Seasonal flooding in the Okavango Delta, Botswana — recent history and future prospects

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Seasonal flooding in the Okavango Delta is influenced equally by local rainfall and inflow from the catchment to the north. Local rainfall is convective, modulated by the semi-permanent anticyclone over southern Africa and easterly waves, and is subject to the well-documented 18-year oscillation of the subcontinental interior. The catchment is more strongly influenced by the ITCZ and CAB. The easterly catchment (Quito River) responds to instabilities in tropical lows in the Indian Ocean easterlies, and the western catchment (Cubango River) to variability in the Atlantic equatorial westerlies. The latter shows a quasi-18-year oscillation, which is out of phase with that to the south. This has buffered flooding in the Okavango swamps in the past. Discharge in the Quito has declined since 1980, which has had a severe influence on flooding in the Okavango swamps. This decline is also evident in discharge records of the Zambezi, and the longer Zambezi record suggests that this may be related to an 80-year oscillation.

Although droughts are a fact of life in Africa, with human pressure on the land increasing annually, their effects are becoming increasingly severe. Even the vast wetland (>12 000 km²) of the Okavango Delta of northern Botswana (Fig. 1) is not immune to their effects. Rapid urbanization resulting from the growth of the tourist industry, coupled with successive years of low rainfall and low outflow from the swamps, created an acute water shortage in Maun at the southern edge of the Okavango Delta in the early 1980s that continues to the present. Originally, this resulted in a proposal to dredge the Boro River, which extends northeast from Maun into the Okavango wetlands, with a view to increasing outflow from the swamps to supply Maun. However, under pressure from conservation groups,[1] the Botswana government invited the IUCN to review the project, and as a result of their recommendations it was cancelled.[2] In its place, a large project was initiated to locate additional groundwater supplies for Maun, and initial results have been favourable.[3]

Little is known of the frequency of droughts in the southern regions of the Okavango. The name Maun means 'the place of reeds' (*Phragmites* spp.) in Setswana, but the reed beds that once grew in profusion along the banks of the Thamalakane River, and which gave the village its name, have all but disappeared. Maun was established in 1915, when chief Mathiba and the local traders and administrators moved there from Tsau[4] at a time when the Thaoge distributary channel, which flowed close to the village, was failing. The move suggests that water was abundant at Maun, and oral accounts of its older residents suggest that there was considerably more water in the Thamalakane in the past. Shaw[5] examined the post-1849 record of flooding in the Okavango based on historical accounts, and found that the record could be divided into three periods: 1849–1900, when average to above-average outflows were evident; 1900–1951, with limited outflow, interspersed with some good years (1910, 1925–1927, 1944); and 1951 to 1983, with good, but cyclic flows.

Tyson and others[6] have examined the rainfall records from South Africa, and although there is a large year-on-year variability, they have been able to identify quasi-regular patterns, with a dominant 18-year oscillation in the summer rainfall region, which results in alternating nine-year periods being respectively wetter than average and drier than average. Most of South Africa, Botswana, Namibia and Zimbabwe fall under the influence of this oscillation.[7] The major droughts of this century are consistent with this pattern.

Systematic hydrological and rainfall recording in the Okavango region began only recently. For example, regular measurement of outflow from the delta in the Thamalakane River only commenced in 1969. Rainfall records in the catchment area of the Okavango River in Angola are particularly sparse.[7] However, there are sufficient data now available to attempt a semi-quantitative investigation of rainfall and runoff patterns in the region. The results may then be compared to those of other areas in the summer rainfall regions of southern Africa. Thereby, a more comprehensive picture of water resource variability in the Okavango is likely to emerge.

The hydrology of the Okavango

The hydrology of the Okavango is well known, largely as a result of the pioneer-

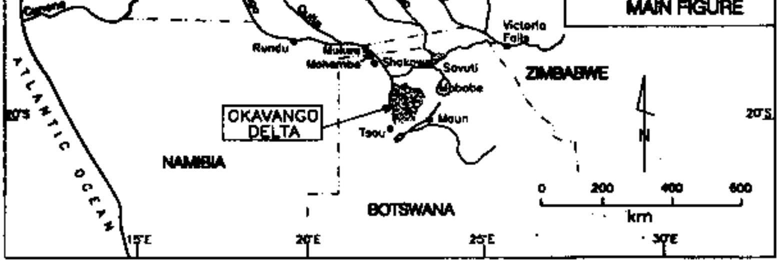

Fig. 1. Map showing river catchments in the Okavango region.

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ing studies by the Department of Water Affairs in Botswana.[8–10] Hydrological models of ever increasing sophistication and predictive accuracy have been developed for the delta over a number of years.[11–14] The hydrological functioning of the Okavango has been described by Wilson and Dincer[9] and McCarthy *et al.*,[15] and will be dealt with only briefly here.

The main tributaries of the Okavango are the Quito and Cubango rivers, which drain catchments of 65 000 and 115 000 km² situated in central Angola (Fig. 1), and which receive rainfall of 876 and 983 mm/yr, respectively.[9] Rain falls between December and March, and runoff accumulates in the Okavango River, which discharges into the wetlands of the Okavango Delta. Peak discharge at the apex of the panhandle region of the delta occurs in April (Fig. 2a). The average annual discharge is 1.01×10^{10} m³ (s.d. 1.2×10^{9} m³), but is quite variable, ranging from a low of 6.0×10^{9} m³ to a high of 1.64×10^{10} m³ over the past 60 years.

The delta is actually an alluvial fan[16] and has a low gradient (1:3300[17]), and limited local relief. Moreover, distributary channel margins consist of vegetation and are permeable. Seasonal flood water therefore leaks from the channels, and spreads laterally by overland flow, seasonally expanding the area of the wetland.[15] Base flow in the Okavango River is sufficient to sustain about 4000 km² of permanent swamp at the apex of the fan and the lower panhandle, while the area of inundation may increase to in excess of 12 000 km² at peak flooding. Because of the low topographic gradient and low local relief, movement of the flood wave across the fan is slow, taking four to five months to traverse the 250 km from Mohembo to Maun (Fig. 1). Outflow thus peaks in the Thamalakane River in August (Fig. 2b).

While the seasonal influx of water from Angola is important, the area inundated is also strongly influenced by local rainfall. The Okavango is located on the northern fringe of the Kalahari desert, and receives an average rainfall of 490 mm/yr, mainly in the form of convective thunderstorms that develop in the late afternoon.[18] Rain falls mainly between October and May (Fig. 2c). Although rainfall is relatively low, the area of the delta is large, so that the annual volume of rain falling over the delta is similar to that of the annual flood, and hence rainfall and inflow contribute about equally to the seasonal flood.[15] The aridity of the region is illustrated by the fact that the class A pan-derived estimate of annual evaporation of 2172 mm is four times the yearly rainfall.

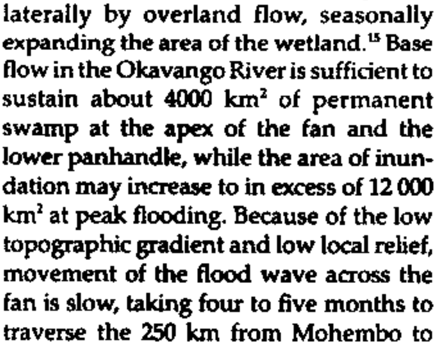

Fig. 2. **a**, Average monthly discharge in the Okavango measured at Mohembo; **b**, average monthly discharge in the Thamalakane measured at Maun; **c**, monthly rainfall over the Okavango delta (average of Maun and Shakawe rainfall records).

As the annual flood wave expands outwards from the fringes of the permanent swamps, it encounters dry ground, where it infiltrates, raising the water table. Therefore, a considerable proportion of the annual flood water is lost to ground water. The depth of the water table is accordingly an important variable in the extent of seasonal flooding. The main contribution of rain appears to be by its effect on the water table. Good summer rain raises the water table, reducing the loss of flood water to ground water, and hence increasing the extent of flooding and of outflow from the delta. Antecedent conditions have a similar effect. If the water table is high due to a large flood in the previous year, a relatively modest inflow can result in extensive surface flooding and a large outflow. Lowering of the water table occurs as a result of transpiration, particularly by the many large trees that grow on islands in the delta.

Climatic controls

The factors controlling climate in southern Africa as a whole are well known,[19] as are those specifically affecting the Kalahari.[18] Solar radiation in the tropics drives the two Hadley cells, the ascending limbs of which are associated with the equatorial trough and the Inter-Tropical Convergence Zone (ITCZ). Over central Africa, the ITCZ exhibits a marked seasonal change in both orientation and position, which has important consequences for rainfall in the region. The subsiding limb of the southern Hadley cell and the more southerly, temperate Ferrel cell are responsible for the subtropical ridge of high pressure centred on about 30 °S, and create the anticyclonic conditions that dominate the interior of southern Africa. This zone of high pressure is relatively insensitive to seasonal change, migrating by only about 6° between seasons. The African landmass breaks this high-pressure ridge into the Indian Ocean and South Atlantic anticyclones, particularly in the summer, when heating of the landmass is at its maximum. The former dominates air flow over most of southern Africa. The situation is more complex in Angola, owing to the Atlantic Ocean transport of moisture into the region via the equatorial westerlies. In summer, the ITCZ migrates southward and develops a prominent embayment over northern Mozambique and southern Malawi, which greatly influences air flow over south-central Africa. North of about 20 °S three major air streams are involved: recurved south Atlantic air that moves across Africa north of about 12 °S (equatorial westerlies), northeast monsoon air of east Africa that moves across the equator from the northeast; and the tropical easterlies from the Indian Ocean. This zone of complex convergence, which extends across central Angola, Zambia and Congo, includes not only the ITCZ, but also the convergence of south Atlantic and Indian Ocean air masses (the Congo, formerly Zaire, Air Boundary, CAB). It is characterized by vertical transport of air and the development of closed tropical lows, troughs and ridges. The position of the CAB fluctuates daily, and is characterized by the fairly frequent occurrence of low pressure systems, which may produce copious general rains. During summer, the CAB may link to thermal lows that develop in the interior of southern Africa, producing widespread rain across the Kalahari. During winter, the ITCZ and CAB migrate northwards, and the Okavango and its catchment come under the influence of intensified anticyclonic conditions over interior southern Africa, and the Indian Ocean anticyclone, and are generally dry.

Because of the dominant anticyclonic circulation over southern Africa, moisture in the interior is derived primarily from the Indian Ocean.[20,21] As the air mass moves westwards from the warm ocean, orographic effects of the eastern escarpment reduce moisture levels, and these decline progressively in a westerly direction, resulting in increasing aridity towards the interior of southern Africa. The cold Benguela Current along the west coast ensures that air masses from the west contribute little to interior rainfall. Consequently, there is a marked decreasing rainfall gradient from east to west across southern Africa.

The climate over southern Africa is not

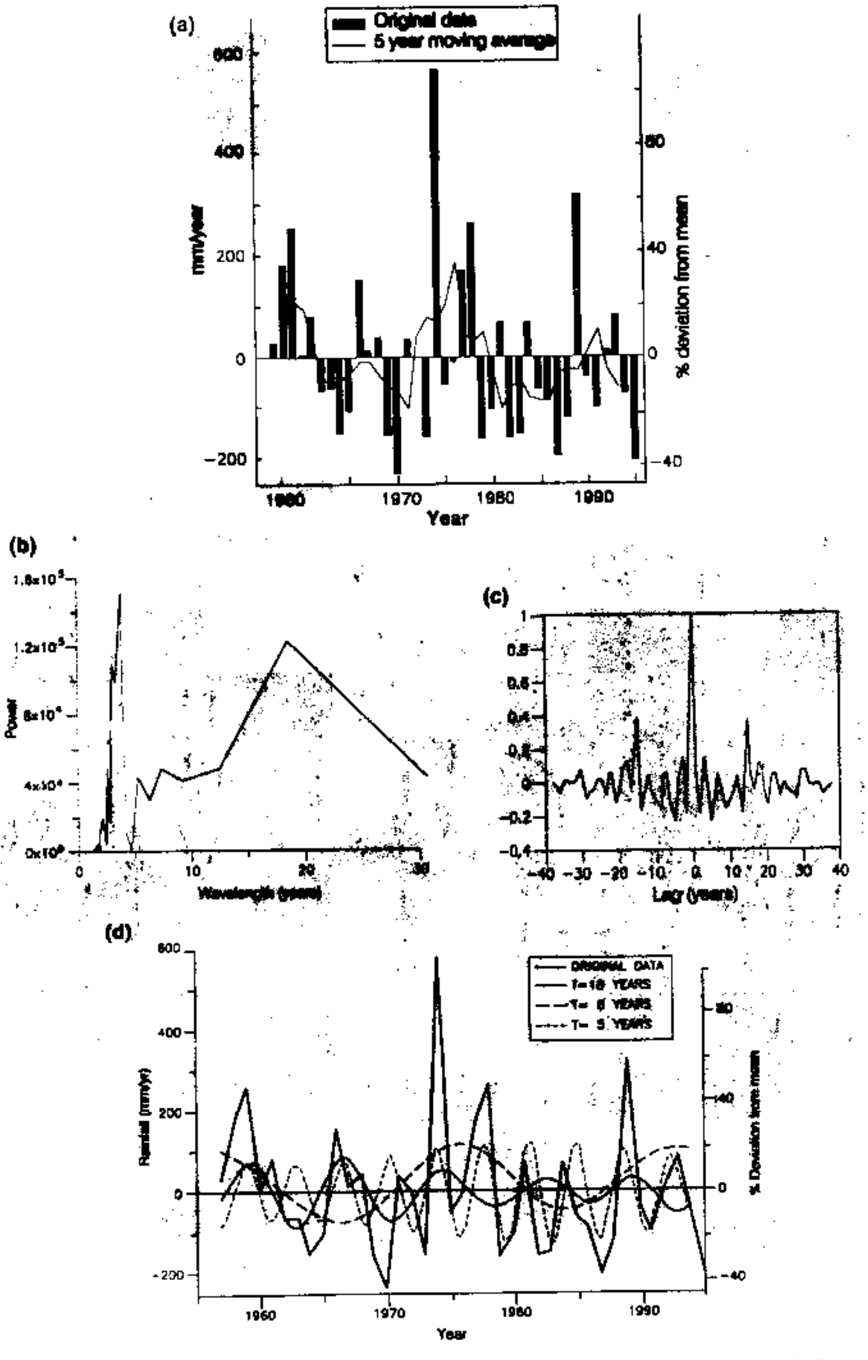

Fig. 3. a, Shakawe rainfall record plotted as a deviation from the long-term mean. A five-year moving average is superimposed on the data; **b**, power spectrum of the Shakawe record; **c**, autocorrelation analysis of the Shakawe rainfall record; **d**, contributions of the 5, 8 and 18-year oscillations to the Shakawe rainfall record.

only affected by seasonal migration of the ITCZ and CAB, but is also influenced by remote events and teleconnections arising from the Walker circulation, which results from interaction between equatorial sea-surface temperature in the Pacific Ocean and atmospheric circulation. This creates a series of east–west meridional circulation cells in the tropics. A rise in sea-surface temperature in the eastern Pacific (the so-called El Niño–Southern Oscillation, or ENSO) causes an eastward shift of the convergence zones in sub-equatorial southern Africa, and a consequent fall in precipitation over central Africa. Increasing sea-surface temperature over the western Pacific in the vicinity of Indonesia, which is associated with increased upwelling of cold, deep ocean water along the coast of Peru and a lowering of sea-surface temperatures in the eastern Pacific, causes a westward shift in the convergence zones over southern Africa, and an increase in precipitation over the sub-equatorial interior (La Niña events).

Rainfall and inflow records of the Okavango region

Rainfall has been recorded intermittently at Shakawe since the early 1930s; continuous records exist only from 1956. These data are shown as a deviation from the long-term mean (532 mm/yr) in Fig. 3a. Throughout the period of the record, rainfall has oscillated about the mean, and the 5-year moving average shows an apparent *ca.* 20-year wavelength. Fourier analysis[22] was undertaken to determine the frequency content of the data in more detail, and the resulting power spectrum (Fig. 3b) shows peaks at wavelengths of 2–3, 5 and 18 years, with a weak peak at about 8 years. The autocorrelation (Fig. 3c) confirms the strong amplitudes at these wavelengths. The contributions of the 5, 8 and 18-year oscillations to the rainfall are shown in Fig. 3d. The calculation of the power spectrum by Fourier techniques produces amplitudes at equal intervals of frequency because data are measured at equal intervals in time. This means that the amplitudes (power) were calculated at variable wavelength intervals, with the short wavelengths being well sampled and the longer wavelengths being progressively more poorly sampled. Hence, the accuracy of estimation of the amplitude becomes increasingly uncertain at longer wavelengths. As the length of the rainfall series increases, so the problem is ameliorated.

The rainfall record for Maun is considerably longer than that for Shakawe, and a continuous record is available from 1925. This is shown in Fig. 4a as a deviation from the long-term mean (448 mm/yr). Pre-1945 rainfall was generally below the mean, from 1945 to 1979 it was above the mean, and again below the mean in the period since 1979. The lowest rainfall on record occurred in 1994. Fourier analysis reveals peaks at wavelengths of *c.* 6, 10 and 22 years, superimposed on a noisy background (Fig. 4b). The autocorrelation analysis (Fig. 4c) is very different in character from that of Shakawe, and suggests that significantly more random noise is present in the data from the Maun station. The 18-year oscillation does not emerge clearly, despite its clear regional manifestation in adjacent areas to the east and southeast.[6,7]

Rainfall at Maun and Shakawe are poorly correlated (Fig. 5) (R^2 is 0.54, but reduces to 0.34 when the single outlier is removed). The poor correlation is partly due to the nature of the convective thunderstorms that produce most of the rainfall in the region, and which cause

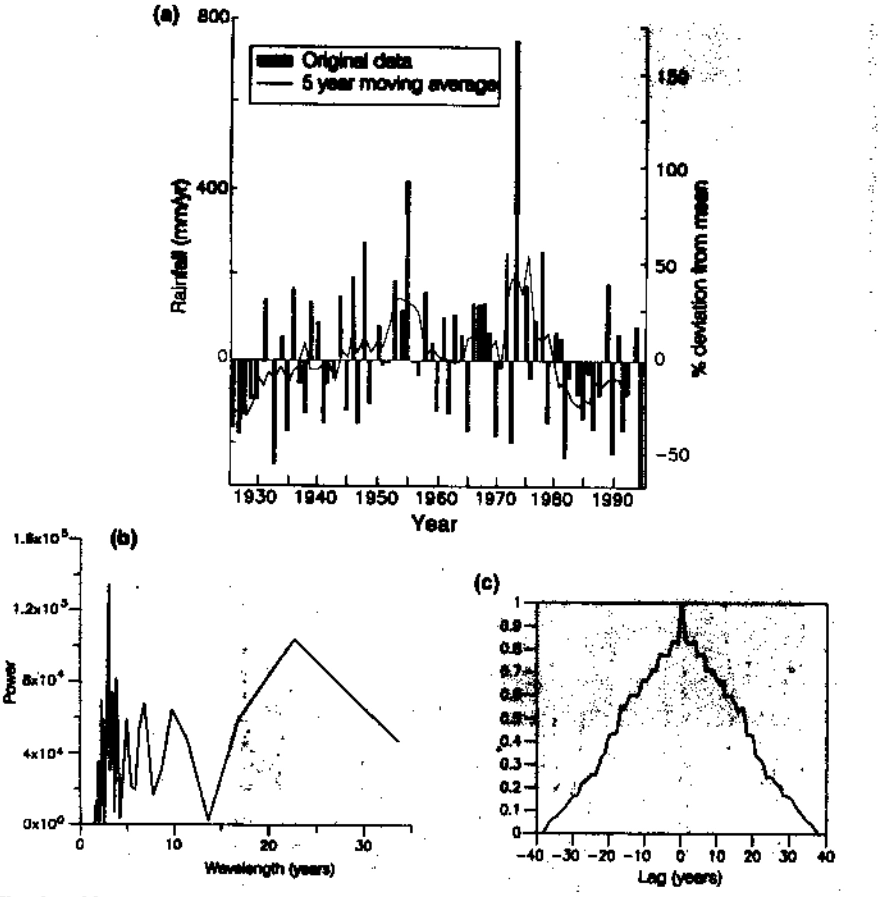

Fig. 4. a, Maun rainfall record plotted as a deviation from the long-term mean. A five-year moving average is superimposed on the data; b, power spectrum for the Maun record; c, autocorrelation analysis of the Maun rainfall record.

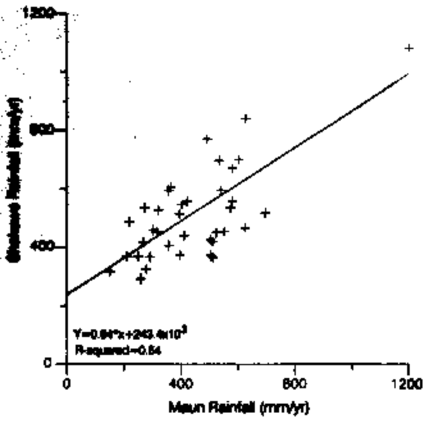

Fig. 5. Correlation between the Maun and Shakawe rainfall records.

isolated and erratic rain. The peaks in the power spectrum of the Maun data are weak in relation to the background. By contrast, the Shakawe dataset shows clear peaks above the background in the power spectrum, and the autocorrelation confirms the existence of regular oscillation. These contrasting characteristics between the two datasets suggest that the two stations may lie in slightly different climatic regimes.

Rainfall over the Okavango Delta as a whole is best approximated by the average of the Maun and Shakawe records. This is shown in Fig. 6a, as a deviation from the long-term mean (490 mm/yr). The 3, 8 and 18-year oscillations are weakly developed in the combined data set (Fig. 6b). It is evident that rainfall over the delta has been below the long-term average since the late 1970s.

Annual discharge (October to September) of the Okavango River at Mohembo from 1932–33 to the present is shown plotted as a deviation from the long-term mean (10134 Mm^3/yr) in Fig. 7a. Several peaks are visible in the Fourier power spectrum (Fig. 7b) at approximately 3, 5, 8 and 15 years, the strongest being the 8-year oscillation. Band pass filtering[25] to remove all variance except the contributions at wavelengths of 5, 8 and 15 years, reveals that the 5-year oscillation appears to be particularly well correlated with the observed data (Fig. 7c), but that there appears to be a decline in the amplitude of both the 5- and the 8-year oscillations in the period since 1980.

Inflow to the delta reflects run-off from the catchment of the Okavango River in Angola, which in turn is a function of rainfall in that region. Inflow is therefore a proxy for integrated rainfall over the catchment. Comparison of the 5-year moving average for the inflow record (Fig. 7a) with that for Shakawe rainfall (Fig. 3a) indicates that in the period

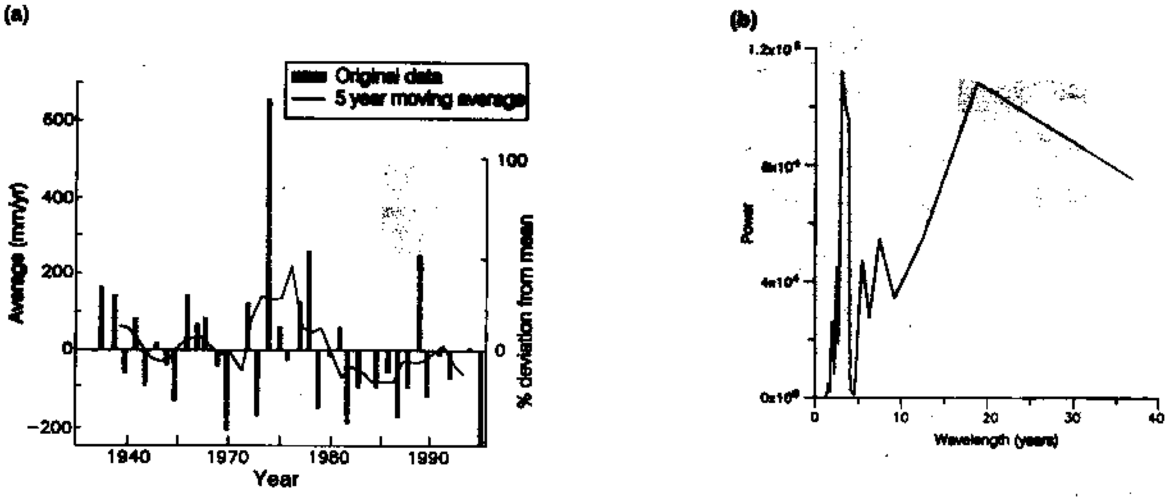

Fig. 6. a, Average of the Maun and Shakawe rainfall records; b, power spectrum of the Maun-Shakawe average rainfall record.

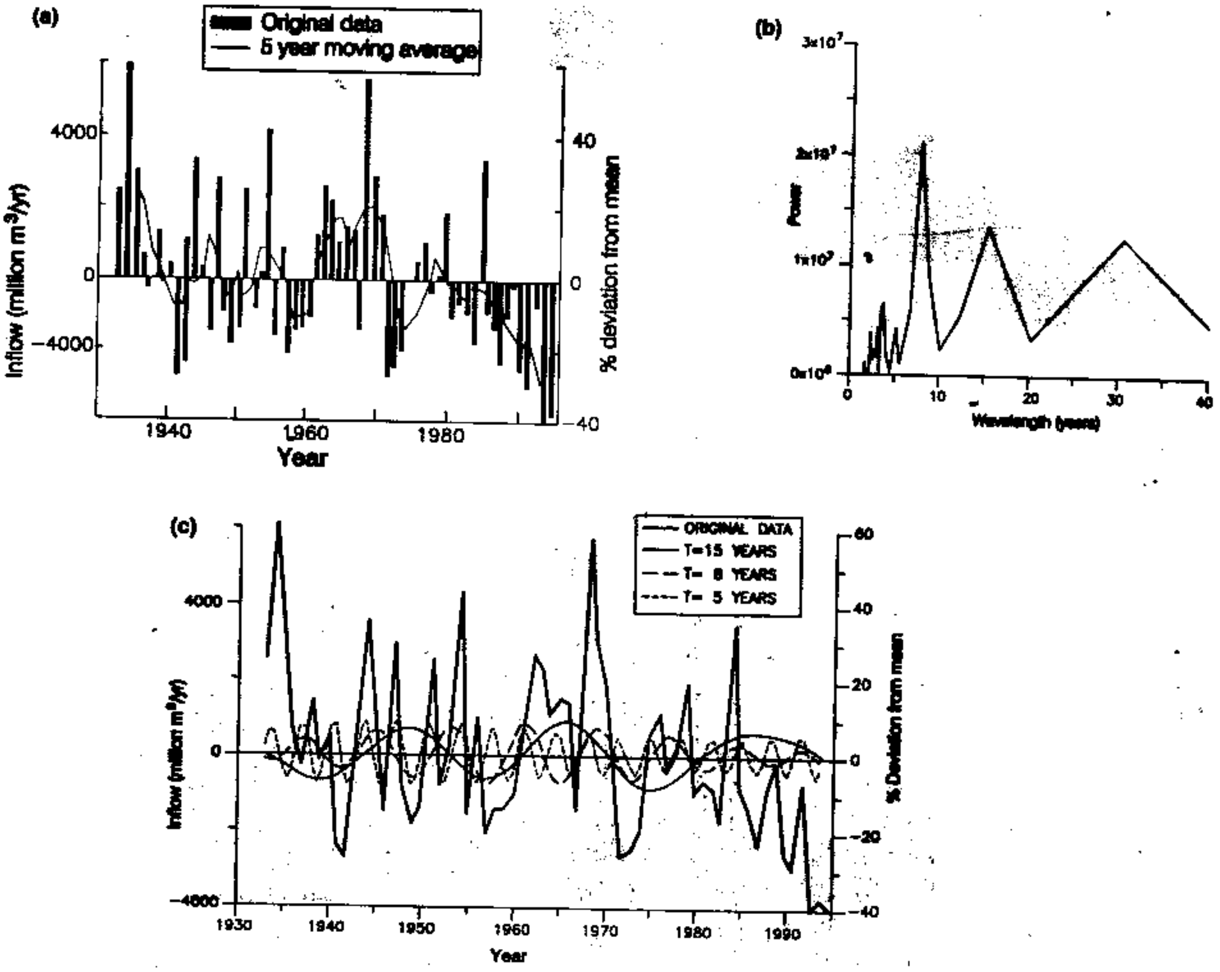

Fig. 7. a, Inflow record measured at Mohembo plotted as a deviation from the long-term mean. A five-year moving average is shown superimposed on the data; **b**, power spectrum of the Mohembo inflow record; **c**, inflow data and oscillations present at periods of 5, 8 and 15 years.

pre-1960 Shakawe rainfall was above the mean, while inflow was below. This situation was reversed in the period 1960 to 1970. In the 1970s, Shakawe rainfall was above average while inflow was below. This suggests an antithetic relationship between Shakawe rainfall and rainfall in the catchment to the north. In the period since 1980, this anticorrelation appears to weaken significantly, and the rainfall in the catchment has declined, while the rainfall at Shakawe has remained closer to, albeit below, the long-term mean. The antithetic relationship is further illustrated by a cross correlation between Shakawe rainfall and inflow (Fig. 8), which shows the strongest correlation at a lag of approximately 10 years. Cross correlation between Maun rainfall and inflow failed to show any significant correlations.

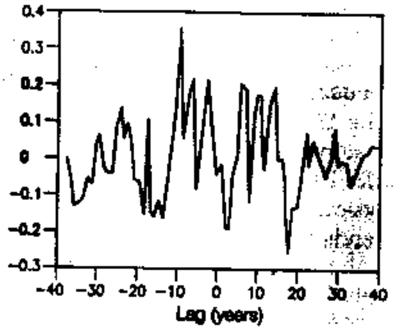

Fig. 8. Cross correlation analysis between the Shakawe rainfall record and the inflow record.

Rainfall and inflow combine in a complex way to create the seasonal flood, and outflow from the delta. Outflow is a proxy for the extent of seasonal flooding: the greater the area flooded, the greater the outflow. Unfortunately, the outflow record is particularly short, commencing only in 1970. Measured annual outflow in the Thamalakane River at Maun is shown in Fig. 9a as a deviation from the long-term mean (236 Mm³/yr). The period used for calculating annual outflow was February to January, because of the delayed arrival of the seasonal flood at the southern end of the delta (Fig. 2). The decade of the 1970s was characterized by relatively high outflows, while outflow in the post-1980 period has been low. In an attempt to extend the record back in time, a numerical relationship between outflow and inflow, rainfall, previous season's flood (outflow) and evaporation (taken as a constant 2172 mm)[15] was used to estimate outflows back to 1956. These are shown in Fig. 9b. Although these are only estimates, the resulting pattern fairly accurately reproduces the post 1970 period, providing some confidence for the projection backwards in time. This projection suggests that the pre-1970 period was also characterized by above-average outflows. During the decade of the 1960s, rainfall over the delta was close to the long-term mean (Fig. 6a), while inflow was high (Fig. 7a), producing good floods; in the 1970s, inflow was largely below the long-term mean (Fig. 7a), but this was compensated for by above-average rainfall. Since 1980, however, rainfall has fallen slightly below the long-term average, while inflow has declined markedly, resulting in very poor seasonal floods.

The Okavango catchment and its environs

The Okavango River derives its water from two major tributaries, the Cubango in the west and the Quito in the east

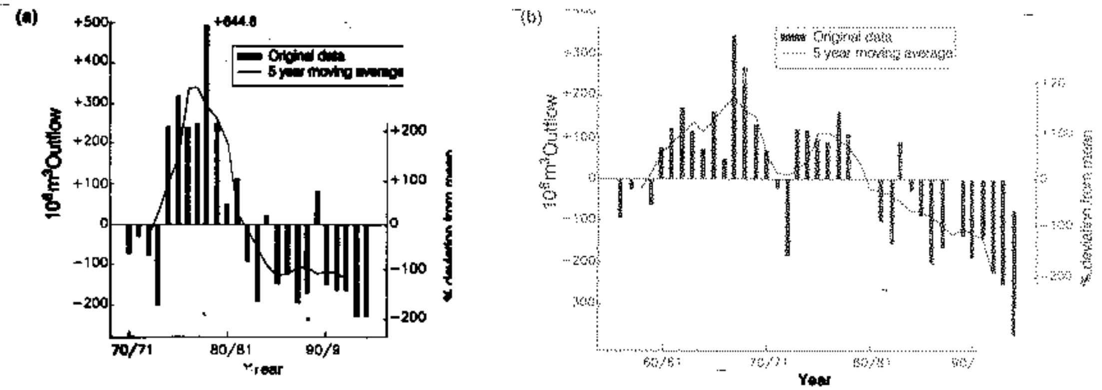

Fig. 9. **a**, Measured outflow from the delta in the Thamalakane River; **b**, calculated Thamalakane outflow. See text for details.

(Fig. 1). The Cubango (or Kavango as it is known in Namibia) has been gauged since 1945 at Rundu, while the combined discharge of the Quito and Cubango has been monitored at Mukwe (Fig. 1) since 1949. The difference between the discharge records for these two stations provides an indication of the contribution of the Quito to inflow into the Okavango.

The average monthly discharge records for the Cubango and Quito rivers (Fig. 10) indicate a more pronounced seasonality in the Cubango, probably due to greater floodplain damping along the lower reaches of the Quito.[9] This also has the effect of delaying the peak flood on the Quito relative to the Cubango by a month. The contribution of the Cubango to inflow to the Okavango Delta is slightly greater than the Quito (559 and 436 Mm^3/yr, respectively).

Surprisingly, there is no correlation between discharges of the Cubango and Quito rivers (Fig. 11; $R^2 = 0.030$), in spite of the fact that their catchments are adjacent (Fig. 1). The long-term records of the two rivers differ in detail. Discharge of the Cubango is erratic, but fairly constant over the record period (Fig. 12). By contrast, the Quito record shows a pronounced decline in the period since 1980 (Fig. 13). The peaks and troughs in the two records nevertheless generally coincide. However, the power spectra of the Cubango and Quito are different (Figs 14a,b). Comparison of Figs 7b (inflow) and 14a,b (Cubango and Quito tributaries) suggests that the short-wavelength oscillation may originate in the Quito catchment, while the 8 and 15-year oscillations probably arise in the Cubango catchment. This observation, combined with the dissimilarities in the two sets of records, suggests further that different rainfall forcing is present in the two catchments.

To investigate this further, the discharge of the Zambezi (measured at Victoria Falls) is compared to the discharge record of the Quito. The correlation coefficient between these two discharges is 0.32 (Fig. 15), and although weak, is still stronger than between the Quito and the Cubango. The discharge record of the Zambezi is the longest in the region, extending back to 1907 (Fig. 16a). Like the Quito, the Zambezi discharge declined markedly after 1980. A power spectrum for the Zambezi record shows a strong 5-year oscillation is evident, with weaker *c.* 10- and 21-year oscillations, and with an indication of substantial energy at a wavelength of around 80 years (Fig. 16b). Circular periodicity analysis[24] confirms the possibility of the 80-year oscillation (Fig. 16c). This long oscillation is shown superimposed on the Zambezi discharge record in Fig. 16a. Despite the corroboration between the Fourier and circular periodicity analysis, the validity of the 80-year oscillation remains uncertain, because of the length of the record.

The low discharges of the Zambezi recorded in the early 1990s are similar to those experienced in the early part of this century. The record of the Quito exhibits a similar form (Fig. 13) for the overlapping period, hinting that a long-wavelength oscillation similar to that of the Zambezi may be present in the Quito record. The Zambezi and Quito records are similar in another respect. In the Zambezi record, the amplitude of the ENSO oscillation of 3 to 5 years increases as the average discharge increases. The Quito record shows a similar effect. These observations suggest that the Quito and Zambezi catchments lie within a similar climatic regime, which differs from that of the Cubango.

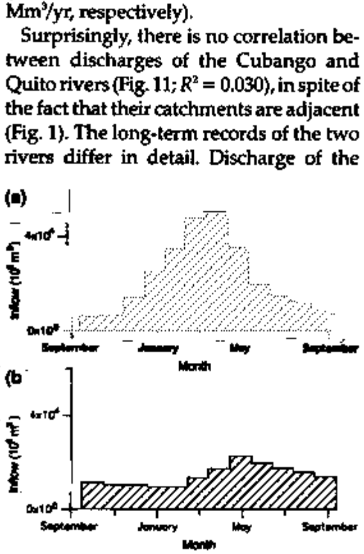

Fig. 10. **a**, Average monthly discharge record for the Cubango River; **b**, average monthly discharge record for the Quito River.

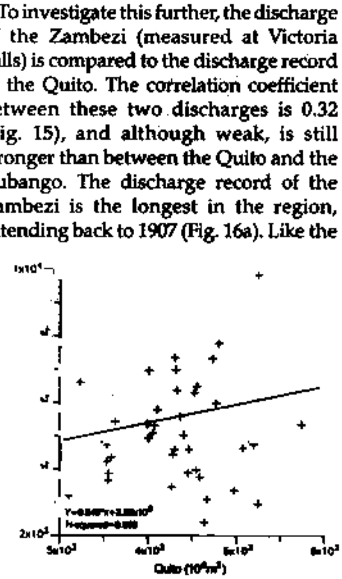

Fig. 11. Scatter plot of annual discharge of the Quito and Cubango rivers.

Discussion

The 18-year oscillation in rainfall over the summer rainfall regions of southern Africa has been confirmed in many geophysical data series, not only rainfall,[6] and extends north into southern Zambia.[7] The oscillation has resulted in alternating spells of around nine years being wetter or drier than average. The decade of the 1980s saw below-average rainfall, the seventies above-average, the sixties