flows of the Nile, which are the principal water resource of Egypt and the Sudan, originate almost entirely from outside the frontiers of those countries. Similarly the flow of the River Senegal is largely derived from Guinea, while it is mainly used for irrigation in Mali, Senegal and Mauritania. This situation has led to the creation of a number of international bodies whose function is to regulate the development and use of individual river basins. River basins in the continent of Africa which are planned by supranational authorities include the Nile, the Senegal (OMVS), the Niger and the Gambia (OMVG). The OMVS has direct control of the implementation of the Manantali dam on a major tributary of the River Senegal in Mali and the Diama barrage on the border between Senegal and Mauritania.

(c) It may be necessary to review the conventional criteria that are used in water resource planning and adopt a more flexible approach. While this may not be realistic in economic terms for urban water supply, where reservoirs may have to be supported by conjunctive use of groundwater supplies, such an approach could be useful in irrigation or hydro-electric planning.

Traditionally irrigation schemes seek to supply water with an assured reliability in, say, 4 years out of 5. If, however, there is a persistence of low flows followed by a series of high flows, it may be preferable to plan systems on the basis of substantial reductions in cropping intensities for long periods, to be increased when hydrologic conditions permit. For example, irrigation development in the Senegal Basin envisages a total area of 375,000 ha, but for certain periods there will only be sufficient water for full intensities on about 250,000 ha.

The same principle holds for hydro-electric planning. It would be economically attractive to take advantage of above average hydrologic conditions by varying the assumptions on firm energy for short periods. This could lead to decreases in thermal generation and deferment of additional capacity. An example of this approach is elaborated in the following section.

Planning of Kariba hydro-electric scheme

Planning studies of the Kariba hydro-electric scheme provide an interesting illustration of a possible response to changes in the hydrologic regime. The initial installed capacity of the scheme in 1962 was 666 MW and this capacity was increased by a further 600 MW in 1977. In the earlier years of operation a firm energy of 8500 GWh per year was adopted, based on reservoir studies for a 44 year period from 1926 to 1970. It was noted, however, that there had been a marked increase in river flows since 1950. When planning studies were carried out in 1975 for the installation of a further 600 MW at Kariba the question arose as to whether it would be appropriate to adopt a higher firm energy for planning purposes based on the more recent period of record, which some argued was representative of changed hydrologic conditions.

This would have important economic advantages as it would permit a reduction in thermal generation and some deferment in new capacity. It was concluded that for short term planning a figure of 10000 GWh per year could be adopted, although it was recommended that for longer term planning the original figure of 8500 GWh should be maintained. Any risk associated with such a policy would be mitigated by the large element of overyear storage in the Kariba reservoir.

It is perhaps fortunate that it did not prove necessary for the system to rely too heavily on the additional firm output, as the three consecutive years 1981-1983 were all extremely low. Firm output was only maintained by drawing down the reservoir to very low levels. This outcome vindicates the view that the evidence of a long period of record is to be preferred to a shorter period.

Nevertheless the principle of reacting to changes in hydrologic regime is still valid. Should there be a return to the conditions of 1950 to 1980 it might be permissible and economically advantageous to adopt a higher firm energy for short periods and optimize the planning of the system accordingly.

Conclusions

This study has concentrated on establishing a number of facts about African water resources. The variability of river flows in both space and time is reasonably well established, but the scientific and practical implications need considerable thought. It is hoped that the facts presented on the scale of variations during this century will provide meteorologists with a useful supplement to the evidence from rainfall records. The key to further advance must be in the domain of global meteorologic study. Any advice on the possible future pattern or, less ambitiously, the scale of periodic fluctuations would provide considerable benefit to the water resources planner.

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