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The effects of climate changes on river baseflow and aquifer storage in Central Africa

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Abstract The effects of climate changes on river baseflow and aquifer storage have been investigated using hydrological and rainfall data bases of the Central African Republic from 1902 to 1994. A decrease in runoff, observed everywhere, coincides with a decrease in rainfall with a time lag of 3 years. Compared with previous droughts, these recent periods of low rainfall and runoff (from 1971 to the present) are exceptionally long. As a consequence, the annual hydrograph in Oubangui has been significantly reduced in volume but not in duration, causing lowering of the groundwater table. A distinct break in time series of rainfall and runoff was detected. The prolonged period of low rainfall irreversibly changed infiltration patterns and sustainability of river flows, with a marked difference on a regional scale. In the north, the part of runoff deficit infiltrating and recharging groundwater reserves has diminished.

INTRODUCTION

Detection of changes in hydrological processes is very complex and inevitably based on the analysis of long time series of climatological and hydrological records. Many studies have shown the effect of rainfall deficit on surface water resources (Mahé & Olivry, 1995; Orange *et al.*, 1995), but very few have discussed its impact on groundwater resources (Wilkinson & Cooper, 1993). Furthermore, documentation on sensitivity of hydrological variations resulting from climate change is scarce (Arnell, 1994).

This paper proposes a temporal and spatial analysis of hydrological and hydro-climatological variations in the Oubangui River basin. The Oubangui River, located in the centre of the African continent, close to the Equator and mostly in the northern hemisphere, drains the northern part of Zaire and most of the territory of the Central African Republic. With annual discharge of 5000 $m^3\ s^{-1}$ at its mouth, it is the second most important tributary to the Congo River (mean flow 41 000 $m^3\ s^{-1}$), after the Kasai River (8000 $m^3\ s^{-1}$) (Bricquet, 1995). The Congo River is the second greatest river of the world, as far as discharge is concerned, after the Amazon River. The average rainfall over the Oubangui basin varies from 1700 mm $year^{-1}$ in the south to less than 1000 mm $year^{-1}$ in the north (Franquin *et al.*, 1988; Mahé *et al.*, 1993). Vegetation is largely uniform, with semi-deciduous tropical forest in the extreme south, steppe in the extreme north and savannah with some trees in most of the drainage basin (Boulvert, 1986).

The Oubangui flow records are analysed at Bangui gauging station to identify homogeneous climatic periods from the beginning of this century. The Oubangui basin upstream of this point covers an area of 488 500 km^2. Then the relationship with rainfall data is discussed and effects of this important hydroclimatological change on the Oubangui runoff regime are described. Finally, the influence of these last twenty years of drought is studied by using the water balance equation (Thornthwaite & Mather, 1955; Schaake & Chunzhen, 1989). These findings are compared with the data for Oubangui's sub-basins to give an overall pattern of the actual groundwater state in this geographical zone.

EVIDENCE OF CLIMATE CHANGES IN CENTRAL AFRICA FROM YEARLY RUNOFF OF THE OUBANGUI RIVER

Hydrology of the Oubangui River at Bangui

According to the flow regime classification described by Rodier (1964), the Oubangui River has a transitional tropical regime. The annual hydrograph of this hydrological regime features one single peak, which here occurs in October. Minimum flows are observed in March. Since 1911, the mean yearly runoff has varied from 6110 $m^3\ s^{-1}$ (in 1969) to 2120 $m^3\ s^{-1}$ (in 1990), which represents a variation as 3 to 1. The highest maximum monthly runoff was observed in October 1916 (14 000 $m^3\ s^{-1}$), and the lowest maximum monthly runoff, in November 1990, was 4690 $m^3\ s^{-1}$. It again represents variation as 3 to 1. The minimum monthly flows show a greater variation. The highest monthly minimum flow is 2100 $m^3\ s^{-1}$ (in March 1963) while the lowest value recorded was 266 $m^3\ s^{-1}$ (in April 1990) (Table 1).

Evolution of yearly runoff during the twentieth century

Hydroclimatological changes in Central Africa are visible in the long time series of the Oubangui River discharges at Bangui. They started in the 1930s and have continued until now (Orange *et al.*, 1995; Orange *et al.*, 1996). The Oubangui runoff experienced three main climatic periods during the twentieth century (Fig. 1). From the beginning of the record up to 1959, annual runoff evolution showed stability around the interannual average of 4220 $m^3\ s^{-1}$. Then the wettest period occurred, lasting eleven years from 1960 to 1970, with an average interannual runoff of 4890 $m^3\ s^{-1}$. Then driest period started, with an average interannual runoff of 3140 $m^3\ s^{-1}$, that is a decrease of 34% in regard to the previous period.

In fact, a distinct break in the runoff time series marks the transition between the wet period in the 1960s and the present dry period. The most humid and the driest year were only two years apart (1969 with 6110 $m^3\ s^{-1}$ and 1971 with 2960 $m^3\ s^{-1}$). Furthermore, the drought in runoff has become more severe since 1983. Indeed the runoff time series features a marked difference between the stable period which ended with a humid decade in the 1960s, and the period of increasing drought since the 1970s (Orange *et al.*, 1996).

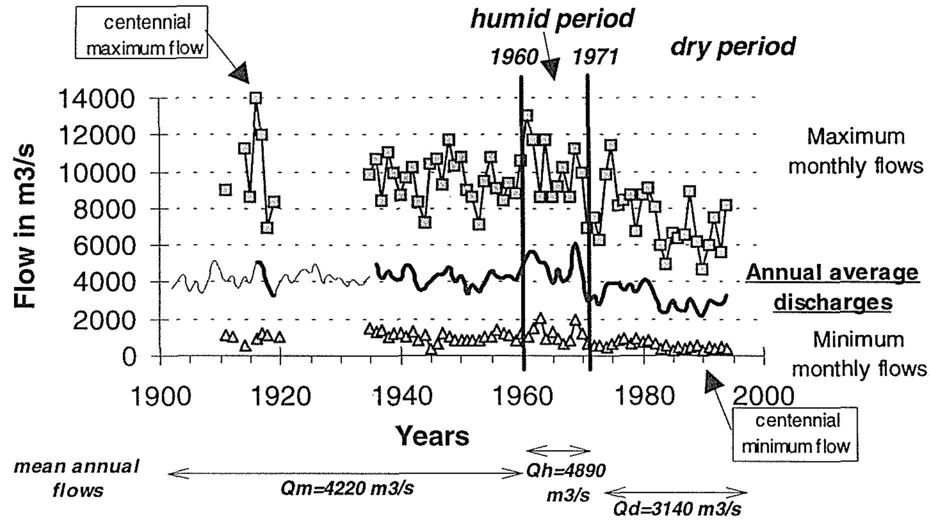

Fig. 1 Time series of flows of the Oubangui River at Bangui (monthly maxima, annual means and monthly minima). The mean annual flow for each homogeneous climatic period is indicated. Annual mean flows represented by a fine line are estimated (Orange *et al.*, 1995).

Table 1 Annual discharges, maximum and minimum monthly flows of the Oubangui River at Bangui (averaged over the years 1916, 1917 and 1936-1994).

	Mean discharge ($m^3 s^{-1}$)	Minimum discharge (date)	Maximum discharge (date)	Standard deviation	Linear trend
Annual	3940	2120 (1990)	6110 (1969)	22%	−35%
Monthly maximum	8960	4670 (11/1990)	14 000 (10/1916)	22%	−36%
Monthly minimum	891	266 (04/1990)	2100 (03/1963)	43%	−60%

Discharges in $m^3 s^{-1}$ and corresponding date in parentheses.

Statistical tests using Bayesian methods (Buishand, 1984) applied to the Oubangui time series confirm breaks in 1960, 1971 and 1983. Many other authors found a marked break around 1970 for other hydrological time series (Hubert *et al.*, 1989; Demarée & Nicolis, 1990).

It is evident, that the regional drought beginning in the 1970s induced a marked shift in the hydrological time series of flows of the Oubangui River. After 25 years, we can suspect a modification in the hydrological processes of this drainage basin.

Links with the evolution of yearly rainfall

The annual rainfall for the Oubangui basin at Bangui was calculated for 1951-1988 using the regional vector method (Mahé *et al.*, 1994). Annual rainfall also shows a maximum in the 1960s and minimum in the 1980s (Fig. 2), but the break in the rainfall series is less marked than for the runoff series. This break appears in 1968, three years before the break in the runoff data. This discrepancy can be explained by the sponge-like functioning of the drainage basin, where interannual variability is less important for runoff than for the rainfall series. Also the maxima and minima of annual rainfall do not completely coincide with the extreme flow events described above.

The decrease in runoff has been much more significant than the decrease in rainfall: around −36% drop in runoff as opposed to around −5% drop in rainfall between the interannual averages in humid and dry periods. Translated in the same unit, the decrease of runoff is around 110 mm year^{-1}, while the drop in rainfall is of the order of 70 mm year^{-1}.

Unfortunately, the break marking the beginning of the humid period cannot be investigated, because rainfall data before 1951 are missing.

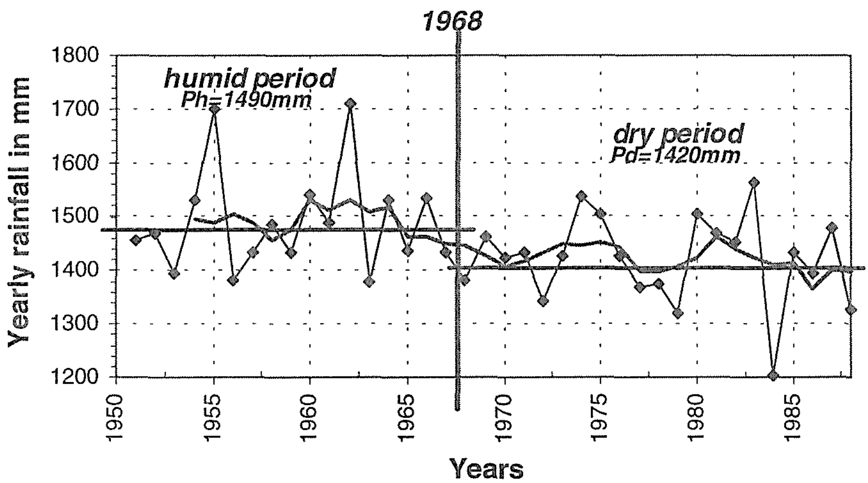

Fig. 2 Time series of annual rainfall in the Oubangui basin at Bangui and average rainfall in a homogeneous climatic period (Ph: rainfall for humid period 1953-1967; Pd: rainfall for dry period 1968-1988).

Regional assessment of drought

Flow records for some tributaries of the Oubangui River start in the early 1950s, as do rainfall data for the sub-basins. The discharges of 1969 and 1970 were above the 1953-1988 average everywhere, whereas the discharge of 1971 was below this average (Wesselink *et al.*, 1996). The same pattern has been observed for the Congo River at Brazzaville, its mouth outlet into the Atlantic Ocean, and for the Sangha River, a tributary of the Congo River in the western part (Laraque & Olivry, 1996; Wesselink *et al.*, 1996). This points to a regional marked break between a humid period and a dry period beginning in 1971. Indeed, even if there are some differences in the evolution of runoff time series between sub-basins before the 1960s, all sub-basins follow the same runoff evolution after this date. That is, the drought of the early 1970s really has regional features.

Furthermore, according to available rainfall figures, the severity of this drought has intensified since 1983 in the whole of Central Africa. Indeed, rainfall decrease has been observed since the 1950s almost everywhere, from the north to the south on the African continent (Mahé & Olivry, 1995).

EFFECTS ON THE RIVER BASEFLOW

Minimum and maximum monthly flows

In general, years of the highest mean runoff coincide with the highest minimum monthly flow and the highest maximum monthly flow. A similar property holds for the lowest flows. That is, the break in 1971 is also found in the time series of minimum and maximum monthly runoff (Orange *et al.*, 1995). However, minimum monthly flow decreased much more in comparison with maximum monthly flow. Indeed, the interannual average peak flow diminished by approximately −35% and the interannual average minimum flow by −60% between humid and dry periods. This significant decline in minimum flows might indicate a lowering of the groundwater table. The drought reached its height in 1990 with an annual discharge of only 2120 $m^3 s^{-1}$; that is the centennial minimum flow (Fig. 1) (Orange *et al.*, 1995).

Effects of the drought on the annual hydrograph

Effects of the drought on the shape of the annual hydrograph of the Oubangui River at Bangui have been described by using five descriptive variables presented in Table 2 and defined as follows:

- *the starting day of the peak*, which is the date when flow starts increasing;
- *the peak duration* (unit of measure in decimal months), which is the time when flow is above the annual average flow;
- *the relative peak height*, which is the difference between the maximum daily flow and the minimum daily flow of the studied peak period divided by the minimum daily flow;
- *the low flow*, which is the minimum daily flow in the year; and
- *the peak flow*, which is the maximum daily flow in the year.

In fact, the decrease in Oubangui flows since 1971 was related to neither a change in the starting day of the peak nor the peak duration. The peak flow always begins in April and continues for nearly five months. So the annual peak is lower but its duration is not shorter, contrary to other tropical rivers (Olivry, 1993). On the other hand, the relative peak height has increased since the 1970s (Fig. 3) while the minimum flow and the peak flow have decreased. In fact, the relative peak height has increased because the minimum flow has decreased more in comparison to the peak flow.

In conclusion, the Oubangui annual hydrograph has been significantly reduced in volume but not in duration. Furthermore, the drop of low flow caused lowering of the groundwater table.

Table 2 Decennial evolution of shade parameters for the annual hydrograph of the Oubangui River at Bangui.

Decennial period	Starting date of the peak (week)	Peak duration (month)	Relative peak height	Low flow discharge ($m^3 s^{-1}$)	Peak flow discharge ($m^3 s^{-1}$)
1940-49	1 May	4.9	15	965	9700
1950-59	3 April	4.9	11	1010	9070
1960-69	2 April	4.9	12	1255	10 340
1970-79	4 April	4.7	15	750	8690
1980-89	2 April	4.8	20	540	7680
1990-94	4 April	5.1	22	325	6720

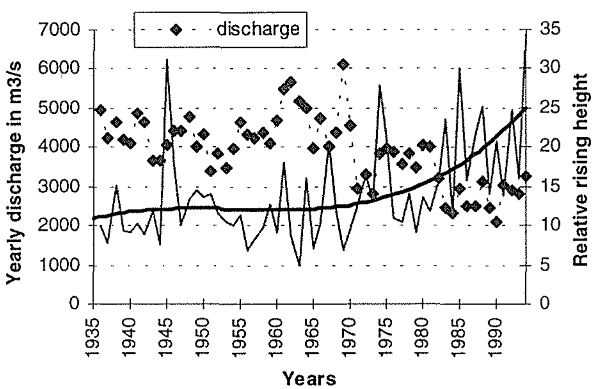

Fig. 3 Time series of relative rising height for flow of the Oubangui River at Bangui. Time series of yearly discharge is also indicated.

In fact, the relative peak height is defined to assess a dynamic measurement of the difference between the minimum flow and the peak flow. From 1935 to 1994, the interannual evolution of the relative peak height describes an exponential curve (Fig. 3). The trend is steady from 1935 to 1970, then increases and curves up more and more since the 1980s. The yield recession curve of the Oubangui River shows the same feature (Olivry, 1993). This exponential increase beginning in the 1970s underlines the large memory effect of the underground basin. It can be concluded that the drainage basin cumulated the persistent decrease of available water resources from year to year.

Indeed, it means that this long period of drought led to a large reduction of the groundwater storage, which is not high enough now to sustain the hydrological regime during the dry season with the same discharge value as before. This new hydrological pattern of river behaviour might be irreversible in spite of the fact that a relatively more humid climatic period seems to have occurred for some years.

EFFECTS ON THE AQUIFER STORAGE

Water balance model and trend analysis

A drainage basin can be described as a dynamic system with two sub-systems: the surface water and groundwater sub-systems. Also the water balance model formulated in its simplest expression (defined by Thorntwaite & Mather, 1955) is a linear equation sufficient to describe the relationship between variations of climatic and hydrological parameters in a drainage basin, and so to understand the relationship between these two hydrological sub-systems of the landscape. The water balance equation can be written as:

$$P = E_T + Q + \mathrm{d}S \tag{1}$$

where P, E_T, Q, $\mathrm{d}S$ are precipitation, evapotranspiration, runoff and change in basin storage, respectively. This equation is simply the expression of the mass conservation law of physics. The term $\mathrm{d}S$ is the rate of change of the volume of water stored within the basin. In fact, this parameter measures the capacity of the drainage basin to store groundwater. To give more physical meaning to the storage variable, the runoff deficit variable, DE, is defined as:

$$DE = P - Q \tag{2}$$

Runoff deficit represents the amount of water which is stored in the catchment, evaporated, or transpired. The vegetation in this region has not been modified (Boulvert, 1992). It is therefore reasonable to think that there is no change in transpiration. On the other hand, the drought has not modified the monthly distribution of rainfall (Feizouré, 1994). So we can suppose that the amount of water evaporation is also not modified (*cf.* Riou, 1980). Furthermore, Schaake & Chunzhen (1989) showed that water resources are more sensitive to changes in precipitation than to changes in evapotranspiration. In the light of all these results, one can speculate that the evapotranspiration has not been substantially modified during the last 35 years.

As a consequence of this hypothesis, the runoff deficit, averaged over the basin and one year, gives an idea of the yearly water availability in the drainage basin. Then statistical notion of linear trend is used to obtain a simplified description of the hydroclimatological evolution for some drainage basins. It is necessary to use sufficiently long time series recorded in a common time interval, that is, in the case of the results presented, 1953-1988. The linear trend of the interannual evolution of runoff deficit provides a dynamic insight into the water availability.

Hydroclimatological evolution and water availability in some sub-basins of the Oubangui River

Time series of runoff and rainfall from several tributaries of the Oubangui River have been analysed to explain the hydrological response of the Oubangui basin at the new hydroclimatological situation induced by long drought. Major results from the hydroclimatological analysis of the Oubangui sub-basins, which are presented in detail by Wesselink *et al.* (1996), are reviewed in the following section.

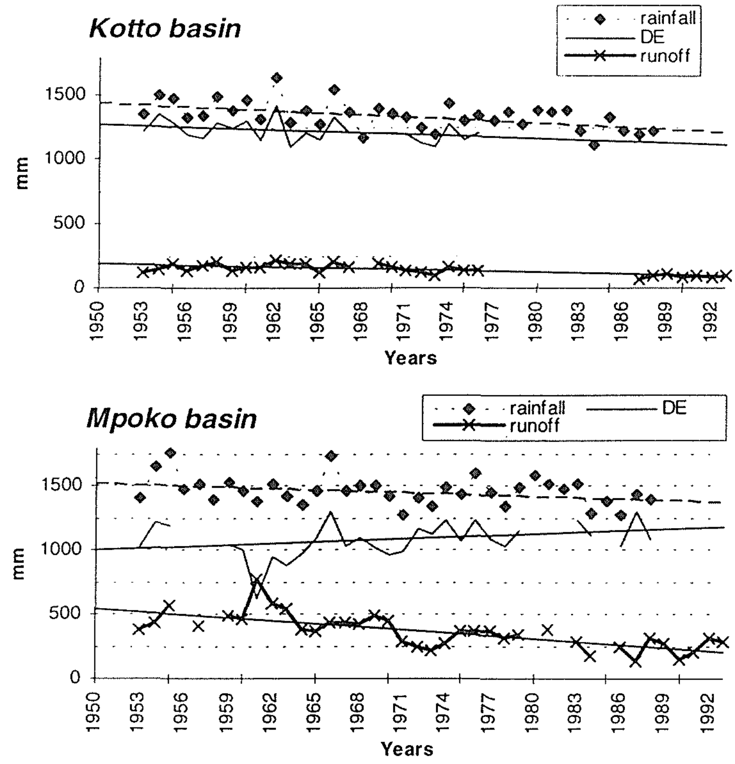

Fig. 4 Time series and linear trends of annual rainfall, annual runoff and annual runoff deficit (DE) of two Oubangui sub-basins. Kotto basin is studied at Kembe gauging station on the Kotto River and Mpoko basin is studied at Boali gauging station on the Mbali River.

The linear trend of runoff has led to a substantial decrease everywhere (between −30% and −60%) while the observed decrease of rainfall was much weaker, on average around −10%. As was the case in the main basin, the decrease of rainfall takes effect on the runoff after a few years. Trend analysis of runoff deficit indicates a diminishing trend of about −10% for the driest sub-basins, e.g. the Kotto sub-basin, and an increasing trend of about +10% for the wettest one, e.g. the Mpoko sub-basin (Fig. 4). This difference in behaviour of the runoff deficit means that the evolution trends of runoff and rainfall may differ for particular basins considered, although all sub-basins show a diminishing trend of runoff and rainfall.

These observations can be summarized to give the following explanation of the hydrological functioning of the Oubangui's drainage sub-basins.

When runoff deficit increases in spite of decrease in rainfall and in runoff, it means that runoff decreases more rapidly than rainfall. That is, the volume of water, which does not take part in surface runoff, increases. This water quantity represents the sum of evapotranspiration and of aquifer storage. Assuming no evapotranspiration change, we can speculate that the increasing trend of runoff deficit means an increase in the aquifer storage. However, analysis of low flow time series does not confirm the hypothesis of rising groundwater table. The river baseflow has been at the same level since 1988.

On the other hand, the diminishing runoff deficit indicates that the water quantity, which does not take part in surface runoff, decreases. In this situation, it is certain that aquifer storage cannot be recharged, due to decrease in volume of available water. The analysis of low flow time series confirms this result. The river baseflow continues to decrease, and this is dramatic in regions where aquifers have been already very strongly reduced (Olivry, 1993; Orange *et al.*, 1995).

Regional hydroclimatological behaviour of the Oubangui basin

To obtain an insight of the effects of climate change on aquifer storage over the Oubangui basin, this main drainage basin has been divided into twelve sub-basins. In this region, Callède *et al.* (1992) showed that the specific runoff largely depends on the amount of yearly rainfall rather than on the basin area. So, the specific runoff is influenced by physical processes in the soil and vegetal cover in reaction to this new hydroclimatological situation.

Using specific runoff, the sub-basins of the Oubangui basin are separated in two groups. The sub-basins with a specific runoff above 10 l s^{-1} km^{-2} are supposed to have a hydrological behaviour similar to that of the Mpoko basin. On the other hand, the sub-basins with a specific runoff below 10 l s^{-1} km^{-2} are supposed to have a hydrological behaviour similar to that of the Kotto basin. This scenario has been confirmed by the analysis of rainfall and runoff time series of the Mbomou and Lobaye sub-basins (Wesselink *et al.*, 1995).

As a result, the behaviour of aquifer storage is assumed to fall under these two categories for both sub-basin types. In result, the whole Oubangui basin is divided in two parts with different hydrological behaviours (Fig. 5). In the north, over the driest part of the basin, the part of runoff deficit recharging groundwater reserves has strongly diminished. It can be concluded that the potential for aquifer recharge has dropped to

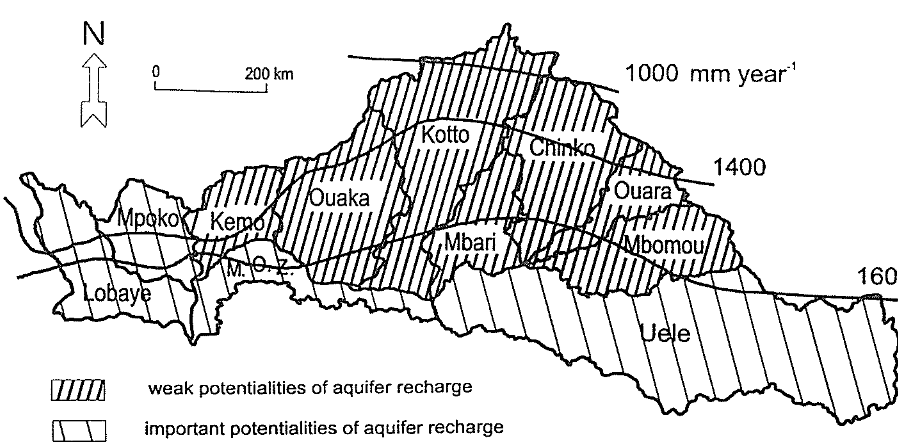

Fig. 5 Spatial variability of potential recharging of the aquifer storage and mean annual rainfall. The Oubangui basin is divided into twelve sub-basins.

near zero. In contrast, the water balance model allows one to believe that the potential for aquifer recharge over the humid part of the Oubangui basin, located in the south is high at the present time.

CONCLUSIONS

The present drought is exceptional in its extent in space and time, in comparison to previous droughts (Sircoulon, 1985). Indeed, the river discharges were still very low in 1994. After 25 years of drought, we can speak about a break in the hydrological time series, noting a new average state of hydroclimatological features since 1971. It means that the idea of using an average for the whole century is not correct when describing the hydroclimatological features of this country.

The Oubangui basin is very interesting because of its continental position in Africa, which enables one to study differences in the hydrological functioning of these landscapes due to a major hydroclimatological shift. No modification has been observed in the annual hydrograph of the Oubangui River at Bangui, only a decrease in monthly minimum and maximum flows. However, the decrease in minimum flows of around −60% is much stronger than the decrease in peak flows, which is around −35%, indicating stress in the drainage basin. This indicated critical conditions of the underground storage.

The runoff response to diminishing rainfall is delayed in all basins, but thereafter gets relatively more important than the change in rainfall. This delay of drainage basins has been caused by their sponge-like behaviour. At the same time, a decrease in runoff deficit has been observed over the driest basins, which are situated in the northern part of the Oubangui basin. This indicates an important hydrological stress in half of the Oubangui basin area. A hypothesis has been arrived at that the part of runoff which infiltrates and recharges the groundwater reserve has diminished. Unfortunately no piezometric data are available to support this hypothesis. However, the rapid decrease of minimum flows confirms lowering of the groundwater table.

All these results support the idea of a climate change, which has occurred in Central Africa. It will be interesting to observe the hydrological cycle in the Oubangui basin and its sub-basins in the next few years and to compare the behaviour of runoff and rainfall. If rainfall comes back to normal, will this restore river flows to normal, or has the prolonged period of drought irreversibly changed infiltration patterns and sustainability of river flows?

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