Regional variations of African river flows

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Abstract The key characteristics of African water resources are their spatial variability, with significant river flows generated from limited areas of high annual rainfall, which often coincide with areas of high relief, and great temporal variability, both seasonal and longer term, related to variations of rainfall and the sensitivity of the rainfall/runoff relationship. Key examples are: the Senegal and Niger, deriving from the mountains of Guinea; the Blue and White Nile, draining the Ethiopian highlands and the Lake Victoria basin; and the Zambezi and Orange rivers. Recent flow records demonstrate the similarities and differences between these rivers.

INTRODUCTION

The variability of river flows is one of the main features of the hydrology of the African continent. The reasons for this are first, low and variable rainfall, and secondly high potential evaporation which exceeds rainfall for much of the year. The effect of this balance on the resulting runoff is illustrated by examples of water balance in African basins, and by comparisons between rainfall and runoff. The effect of these factors on the variability of African rivers is shown by the records at key points over the continent covering this century and in some cases the final quarter of the last century.

RAINFALL OVER THE CONTINENT

The rainfall over the African continent is extremely variable in both time and space. The variability of average rainfall over Africa can be illustrated by an isohyetal map (e.g. Sutcliffe & Knott, 1987) which shows that high rainfall is in fact confined to comparatively small and isolated areas. For example, much of the flow of the Senegal and upper Niger rivers derives from the mountains of central Guinea, where the rainfall reaches 2000 mm. Similarly, much of the flow of the White Nile derives from the mountains surrounding Lake Victoria. However, recent research (Sene & Plinston, 1994) has shown that the rainfall over the lake itself, caused by the interaction of prevailing easterly winds and westerly lake and shore breezes at different times of the day, is the most important source of inflow to the lake. On the other hand, the western Ethiopian highlands are subject to heavy rainfall over a single season which reduces in duration from south to north, and therefore provide significant runoff to the Sobat, Blue Nile and Atbara and thus the bulk of the flow of the main Nile.

In southern Africa the mountains of Angola give rise to the Okavango river, while those of Lesotho provide the source of the Orange river. However, the Zambezi and the Congo draw their runoff from a wide plateau area of higher rainfall.

Variability of annual rainfall

In the same way as rainfall in Africa is extremely variable from place to place, so it varies from year to year. Rainfall is liable to random variations, which are high by comparison with mean rainfall. Moreover, there have been longer term variations which are more important from a water resources point of view; for periods of several years or even decades rainfall has persisted at levels above or below the long-term average. Examples are the long periods of low rainfall which have been observed in the Sahel for periods since 1968, and the periods of relatively high rainfall which have occurred in East Africa since 1961. Indeed, some have queried the meaning of long-term average in the context of African climate. Although the divergence of rainfall from the mean may not be large in percentage terms, the rainfall/runoff process exaggerates such a divergence in terms of runoff, so that variations are more easily identified in runoff records than in raw rainfall records.

Seasonal distribution

The rainfall of much of Africa depends on the migration from south to north and back of the Inter-Tropical Convergence Zone (ITCZ) and thus varies in latitude bands between zones of double rainfall seasons to single seasons of decreasing length away from the equator. The seasonality of rainfall itself determines the seasonal distribution of runoff, and it is the comparison of rainfall with evaporation which determines its amount. Examples of seasonal distributions of annual rainfall are included in Fig. 1.

EVAPORATION

The evaporation of available water is as important a factor in the availability of runoff as rainfall itself. Unfortunately, evaporation has not been measured over as long a period as rainfall, and its measurement has been dominated in Africa by such methods as the use of Piche evaporimeters or Class A pans, whose interpretation in terms of basin loss is not clear. It is generally accepted that the combined method developed by Penman provides realistic estimates of either open water evaporation or potential transpiration.

Examples of potential evaporation estimates, compared with corresponding rainfall estimates, are included in Fig. 1. It will be seen that the seasonal variation of evaporation is much less than that of rainfall, so that the rainfall surplus depends on the rainfall in a few key months. On the other hand, there are few records of actual

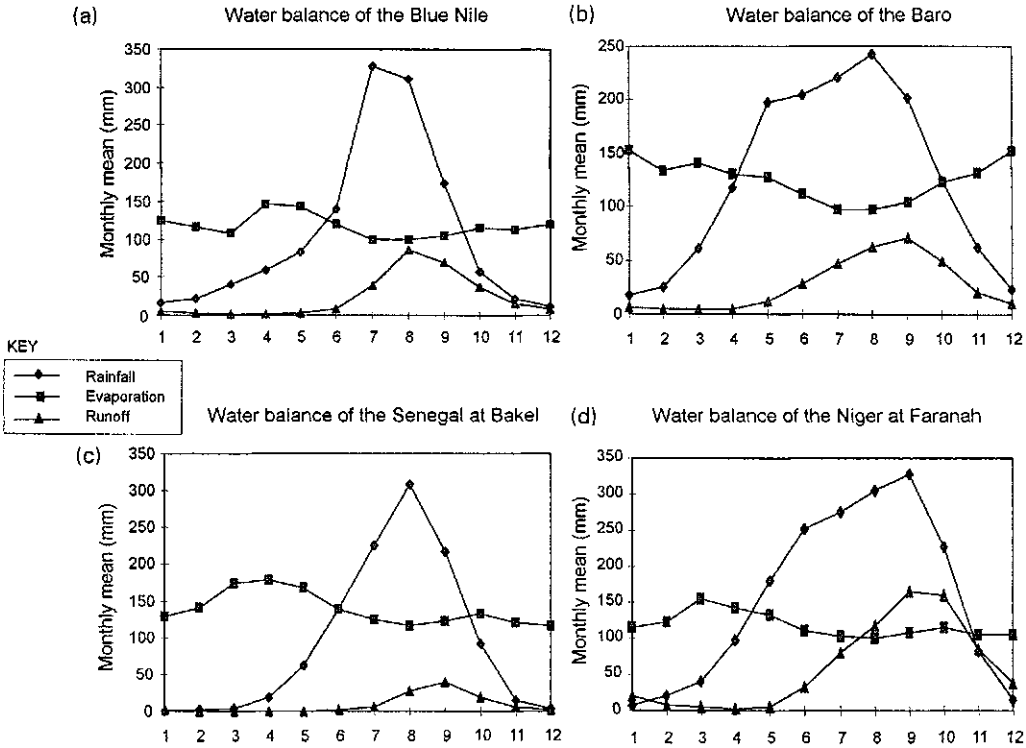

Fig. 1 Annual water balance of selected rivers.

or potential transpiration which extend over many years. As the variations from year to year will depend largely on cloud cover, controlling net energy at the surface, it is reasonable to assume that they are linked inversely with rainfall; however, as the variations of evaporation are likely to be much less than rainfall, it is not unreasonable to equate losses with the mean estimate of evaporation.

WATER BALANCE

In Fig. 1 (a)–(d) examples of average rainfall and potential evaporation are compared for some key basins. Assuming that the period of soil moisture recharge requires a moisture depth of some 300 mm, the periods of water surplus or runoff are limited in duration, as illustrated by average runoff depths. Where the period of rainfall and thus actual evaporation are extended, as in a bimodal rainfall distribution, this will result in higher losses and thus less runoff for a given gross rainfall.

Although comparisons of rainfall and evaporation explain differences in the seasonal runoff distribution, the uncertainties of deriving basin rainfall from a sparse raingauge network mean that it is difficult to deduce runoff from rainfall by hydrological modelling. The sensitivity of the runoff process is illustrated by annual rainfall and runoff in the Senegal and Niger basins (Fig. 2), derived from mean values from different tributaries, but should approximate to the variation of

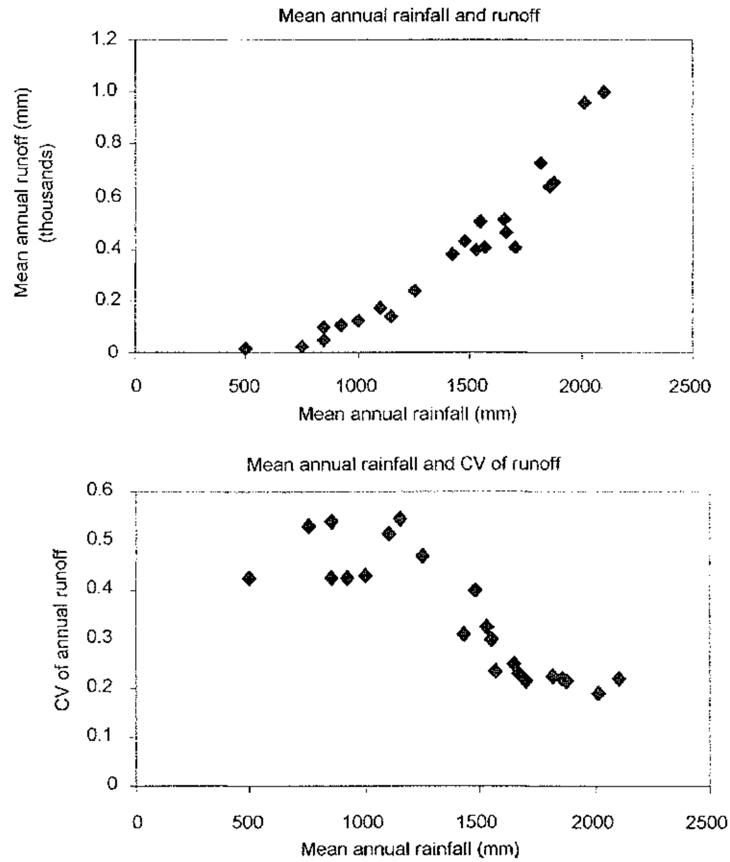

Fig. 2 Relationship between rainfall and runoff for selected catchments in the Senegal and Niger basins.

runoff from year to year with varying rainfall. The relation between runoff variability and mean rainfall is also illustrated. The inverse is perhaps more useful; the monitoring of river flows at a single point, integrating the rainfall–runoff process over a wide area, provides a reasonable picture of the time variations of water availability.

Thus the emphasis of this paper is on the variations of river flow at key points over the continent, where long and consistent periods of flow record provide a reasonably reliable record of the history of water resources over the continent. In a previous study, Sutcliffe & Knott (1987) showed that there were links between the behaviour of the Senegal and Niger, and other West African rivers, and the Ethiopian tributaries of the Nile, the Blue Nile in particular. A wide belt of the Sahel, ranging from the West African coast to western Ethiopia, has experienced similar histories of water variations during this century.

Sutcliffe & Knott (1987) also showed that the outflow of Lake Victoria at Jinja is linked with not only the Kagera upstream and the Bahr el Jebel downstream but also with the Shebbeli and Tana to the east. Thus the Lake Victoria outflow provides a proxy record for a wide area of East Africa, albeit damped by lake storage.

FLOW RECORDS

In order to appreciate the precision and the context of these key records, a brief description of their background is useful. In most cases the upstream basin has not been developed until recent years, but in some cases the flows (Fig. 3) have been naturalized to provide consistency of record.

Senegal and Niger

The key stations on these rivers are on the Senegal at Bakel (Rochette, 1974) and the Niger at Koulikoro (Brunet-Moret *et al.*, 1986). The Senegal river drains a wide area (218 000 km^2) ranging from the mountains of Guinea with rainfall approaching 2000 mm to areas of Mauritania with rainfall of 200 mm. Since 1987 flows have been affected by reservoir storage.

The Niger has been measured at Koulikoro since 1907, and drains an area of 120 000 km^2, mostly in Guinea, with rainfall ranging from over 2000 mm in the headwaters to below 1000 mm at the gauging station.

White and Blue Nile

The three key stations on the Nile system are the Victoria Nile, the main tributary of the White Nile, at Jinja, the Blue Nile at Roseires/el Deim, and the main Nile at Dongola above the reservoir of the Aswan High Dam.

The outflow from Lake Victoria, before the construction of the Owen Falls dam in 1951–1953, was controlled by the Ripon Falls and thus linked to lake levels, which have been measured since 1896, with a short gap in 1897. Since 1954, the dam has been operated by international agreement so that the outflow is similarly linked to lake level according to an "Agreed Curve" based on earlier gaugings below the outflow extended by hydraulic modelling. The flows reflect the balance of the lake itself (67 000 km^2) and its tributaries (194 000 km^2) in Rwanda, Burundi, Kenya, Tanzania and Uganda. The flow record shows a remarkable discontinuity in 1961–1964, when the lake rose after exceptionally high rainfall. There is evidence that there were similarly high lake levels in 1878 and 1890–1995.

The Blue Nile has been measured with regular gaugings at Khartoum and upstream since 1900. These flows reflect the water balance of the Blue Nile basin (about 176 000 km^2) within Ethiopia. The record shows the decline of runoff since the 1960s which is similar to those of Sahel rivers.

The flows of the main Nile have been measured at Aswan and upstream since 1870. Although the early records are subject to some uncertainty, this is insufficient to explain the very high flows of the late 19th century, and the composite record provides valuable evidence of this period. The flow record in recent years has been adjusted to take account of upstream abstractions but not reservoir evaporation. The record shows the combined effect of the recent fall in Blue Nile flows, offset to an extent by the increase in the flows of the White Nile, which are halved by the evaporation losses within the Sudd or Bahr el Jebel swamps. Together these three records provide a long record of conditions over much of northeast Africa.

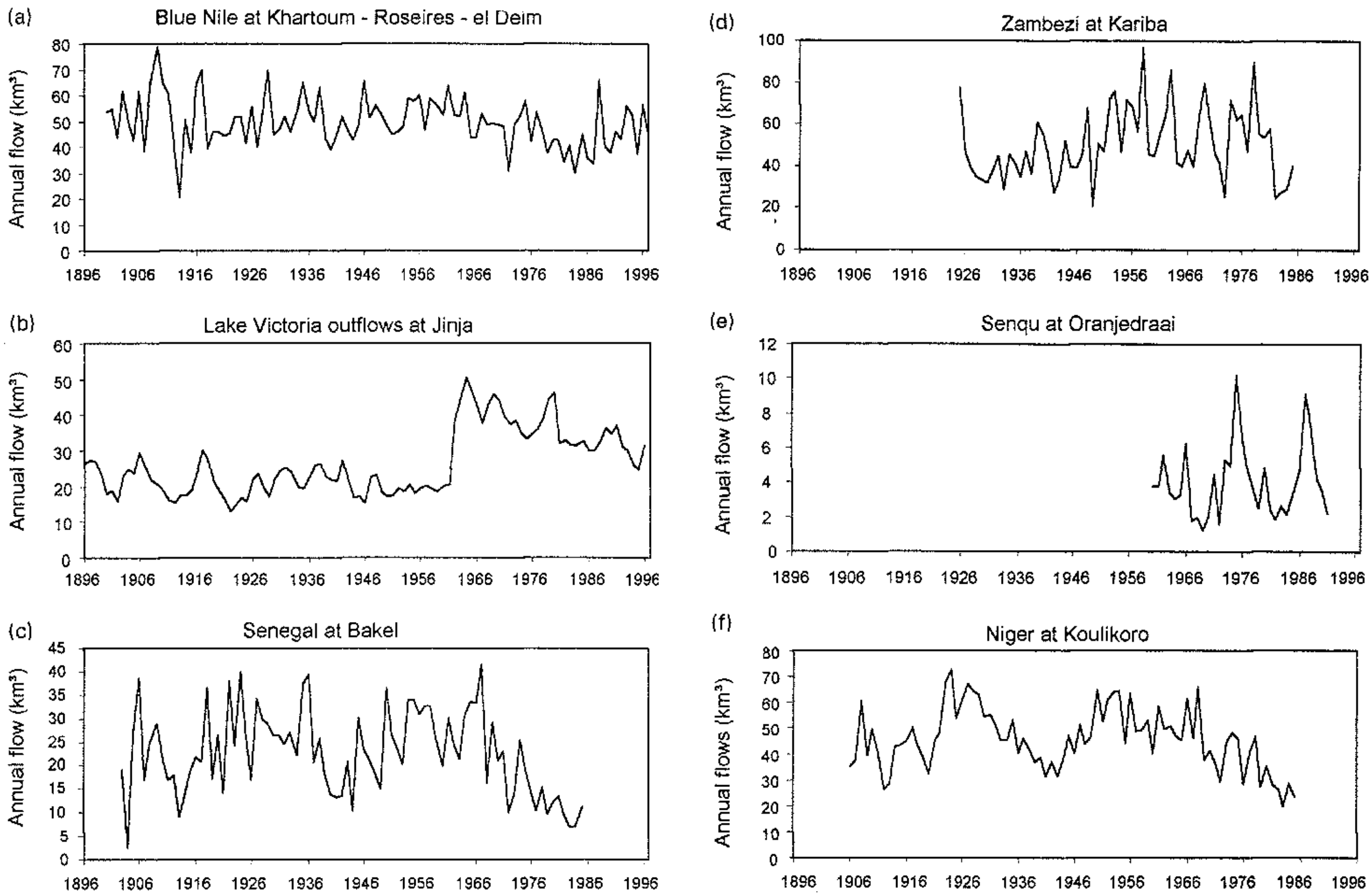

Fig. 3 Selected long-term flow records of African rivers.

Zambezi at Kariba

The Zambezi drains a wide area from Angola to the plateau of western Zambia, and although it shows a degree of variation between periods of relatively high and low flows, these do not coincide with the previously discussed records.

The Orange/Senqu at Oranjedraai

Another record illustrates the water resource of a high-yielding mountain area of Lesotho, which again has periods of varying flows but little correspondence to the other African records. It appears that runoff from the Lesotho Highlands is affected by different rainfall patterns from those which influence the larger rivers further north.

REGIONAL SUMMARY

It appears that there are several distinct regions in Africa in terms of water resources variations. These have similarities within each region but exhibit quite different characteristics from the other regions. The distinctive regions appear to be: the Sahel, extending from the Senegal to the Blue Nile basins, which have been subject to severe droughts in recent years; the East African region, which includes the lake basin of the White Nile but extends into Kenya and southeast Ethiopia and Somalia; the Congo basin, which is fairly unique; and several basins in southern Africa which do not share a common history but suffer wide variations.

LONGER TERM VARIATIONS

The river flow records discussed above provide the most reliable history of water availability of the last century over Africa. Discussion of previous variations must depend on either rainfall records, lake level records or oral or written histories of periods of flooding or water shortage. An example is the long record of maximum and minimum annual levels of the Roda gauge at Cairo, which provides information from 622 AD but is subject to gaps, aggradation, and possibly scale changes. These sources have been examined by Nicholson (1980) and others; examples show that Lake Victoria levels were high at the end of the 19th century. Lake Turkana levels (Butzer 1971) show similar characteristics. These fluctuations, which in the case of Lake Victoria are confirmed by flows at Aswan, are also supported by rainfall information. This information confirms that the behaviour of African water resources has not been much different to the recent period.

POSSIBLE EXPLANATIONS

The search for possible explanations of these variations leads to the less familiar fields of global meteorology. It appears evident that any explanation must deal with fluctuations upwards as well as downwards, which rules out somewhat simplistic views like that which attributes the increase in flows in the Lake Victoria basin to sudden deforestation; the corresponding fall in the last years of the 19th century would require a concerted campaign of afforestation in an area where this is implausible, although Calder *et al.* (1995) have attributed a smaller rise in Lake Malawi to land use changes. The reasons for the sudden and dramatic rise in Lake Victoria levels, and hence outflows to the White Nile, are discussed very clearly by Sene & Plinston (1994). Similarly, the explanation must explain simultaneous rises in rainfall in one area and falls in another area, like the difference in the White and Blue Nile contributions after the 1960s. It follows that changes in regional circulation must feature in any explanations, and these include El Niño Southern Oscillation

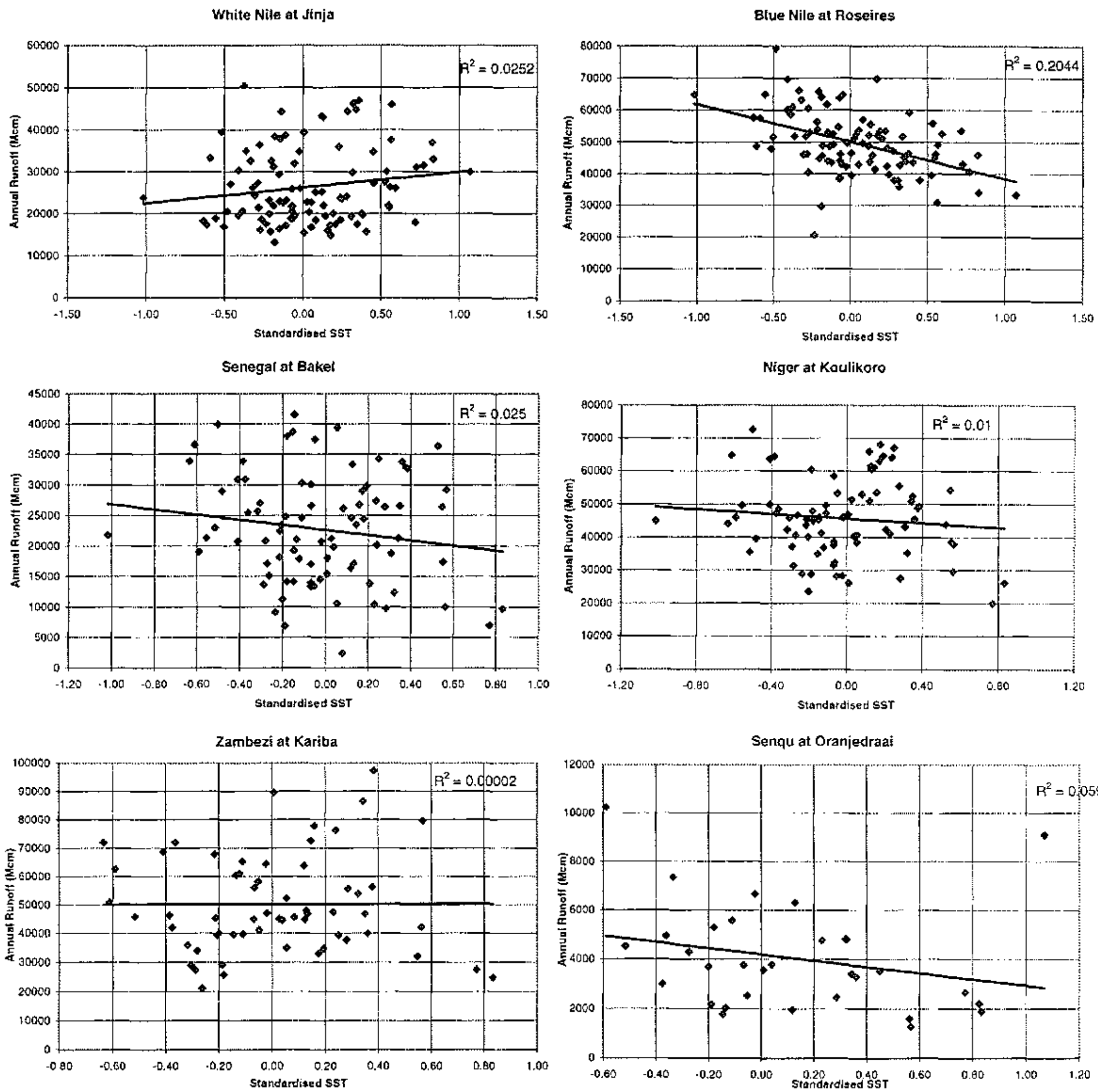

Fig. 4 Relationship between sea surface temperature (SST) and annual flows.

(ENSO) effects and sea surface temperatures. The so called ENSO effect is a combination of two phenomena, one being the Southern Oscillation Index (SOI), which is simply an index which measures the differences in air pressure between Tahiti and Darwin, and which ranges between +30 and -30, and the second being a measure of sea surface temperatures in the eastern Pacific (SST). When the SOI is strongly negative (less than -5), the eastern trade winds are weakened or reversed and sea surface temperatures in the eastern Pacific rise. Eltahir (1996) has demonstrated a weak inverse linkage between inflows to Lake Nasser on the Nile and the ENSO, which he showed was responsible for about 25% of the natural variability in inflows. Below average inflows correspond to strong positive SST, or to negative SOI values. Figure 4 illustrates a similar relationship between SST and flows on the Blue Nile at Roseires, and also a much weaker linkage for the Senegal at Bakel and the Senqu at Oranjedraai. However, the link between ENSO and annual flow does not appear to be universally true, as there is no obvious relationship for either the White Nile or the Zambezi. Similar, but inverse, relationships with SOI were also found, and it is apparent that either the SOI or SST are weak indicators of annual runoff for some, but not all, major river basins in sub-Saharan Africa.

CONCLUSIONS

River flow regimes throughout much of sub-Saharan Africa are characterized by marked temporal variability and occasional periodicity. This variability may well be affected in part by the ENSO effect, although other factors such as land use change may also be significant in some cases. However, the primary cause of inter-annual variability is caused by variations in rainfall inputs. Given that annual potential evaporation is relatively conservative, a small increase or decrease in rainfall can lead to marked changes in runoff, which is the difference between rainfall and evaporation, and which is markedly seasonal over much of the region. Whilst projected climatic and anthropogenic changes will undoubtedly have an impact upon future runoff, it is apparent that the long-term natural variability of flow regimes throughout Africa will continue to result in periods of flood and drought.

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