

Influences of variability of rainfall on flow regimes in central Ethiopia

FEKADU MOREDA & WILLY BAUWENS

Laboratory of Hydrology, Free University Brussels, Pleinlaan 2, B-1050 Brussels, Belgium

e-mail: fmoreda@vub.ac.be

Abstract This study investigates the link between the variability of annual runoff and the corresponding annual rainfall and flow regimes by using a headwater catchment of the Upper Awash River basin located in central Ethiopia. The flow series of the Awash River at Hombole station is extended from a longer time series of rainfall using a monthly water balance model, which enables the investigation of the long-term variation of flow regimes. The analysis of the reconstructed flow shows that there is an amplified variability of flow during the main rainy season (June–September). On the other hand, it is observed that the low flow regime (November–February) is less affected by variability of summer rainfall.

INTRODUCTION

From the annual rainfall record of this century, researchers have shown that there has been a shift of mean annual rainfall over northeastern Africa during the last half of this century. Sileshi (1994) reported that there is a decline of mean summer rainfall over this region since the mid-1960s, which has also been observed for the Sahel regions. Comparing the data of the Blue Nile catchment for two 20 year windows (1946–1965) and (1965–1984) Conway & Hulme (1993) estimated that there is an 18% reduction of the mean annual flow corresponding to an 8% reduction of annual mean rainfall in the second 20 year period. Earlier from analysis of 5 and 10 year moving averages of flow of the Blue Nile at Dongola, Misganaw (1989) asserted that there is a general trend of decline of the annual flows after the mid-1960s.

Due to the high local variability of rainfall and to the limited number of observations over the large area of a basin like the Blue Nile, it is always difficult to precisely determine the degree of influence of the anomaly of rainfall on the flow regimes. In the present study, a medium sized catchment is selected from the central part of Ethiopia with fairly distributed rainfall stations. Because of the limited years of record of runoff (30 years), extension of flow data is achieved through rainfall–runoff modelling of the catchment. It is evident that decline of the annual rainfall amounts is echoed by the annual flows. However it is important to know the extent of the influences and to study the variability of flow regimes caused by the temporal variability of rainfall on a seasonal basis. Hence monthly rainfall and flow data are analysed to obtain a clearer link between the two variables.

THE STUDY AREA AND DATA

The Awash River basin is located in the central part of Ethiopia. The catchment receives about 70% of the annual rainfall during the main rainy season (June–September) and the rest during the small rainy season (March–April). In general the annual rainfall decreases from above 1200 mm at the source to less than 500 mm in the lower part of the basin. Local variation of the amount of rainfall is strongly associated with topography. The present study focuses only on the headwater area of 7560 km² upstream of Hombole gauging site (Fig. 1). In this subcatchment, minimum human interference such as dams and diversions on the river flow regime is anticipated. Five rainfall stations with concurrent data length (1980–1995) were used to calculate the areal rainfall.

To assess whether the use of the longer data of rainfall of Addis Ababa (1900–1995) is justifiable, the correlation between the calculated areal rainfall and main station is analysed. Areal monthly rainfall computed using the mean of the five stations and rainfall series at Addis Ababa are well correlated (Fig. 2). The linear regression line relating the two series has a coefficient of determination $R^2 = 0.9$. Therefore rainfall data at Addis Ababa can be considered as an index station for further investigation of the temporal variability of rainfall of the catchment as well as its effect on the flow regimes. The linear equation obtained $R_{area} = 0.794R_{AddisAbaba}$ is used to extrapolate the areal rainfall from data of Addis Ababa.

Monthly river flow data of Awash River at the Hombole gauging site for the years 1963–1992 are used in the study.

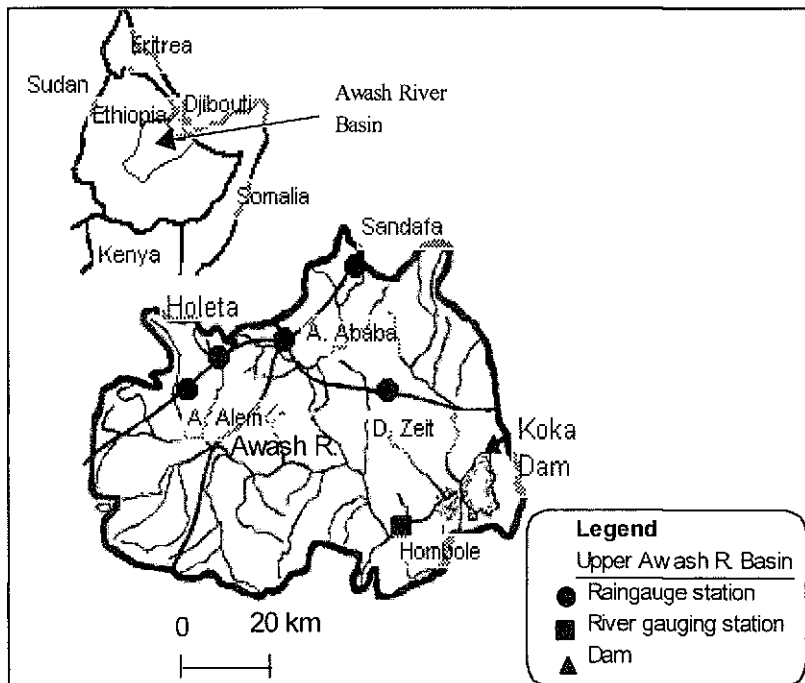


Fig. 1 The upper catchment of the Awash River upstream of the Koka dam.

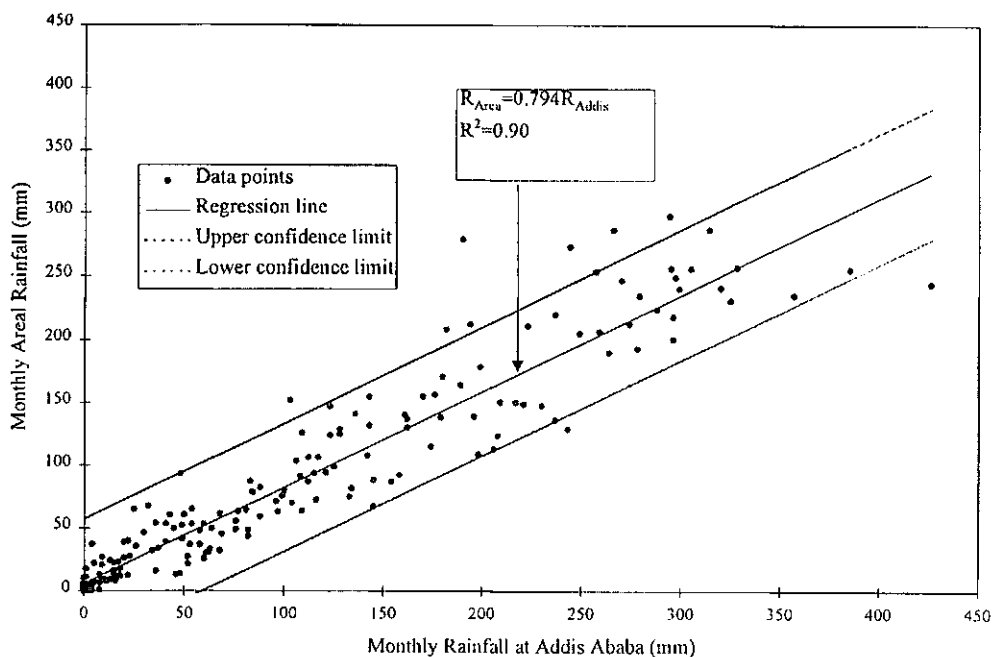


Fig. 2 Relationship between areal and Addis Ababa monthly rainfall.

ANNUAL RAINFALL VARIABILITY

According to the observed data of the Addis Ababa station, it can be generalized with the exception of the decade of 1930s that the first half of the twentieth century has experienced higher rainfall amounts than the second half. The lowest rainfall on the decade basis was observed during the 1950s. The lowest annual rainfall (904 mm) was observed in 1962. From Table 1, one can see that there is a persistence of the lower annual mean values during the years after 1960. The linear and polynomial trends fitted to the rainfall and runoff series resulted with statistically insignificant coefficient of determination $R^3 = 0.023$ and 0.004 respectively. However the 5 and 10 year moving average curves confirm the general decline of the amount of flow and rainfall (Figs 3 and 4)

Table 1 Rainfall variability during the last nine decades based on Addis Ababa observations.

Period	Annual rainfall (mm)	Summer rainfall (mm)	Period	Annual rainfall (mm)	Summer rainfall (mm)
1901-1910	1213 (+)	886 (+)	1951-1960	1112 (-)	787 (-)
1911-1920	1327 (+)	981 (+)	1961-1970	1176 (-)	807 (-)
1921-1930	1317 (+)	951 (+)	1971-1980	1166 (-)	854 (-)
1931-1940	1113 (-)	803 (-)	1981-1990	1198 (-)	800 (-)
1941-1950	1231 (+)	933 (+)			
Long term Mean (1900-1995) Annual = 1203 mm Summer = 864 mm					

(+) and (-) indicate values above and below the long term mean respectively.

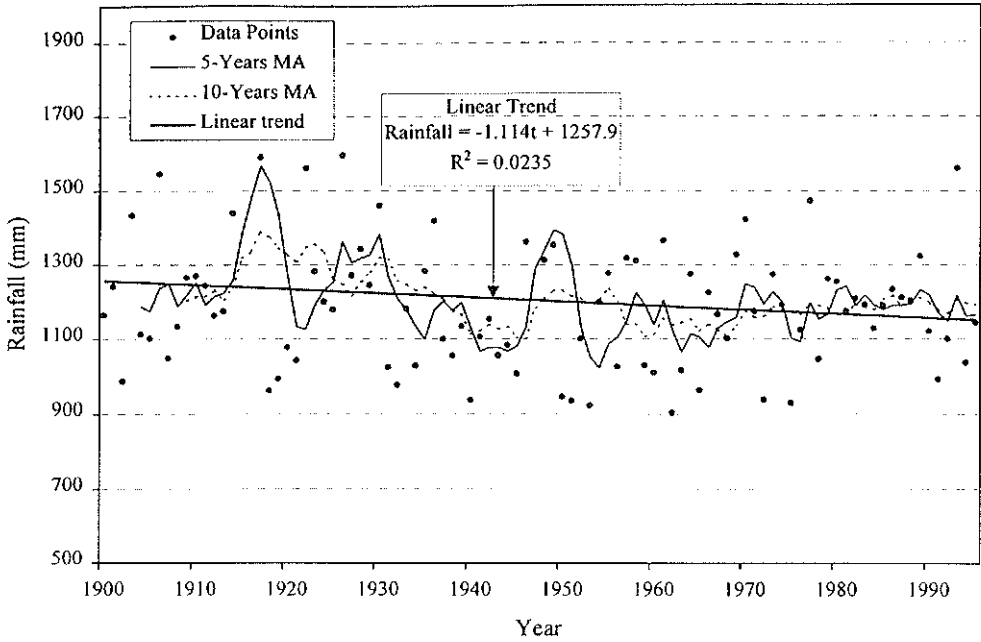


Fig. 3 Annual variability of rainfall at Addis Ababa station.

INFLUENCE OF RAINFALL VARIABILITY ON THE FLOW REGIME

In order to compare the long-term link between rainfall and flow, the short length record (30 years) of flow is extended using a monthly water balance model developed

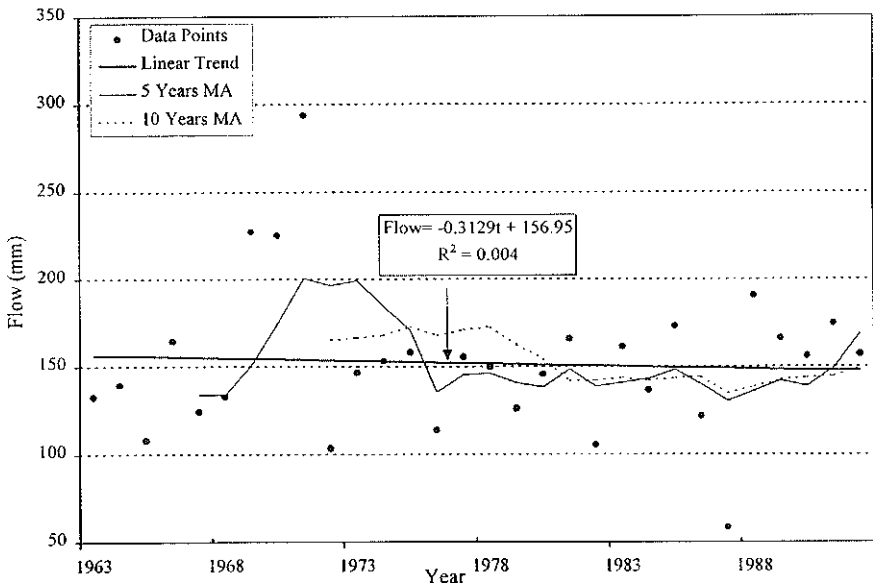


Fig. 4 Annual variability of Awash River flow at Hombole.

by Vandewiele *et al.* (1992), and further modified for application in semiarid cases by Moreda & Bauwens (1997).

The monthly water balance model

The model is based on a simplified representation of the hydrological processes and the balances of incoming and outgoing water from the catchment on a monthly time step. The model has generally three components:

- (a) Computation of actual evapotranspiration, r_t which is empirically related to the areal potential evaporation, e_t and the available water in the catchment expressed as the storage index m_t :

$$r_t = \min[w_t(1 - e^{-w_t/a_t}), e_t] \quad a_t \geq 1 \quad (1)$$

where w_t is available water = $m_{t-1} + P_t$

- (b) Computation of flow, d_t which is partitioned as fast flow, f_t (a function of excess rainfall and wetness of the catchment) and the slow flow, s_t , as a function of catchment storage:

$$f_t = a_3 \bar{m}_t^{-b_2} N_t \left\{ p_t - r_t - [1 - \exp(-P_t/r_t)] \right\} \quad (2)$$

where $\bar{m}_t = \frac{m_{t-1} + m_t}{2}$

$$s_t = a_2 (m_{t-1}^+)^{b_2} \quad (3)$$

Eventually the total flow d_t will be the sum of the two components.

- (c) The water balance of the single storage augmented by rainfall p_t and depleted by the flow of the river and evaporation.

$$m_t = m_{t-1} + p_t - r_t - d_t \quad (4)$$

The set of parameters (a_1 , a_2 and a_3) is optimized by minimizing the sum of squares of error (observed flow minus the computed flow) while b_1 and b_2 are fixed to known values (0.5, 1 or, 2). The model requires monthly rainfall, potential evaporation and river flow as inputs.

The areal rainfall data obtained from relating the Addis Ababa rainfall is used. Due to the fact that evaporation in such regions is much more controlled by available water rather than potential evaporation, the long-term changes of potential evaporation over the whole period of simulation may not greatly influence the rainfall runoff processes. Hence we used a seasonal variation expressed as mean monthly evaporation throughout the simulation period. The optimum parameters obtained for the entire date set are applied for reconstructing the flow series corresponding to the historical rainfall series. It is further assumed that the catchment characteristics have not altered greatly. Therefore, the parameters are assumed to be time invariant and consequently the monthly flows series of the years (1900–1992) is simulated for the analysis in the following sections. Figure 5 shows the comparison of the annual historical rainfall and reconstructed flows. One can see good agreement for the segment of the time series compared to the observed flow for the period 1963–1992.

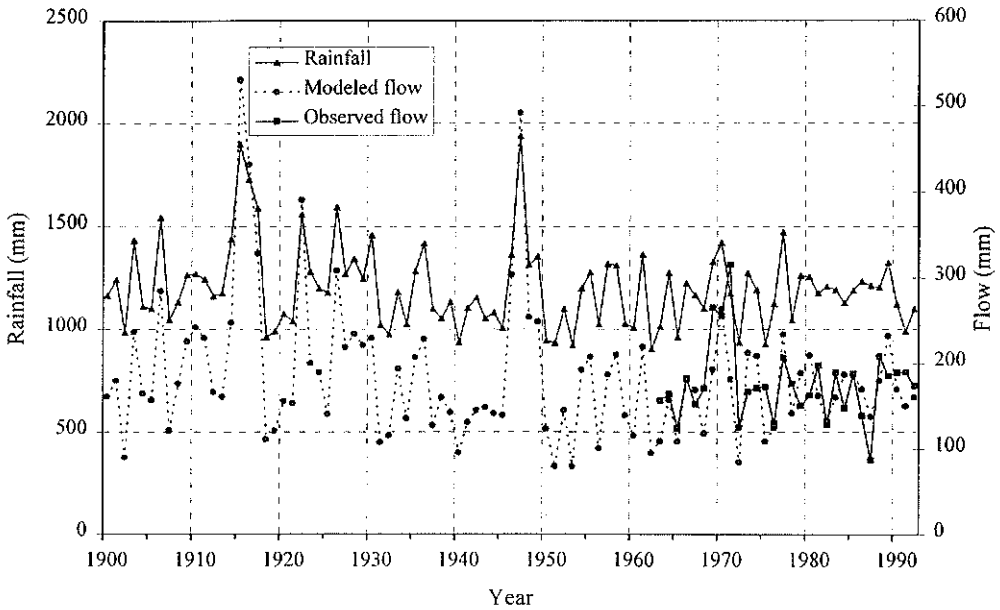


Fig. 5 Time series comparison of long-term rainfall series and modelled annual flow.

Influence of rainfall timing on flow regimes

The correlation coefficient between the annual areal rainfall and reconstructed flow is 0.6, which indicates that mere annual magnitude anomalies of rainfall can not fully explain the effect on the total generated flow. Hence it is useful to dissociate the rainfalls in to seasons, to study the influence of the timing and length of the rainy season on the flow regimes. It can be argued that in regions with long dry periods, the first arrival of rain on bare soil will generate high flows and leave little or no water for ground water supply. Consequently, smaller or no base flow will occur during the non-rainy season. A more favourable condition for higher flows in summer is when there is intense rain during the last days of the rainy season when the upper soil is saturated.

From the cross correlations of monthly rainfall and summer runoff (Table 2), it is observed that the rainfall of June is more important than the July rain. The explanation is that the first arrival of rain determines the losses. The most

Table 2 Cross correlation coefficients of rainfall and flow regimes: Under lined values show significant correlation at 95% confidence limit = ± 0.2).

Flow regimes	Rainfall:					
	June	July	August	September	October	Summer
Summer flow (June–September)	<u>0.43</u>	<u>0.36</u>	<u>0.63</u>	<u>0.46</u>	-0.05	<u>0.73</u>
Low flow (November–February)	-0.01	0.14	0.04	0.16	<u>0.21</u>	0.11

significant cross correlation of monthly rainfall with the summer flow is obtained for the August rainfall. The interpretation is that in August, there is greater opportunity for flow generation (even for small storms) since the catchment is already moist the losses are minimal. The total summer rainfall is also well correlated with the summer flow (correlation coefficient $r = 0.73$). On the other hand, the individual monthly rainfall and also the total summer (June–September) rainfall have less influence on the low flow regime (November–December), due to fast response of the catchment.

Influence of long-term rainfall variability on flow regimes

The reconstructed annual mean flows of the second half of the century are observed to be below the long-term mean which is consistent with the rainfall variability. It is also noted that there is an amplification of the variability of the flow, especially for the summer flows. For example in the 1950s there was a departure of the flows by 25% from long term mean (163 mm), corresponding to only a 10% departure of rainfall from long term mean of (1200 mm) (Figs 6 and 7). On the other hand, during the same decade the base flow component of annual flow has shown a departure of only 10% from the long-term mean of (25 mm) and the annual low flow has only a departure of 7% (Fig. 8). Moreover, the base flow and annual low flow (November–February) does not show high variability during the whole period of analysis.

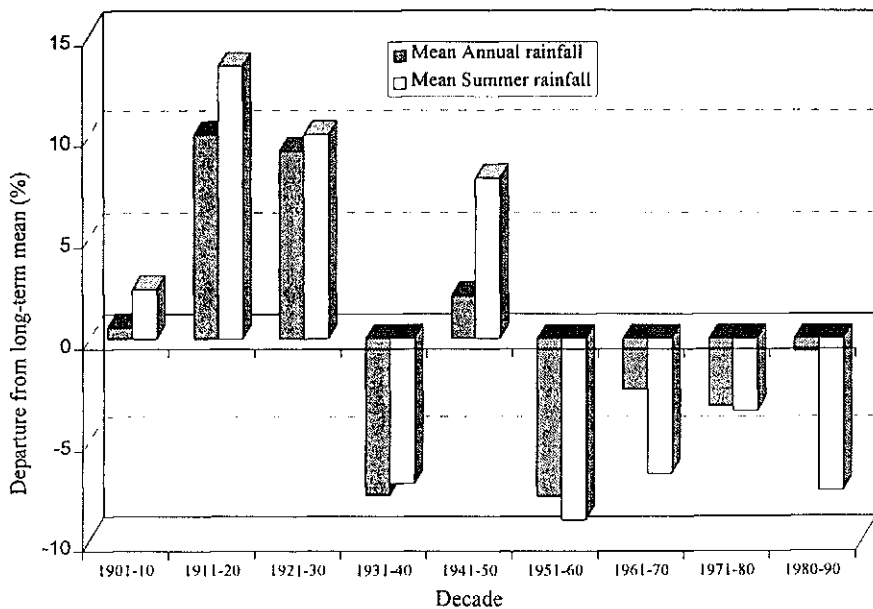


Fig. 6 Departure of annual and summer rainfall from long term means (in decades).

CONCLUSIONS

From simple correlation analysis of the available data in the catchment, it is shown that the Addis Ababa rainfall station can be used as an index station to study the long-term temporal variability of rainfall over the upper Awash catchment. It has been observed that the mean annual and summer rainfall amount has declined since the second half of this century and that this low mean is maintained up to the

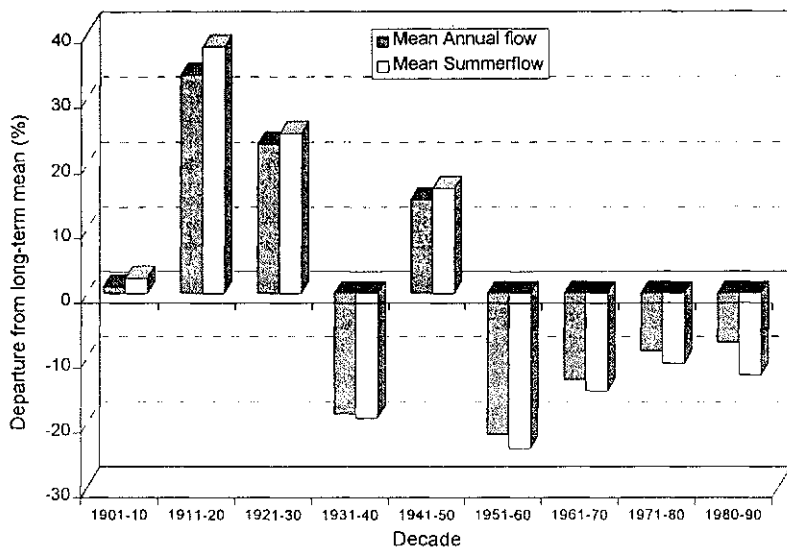


Fig. 7 Departure of annual and summer flow from long-term means (in decades).

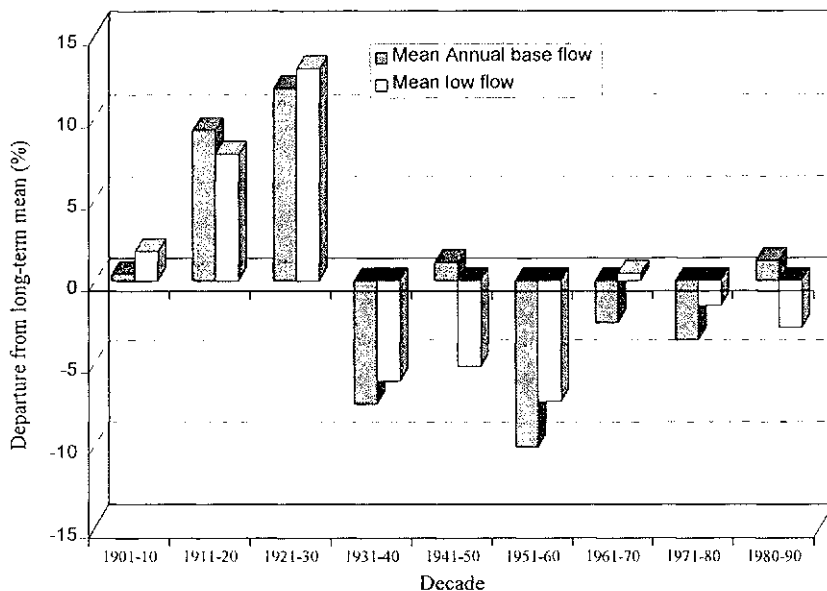


Fig. 8 Departure of annual base flow and low flow from long term means (in decades).

beginning of the 1990s. However, the linear trend of the decline is found to be not significant.

The study has also shown that the runoff variability is amplified compared to the rainfall variability. It is also demonstrated that the major flow regime (summer flow) is affected greatly by the low anomalies of rainfall and that the low flow, which is normally small, does not show large variation in this century. The analysis on the timing of rainfall showed that June rainfall is significantly important for the total summer flow to the river, though August rainfall is the most significant cause of high summer flows. It should be noted that this study is limited on the causality of rainfall on the flow regimes. Further, the influence of land use and vegetation cover changes on the flow regimes should be studied with more detail, e.g. by means of distributed hydrological models.

Acknowledgements The authors would like to thank the Hydrology Department and the National Metrology Agency, of the Ethiopian Ministry of Water Resources for providing hydrological and meteorological data of Awash River basin.

REFERENCES

- Conway, D. & Hulme, M. (1993) Recent fluctuations in precipitation and runoff over the Nile subbasins and their impact on main Nile discharge. *Climate Change* **25**, 127–151.
- Misganaw, D. (1989) Analysis of drought in Ethiopia based on Nile River flow records: In: *Proceedings of the Sahel Forum—The State-of-the-Art of Hydrology and Hydrogeology in the Arid and Semiarid Areas of Africa* (Ouagadougou, Burkina Faso, 18–23 February 1989).
- Moreda, F. & Bauwens, W. (1997) Conceptual monthly water balance models applied to arid and semiarid catchments. Paper presented to 5th Scientific Assembly of IAHS in the Workshop on Flow Forecasting under Conditions of Limited Data (April 1997, Rabat, Morocco).
- Vandewiele, G. L., Xu, C. Y. & Ni-Lar-Win (1992) Methodology and comparative study of monthly water balance models in Belgium, China and Burma. *J. Hydrol.* **134**, 315–347.
- Sileshi, Y. (1994) Stochastic predictions of summer rainfall amounts over the northeast African Highlands and over India. PhD Thesis, Laboratory of Hydrology, Free University Brussels, Belgium.