CHANGING FLOWS IN SOUTHERN AFRICA AND ITS RELATIONSHIPS TO RAINFALL VARIATIONS

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ABSTRACT

Flow duration curves (FDCs) were used to study characteristics of daily flows in southern Africa and thereafter used to define the thresholds of low and high flows. Change-point analysis methods were used to identify the existence of any discontinuities in the indices of streamflow. FDCs identified three types of rivers (ephemeral, seasonal and perennial) in southern Africa with ephemeral rivers found mainly in the dry western part of the region. Seasonal streamflow patterns were observed to follow those of rainfall. Change-point analysis indicated significant changes in the river flows regimes in the southern African rivers which have occurred in the 1970s through early-1980s. The changes mainly affected the mean flows with little evidences of high and low flow regime. These changes led to decreases in river flows in western Zambia, Namibia and northeast South Africa considerably affecting the flows during the high flow months in which 34-80% of the annual flow volumes are observed. The results further indicated occurrences of periods of no flow in recent decades in some perennial rivers while lengthening of the no flow period in seasonal rivers. In some parts of southern Africa, alternating increases and decreases in river flow indices were observed which corresponded mainly to interannual patterns of rainfall variation. In other parts like in the eastern Mount Kilimanjaro, the influences of degrading landuse practices contributed significantly to declining flows. However, it was not possible to provide strong links between the identified changes in streamflows and those in rainfall.

Keywords: streamflow variations, flow duration curves, flow extremes, change-point analysis, interannual variability

INTRODUCTION

Surface water resources in southern Africa are declining leading to growing conflicts between different competing users such as agriculturalists, hydropower plants and water suppliers. Dam levels have been reported to decline since the mid 1970s in Namibia (Jury and Engert, 1999), in South Africa since the early 1980s as a reflection of prolonged rainfall deficit in the 1980s and early 1990s (Mason, 1996). Berhanu (1999) found a recent decrease in mean annual runoff in southern African catchments that occurred since 1975, particularly marked in Zambia, Angola, Mozambique and the South African High Veld. The decline is attributed mainly to declining and unreliable rainfall, population increase and changing land and water uses.

It is plausible to hypothesize that identified changes in southern African surface water resources are reflected from changes in rainfall as observed in West Africa (Mahé and Olivry, 1991; Servat *et al.*, 1997a) and their severity is increased by human-related influences. Past studies have identified a mixture of increasing and decreasing rainfall amounts in some parts of southern Africa (Mason *et al.*, 1999; Mkhandi and Ngana, 1999; Mutua, 1999) while in others there was no strong evidence of declining or increasing trends. However, there is evidence of increasing frequency of high rainfall events in some parts of southern Africa (Mason and Joubert, 1997; Smakhtina, 1998; Mason *et al.*, 1999). Such changes in rainfall alone could have serious negative consequences to water resources, the population and properties. Frequent floods have been reported in recent decades in both the humid and dry parts of the region (e.g. the 1984 floods along the Namibian coast; the February 2000 severe floods which hit Mozambique; the November-December 1997 floods in east Africa).

Moreover, the southern African population is dynamic and has been growing rapidly in recent decades with the highest population densities and growth rates in the humid and fertile eastern part. Its rapid growth and consequential increased water demand have led to changes in the landuse and water use patterns in the region with more land being cleared for modern agriculture mixed with modern animal husbandry. Consequently large land areas become exposed to actions of the weather and man which may alter soil surface characteristics resulting in increased frequency and/or volumes of flash floods due to poor infiltration. Insufficient groundwater recharge due to poor infiltration during the wet season may further lead to declining dry season flow and hence the danger of severe streamflow droughts.
Therefore, this study investigates changes in flow volumes and flow regimes for selected rivers in southern Africa to highlight their spatio-temporal characteristics and their relationships to changing rainfall and the climate.

DATA, METHODS AND STUDY INDICES

Data

Average daily flow data in rivers in the 11 southern African countries have been acquired from the southern African FRIEND HYDATA database at the Department of Water Resources Engineering (WRE) of the University of Dar Es Salaam. The database was compiled by the Centre for Ecology and Hydrology (formerly the Institute of Hydrology, Wallingford) for the Southern African FRIEND. It comprises time series of average daily river flows for 676 gauging stations. Additional 23 records of average daily flows and updates of the 79 records in the FRIEND database for gauging stations in the Pangani and Rufiji River basins in Tanzania were obtained from the Hydrology Section of the Department of Water Resources in the Ministry of Water and Livestock Development (Tanzania). The spatial distribution of the river flow gauging stations is dense in the eastern, northeastern and southern South Africa, in the eastern and southwestern Zimbabwe, in central-western Namibia and in the two Pangani (northeast) and Rufiji (southwest) basins in Tanzania.
The preliminary data analysis indicates that the southern African region is characterised by short streamflow records. Therefore, the selection criteria of record length, missing data and period of interest were applied to preliminarily screen out unsuitable records. Moreover, Valimba (2004) showed that areas such as part of the southern highlands of Tanzania, northern half of Mozambique and the South Africa lowveld are characterized by intense daily rainfall events and are therefore prone to flooding. The western part of southern Africa is dry and rivers there experience frequent and prolonged dry conditions. Basins whose rivers drain these areas are of particular interest in studying relationships between rainfall and flow variations. The selection process further excluded all gauging stations located downstream of any artificial regulation points. Gauging stations within the selected basins were further selected in such a way to avoid closely located gauges while retaining as many gauges as possible along the river lengths. The overall requirements of analysing long continuous records from unregulated catchments within the selected basins, therefore, retained 38 river flow records (Fig. 1).

Methods

Interannual variability of flow indices was investigated using the change-point analysis methods which identify discontinuities (shifts) in the mean values of a time series. The procedure is described in detail and used in Valimba (2004), Valimba *et al*. (2004a) and Valimba *et al*. (2004b). In summary, the non-parametric test of Pettitt and autosegmentation procedure of Hubert (Lubès-Niel *et al*., 1998 and references therein) were used with some procedural modification of the Pettitt test, as described in the mentioned articles, to provide multiple segmentation. The interpretation of results of these tests assumed shifts only when segments were at least 5 years long. Segments of less than 5 years were treated as grouped outliers while those comprising single years as isolated outliers.

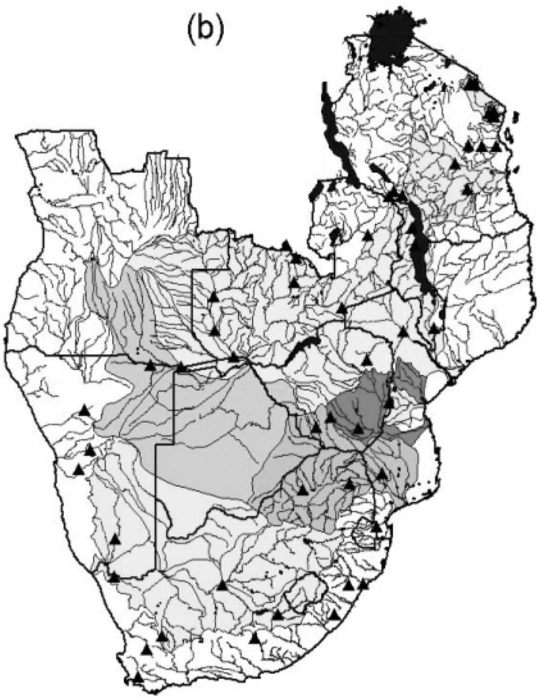

Fig. 1: Spatial distribution of selected flow gauging stations used in the interannual variability analysis in southern Africa. The coloured background indicates some of the important and shared river basins in the region.

Study indices and time series reconstruction

In order to verify the study hypotheses of reduced flows and enhanced frequency and severity of flow extremes (floods and droughts), various indices were extracted from available flow records. Average discharges were appropriate to highlight the flow increase or decrease. The frequency and severity of floods and drought in southern Africa were studied using frequencies and volumes of excess and deficit flows. The excess (deficit) flow frequency was defined as the number of days above (below) the threshold defining the flood (drought) flow while excess (deficit) flow volume was the cumulative flow volume above (below) the respective thresholds (Valimba, 2004; Valimba *et al*., 2004a).
The analysis of the flow duration curves at various gauging stations indicated that the flows that have been equaled or exceeded 5% (Q5) and 70% (Q70) of the time when it flows appropriately defined the flood and drought flow thresholds respectively. The indices provide a significant number of daily flows above or below them appropriate for interannual variability analysis while avoiding the problem of the frequent zero-drought/flood years, which were apparent when higher (e.g. Q1) or lower (e.g. Q90) thresholds were used.

RESULTS

River flow regimes

The FDCs calculated with zero flows included distinguished i) seasonal rivers from perennial rivers and ii) highly seasonal (or ephemeral) rivers from moderately seasonal rivers. in the southern Africa region. Ephemeral rivers flow when there is rainfall and cease almost immediately afterwards and are found in Botswana, Namibia, western Zimbabwe and South Africa. Moderately seasonal rivers flow continuously during the rainy season and cease sometime after the end of the rains and dry up completely during the dry period. They are a characteristic of small catchments in the Limpopo and in the Western Cape in South Africa and flow continuously between May and December (Western Cape) and November and April-July (other parts of unimodal southern African), the exact end month of the flow between April and July being dependent on catchment characteristics. Perennial rivers flow throughout the year and are a characteristic of most rivers in southern Africa, particularly the main rivers in the large river basins or their main tributaries in the large river sub-basins. The rivers are characterised by non-zero FDCs indicating residual flows during the dry period and experience periods of high and low flows.

Flow seasonality

Seasonal flow variations in the perennial rivers in southern African are characterised by double flow peaks in northern Tanzania, as well as parts of the southern and Eastern Cape and a single flow peak in the rest of the southern African subcontinent. The peaks correspond to seasonal rainfall variations in the region with double peaks in northern Tanzania corresponding to the bimodal rainfall regime (the short and long rains) and those in the southern South Africa and Eastern Cape in April and December corresponding to early and late summer rainfalls while a single peak in the remaining part corresponding to the unimodal rainfall regime.

A comparison of mean monthly flows (μ_{mon}) and mean annual flows (μ_{an}) indicated generally that the periods June-September and January/February-April/May are respective high flow periods in the Western Cape and the rest of the unimodal southern Africa and April-June in northern Tanzania. The highest monthly flows are observed in January-February in most parts of unimodal southern Africa, in August in the Western Cape, in March-April in Zambia and Malawi and in May-June in northeast Tanzania. Similarly, low flows are observed during the dry periods, July-November in unimodal southern Africa, December-March in the Western Cape and both August-October and February-March in bimodal northeast Tanzania. Moreover, mean monthly flows vary greatly between southern African catchments with the highest mean flows observed along the length of the main rivers in the large basins or their main tributaries (e.g. the Zambezi basin or its Luangwa sub-basin; the Okavango basin, etc) which drain the humid part of southern Africa.

Interannual variations

Results (Tab. 1) of change-point analysis performed on seasonal flow indices indicate that excess and deficit flow volumes and frequencies exhibit almost similar patterns of interannual variability. However, for flow extremes, shifts were predominant in the frequency indices than the volume indices. The results further indicated that shifts were predominantly in mean seasonal flows than in the frequencies and volumes of high and low flows and characterised mainly the late summer (February-April, FMA) season. Moreover, shifts in the low flow indices were mostly identified during the the austral winter (June-August, JJA) season. The identified shifts during both the early (November-January, NDJ) and late (FMA) austral summers were predominantly unidirectional and towards a decrease, except in some rivers in northeast Tanzania. These abrupt changes were mainly identified in the 1970s and early-1980s although changes were identified as early as in the late-1950s and early-1960s (Fig. 2).

Tab. 1: Summary of shifts in seasonal flow indices in southern Africa.

	Seasonal Flow Index							
	Mean flow			Excess Flow Freq.		Deficit Flow Freq.		
	NDJ	FMA	JJA	NDJ	FMA	NDJ	FMA	JJA
Total number of analysed stations	41	43	43	43	43	42	44	44
Total number of stations with shifted flows	13	22	14	7	19	12	13	19
Total number of unidirectional shifts in	12	20	13	7	16	9	8	11
Total number of upward unidirectional shifts in	4	6	5	1	3	2	3	4
Total number of downward unidirectional shifts in	8	14	8	6	13	7	5	7

The cumulative flow volumes during the whole austral summer (November-April) account for 56.7-99.2% of annual flow volumes and the two seasons, NDJ and FMA, account separately for 9.7-59.0% and

34.0-79.9% of annual flow volumes, the largest percentages being for seasonal rivers in the unimodal southern Africa. The mean flow decreases, particularly during the FMA season, were related to changes of up to 50% or higher. This is illustrated by complete declines in the Namibian rivers and abrupt decreases in FMA and JJA seasonal mean flows and deficit flow frequencies in the upper Zambezi in western Zambia (Fig. 2). The start of the declining flows in Namibia is consistent with the start of declining rainfalls (Valimba, 2004) and dam levels (Jury and Engert, 1999) around the mid-1970s. Berhanu (1999) reported declining annual runoff in parts of Zambia and Angola. Furthermore, frequent and lengthening periods of no flows were observed in some of the perennial rivers since the early-1980s suggesting that these rivers are being progressively transformed into seasonal rivers, results which were similarly observed in Zimbabwe (Magadza, 1995).

DISCUSSION

Changes in river flow regimes may result from a variety of factors such as changes in the climatic parameters (precipitation, temperature) and artificial influences in the catchment, including changing land and water use patterns (Hisdal *et al.*, 2001). The selection of flow records used in this study tried to avoid gauges which were regulated. Since no information on land and water uses patterns were available, a comparison of the interannual patterns of variability of streamflows and rainfalls would indirectly highlight the contributions of artificial influences on the streamflow changes, particularly since the 1960s.

In general, NDJ mean flows in southern African rivers have either remained unsegmented or abruptly increased, except for the rivers in Namibia, northeast South Africa and southern Zimbabwe (Fig. 2a). This is identical to changes in early summer (NDJ) seasonal rainfall amounts (Valimba, 2004). Similarly, predominantly decreasing FMA mean flows in unimodal southern Africa correspond to declining overall rainfall amounts in late summer (FMA) (Valimba, 2004). However, the abrupt decreases in FMA overall rainfall amounts in Namibia identified in the 1977-1980 period lagged flow decreases in the mid-1970s (Fig. 2). Due to their seasonal nature, the slight changes in rainfall since the mid-1970s might have caused the early decreases in river flows.

The lack of abrupt decreases in seasonal as well as annual amounts in western Zambia (Valimba, 2004) could be hardly linked to abrupt decreases in mean seasonal flows in the upper Zambezi (western Zambian) catchments, which bordered the Congo River basin. However, the results of linear trends for the 1961-1991 period (not shown) showed decreasing trends in seasonal amounts in these parts of Zambia. Sichingabula (1998) found decreasing annual rainfall in southern and eastern Zambia since 1975, while Bigot (1997) and Bigot *et al.* (1998) identified declining annual rainfall in the Central Africa and the Congo basin since the late-1960s, a decline which was similarly identified in the catchments within the Congo River basin (Laraque *et al.*, 1998, 2001) and which was reflected by decreasing annual flows since the 1970s. The changes in the western Zambian catchments could be partly related to the changes in rainfall identified in the Congo River basin.

Long rainfall records indicate abrupt changes towards persistent wetter conditions in areas around Mount Kilimanjaro (Valimba *et al.*, 2004a, 2004b). Despite a number of existing flow abstractions upstream, mean flows in all months at the most downstream gauge in the Kikuletwa River, which drains the western part of the Kilimanjaro, have increased since 1960/61 (Valimba *et al.*, 2004c), consistent with the reported increases in rainfall amounts. A number of past studies have identified similar increases in rainfall and other hydrological variables such as lake levels since the early-1960s in East Africa which includes Tanzania (Bergonzini, 1998; Nicholson, 1999; Nicholson, 2000). However, the rivers which drain the eastern part of Mount Kilimanjaro were characterised by decreasing flows in all months, contradicting the rainfall increases. A number of studies have linked such flow decreases to the population increase and degrading land and water use practices (Mujwahuzi, 1999; Ngana, 2002; Shishira, 2002; Yanda, 2002; Yanda and Shishira, 1999).

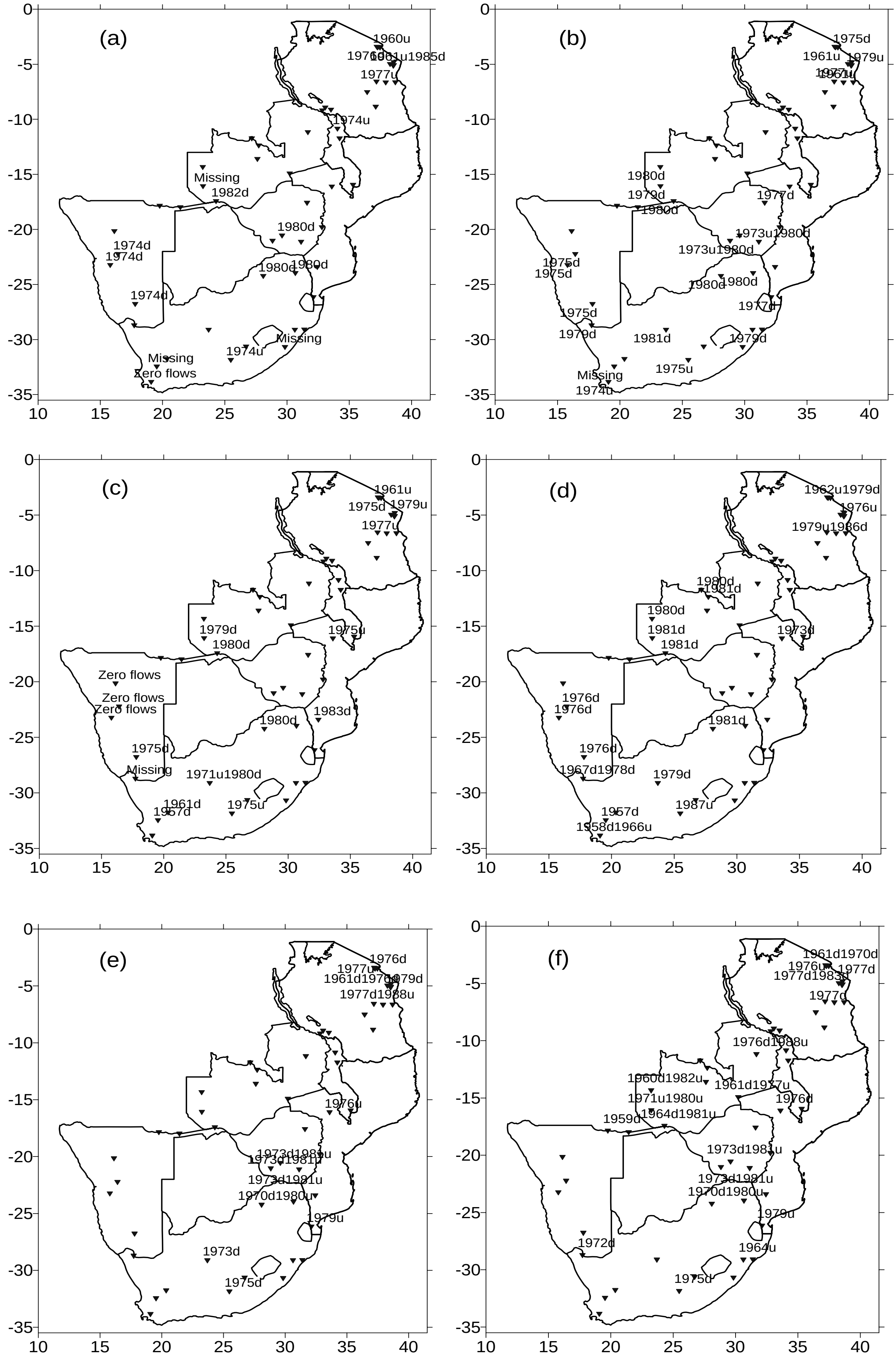

Fig. 2: Dates of shifts in a) NDJ, b) FMA and c) JJA mean seasonal river flows; in the frequencies of d) excess flows (see text for the high flow seasons), e) FMA deficit and f) JJA deficit flows in the southern African rivers. The year indicates the date of shift while the letters indicate the direction of shifts, u for the upward and d for the downward shift.

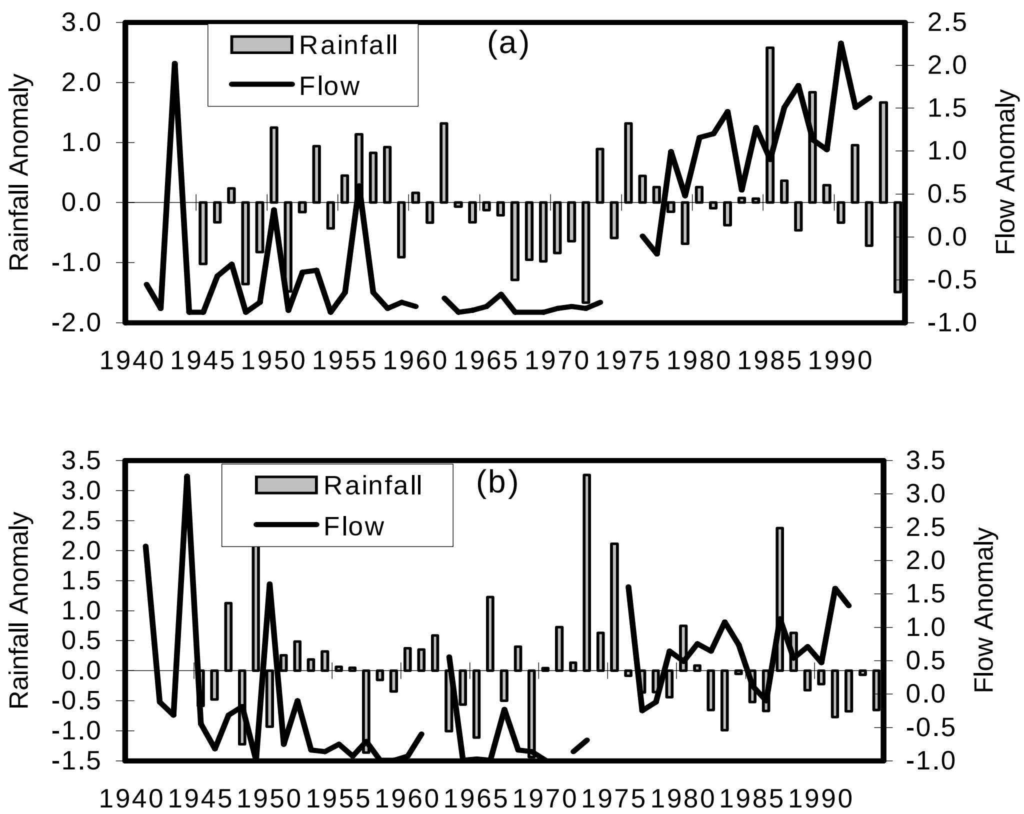

Fig. 3: Time series of anomaly a) NDJ and b) FMA seasonal flows and catchment overall rainfall amounts for the catchment of the gauge 27673901 in the Groot-Vis (Fish) River.

The importance of a thorough knowledge of changes of land and water use pattern within the catchments was illustrated by the flow regime transformation of the Groot-Vis (Fish) River located in the central southern part of South Africa that did not correspond to the pattern of rainfall variability (e.g. Fig. 3). The river has become perennial since around 1974/75. Time series of NDJ seasonal flows are persistently below average before the mid-1970s even during the period of above average rainfall in the 1950s (Fig. 3a) while the FMA rainfall series is predominantly below average after the mid-1970s contradicting the FMA flow series (Fig. 3b). The cause of the observed flow regime change in this river was the water transfer from the Orange River since the completion of the Gariep Dam in 1972.

Changing characteristics of flow extremes are affected partly by changing characteristics of intense rainfalls and changes in the catchment characteristics that affect runoff generation mechanisms. The results (Fig. 2d) show consistent and persistent decreases in the frequency of excess flows in rivers in western and northern Zambia since the early-1980 and in Namibia since the mid-1970s. In other southern African rivers, the changes were heterogeneous as they characterise only a few stations and not persistent as only segments of high or low frequencies were observed, after which, the series returned almost to the pre-change states. The pattern of the changes in the frequencies of excess and deficit flows, therefore, reflected generally the wet and dry periods in southern Africa (Valimba, 2004). Abundant rainfall observed in the 1970s in southern Africa (Chenje and Johnson, 1996) could have caused considerable groundwater recharge which lead to increased groundwater contributions to streamflows and therefore corresponded to decreased frequencies of deficit flow volumes. The rainfall deficits since the early-1980s and low between-the-years flow carry-over in most of the catchments caused a return to the pre-change state and was reflected to an increase of deficit flow frequencies since the early-1980s (Fig. 2e, 2f).

CONCLUSIONS

Seasonal and interannual variations of streamflows were almost similar to seasonal and interannual variations of rainfall. Seasonally, flow peaks correspond to rainfall peaks and occur mainly during the core of the rainy seasons. Interannually, significant unidirectional abrupt changes in mean flows have occurred mainly since the mid-1970s to early-1980 which i) significantly affected streamflows during the late summer (FMA), ii) led to significant reduction of streamflows in the upper Zambezi basin, Namibia and northeast South Africa, iii) were gradual in the upper Zambezi suggesting that slight changes in rainfall could translate into significant changes in streamflows and iv) indicated little evidence of changes in the flow extremes (high and low flows) except in the upper Zambezi and Namibia.

Since it has been a common practise to calibrate and verify parameters of the hydroclimatological models using long records, the results of this study suggests a revision of the operational and forecasting hydrological models to use pre- or post-change records during model developments to avoid non-stationarities in the 1960s and 1970s. The study found flow changes in Namibia and western Zambia which were consistent with rainfall changes while in other parts it was very difficult to associate changes in streamflows with identified changes in rainfall. Therefore, to accurately quantify the magnitude of the influence of rainfall changes on changes of streamflows, studies at finer spatial scales like catchment scales are recommended. The use of water balance models can assist in quantifying the influence of climate and rainfall changes on streamflows once other model components have been quantified and accounted for.

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