Progressive aridity impact on the hydrological regime in the Volta River basin in Benin (West Africa)

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Abstract The Volta River basin within the Soudano-Sahelian climate zone in Benin is experiencing progressive aridity, of which the impacts on surface water runoff are large. In this context, it is necessary to understand the hydrological regime change to provide the best decision tools for water managers. For this purpose, methods of statistical variability analysis, calculation of aridity index based on the UNEP classification and discontinuity detection on rainfall and flow series were used over the period 1961–2010. The water deficit index, the base flow index and the seasonal irregularity index were calculated. This study revealed that since 1975 the Volta basin in Benin has experienced a drought persistence leading to an increased climate aridity (20% from 1961 to 2010). Rainfall decreased by 13% while the aridity index varies from 0.01 to 2.66, indicating dry sub-humid climate to hyperarid climate at the monthly scale. Indeed, annual variation in flow decreased by 41% in the sub-basin of Porga and 32% in that of Tiele over the period 1975–2010 compared with 1961–1975. Also, an increased base flow index of 0.6 to 0.8% at Porga, 0 to 0.1% at Tiele supported by very marked seasonal irregularity were relevant indicators of hydrological drought and surface water scarcity. The sensitivity of the hydrological regimes to the change of aridity in the Volta basin should be a basis for sustainable water management strategies development in the Sudano-Sahelian area of Africa.

Key words hydrological regime; aridity index; surface water scarcity; sustainable management; Volta River basin; Benin

INTRODUCTION

Surface water resources, dependent on very irregular rains become increasingly limited because of climate change resulting in decreasing precipitations, rising temperature and consequently higher evaporation. According to Smakhtin (2001), long-term periods of little rain in catchment areas bring about hydrological drought that manifests in rivers as low flows.

Surface water reduction on the mean West African basins reached 40–60%, much more marked than that of precipitation (15–30%) (Afouda *et al.*, 2007). Climate warming may lead to important changes in river flow (Kunstmann & Jung, 2005; Opoku-Ankomah & Minia, 2005; Jung, 2006; Idieti, 2009; etc.). Changes in water flux between the surface of the Earth and the atmosphere are not expected to be spatially uniform but to vary much like the current daily mean values of precipitation and evaporation (IPCC, 2007). The impact of a drought persistence (Totin *et al.*, 2009) is indeed largely amplified in the flow which records a reduction three to four times more significant (30–40%) than that of rainfall in the Benin basin of the Volta River (Totin *et al.*, 2010). In this basin, the evidence of drought impact on the surface water resources is its increasing water scarcity.

Decreasing rainfall does not only affect flowing river water within catchments, but it also causes considerable changes in the hydrological regime, especially on the Sudano-Sahelian climate zone of Africa including the study area. But the effects of drought or aridity on the streams and rivers regime are less on the Volta River basin in Benin.

The Volta basin, situated between latitudes 0°40′N and 2°10′N and longitudes 11°40′E and 9°21′E (Fig. 1) in northern West Benin (12.1%) covers an area of 13 590 km^2 representing 3.4% of the whole basin extended to Burkina Faso, Cote d'Ivoire, Ghana, Mali and Togo.

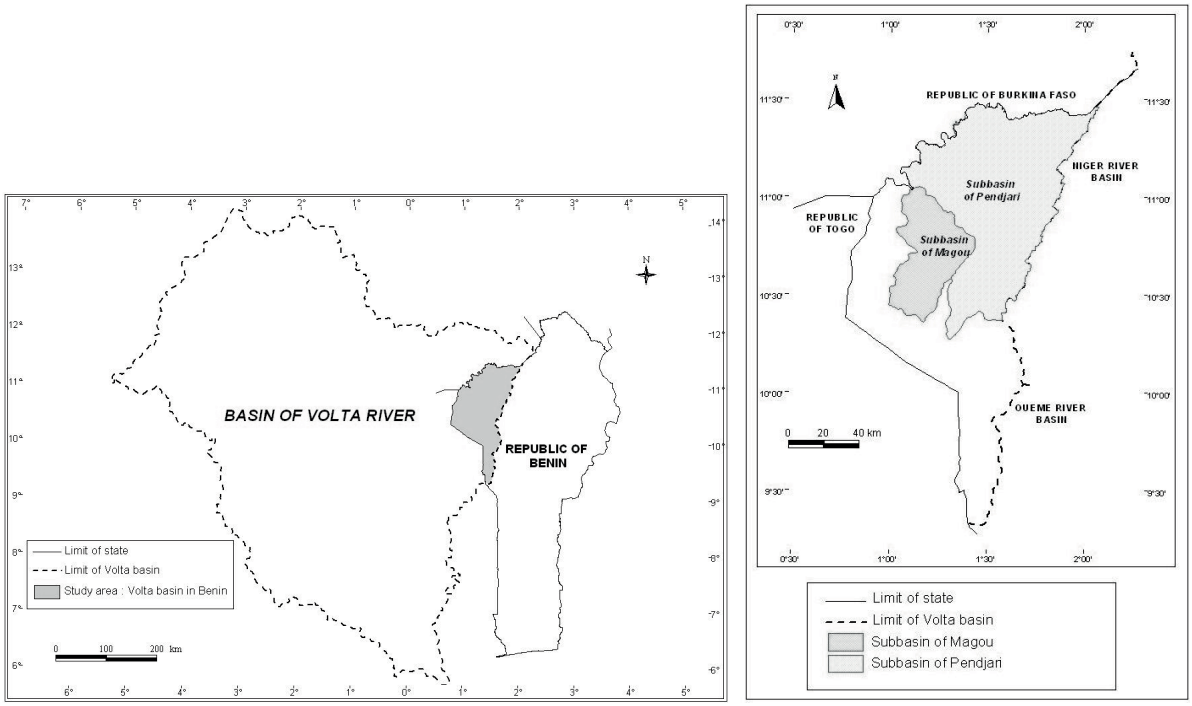

Fig. 1 The geographical location of the Volta River basin in Benin.

It is formed by the gauged sub-basins of the River Pendjari (22 280 km^2 include Burkina part) and Magou (836 km^2) and the non-gauged streams sub-basins of Koumongou, Keran and Kara. Within the Inter Tropical Convergence Zone, its climate is dry tropical (Sudano-Sahelian climate zone), featuring one dry and one rainy season from April to October and November to March, respectively. Climate variation at all time scales influences the hydrological process which directs water availability necessary for the ecological and economic systems in this basin.

The aim of this study is to assess the change of the Volta hydrological regime in the context of a drying climate in northern Benin.

DATA AND METHODS

Data

To investigate the sensitivity of the Volta River regime to changing climate in Benin, rainfall records, potential evapotranspiration data and the Pendjari and Magou River flows data were used over the period 1961–2010.

Also, existing literature (Moron, 1994; Mahé *et al.*, 2001; Afouda *et al.*, 2007; Idiéti, 2009; Totin *et al.*, 2009, 2010) helped to assemble complementary data necessary to analyse the vulnerability of the study area to climate variation. Field work enables the identification of the environmental tracers of the hydroclimatic variation in the Volta basin.

METHODS

Estimation of the aridity index

The aridity index (*AI*) (UNEP, 1992; Middleton & Thomas, 1997; Turkes, 1999; Tsakiris & Vangelis, 2005; Tsakiris *et al.*, 2007) is determined by the ratio of mean precipitation (*P*) to mean potential evapotranspiration (*PET*) on a monthly scale for each monitoring station.

$$AI = \frac{P}{PET} \tag{1}$$

The Aridity Index was used to delineate the dry and wet months based on the meaning of the terms hyperarid ($AI < 0.05$), arid ($0.05 < AI < 0.20$), semi-arid ($0.20 < AI < 0.50$), and sub-humid ($0.50 < AI < 0.65$)), as defined in the *World Atlas of Desertification* (UNEP, 1992).

Computed aridity indexes are compared over the months, seasons and the periods determined using statistical variability analysis and discontinuity detection on rainfall and flows records by the test of Pettitt under the software Khronostat 1.01.

Assessment of hydrological sensitivity to aridity

Calculation of the water deficit index, base flow index and seasonal irregularity index helps to appreciate change in the hydrological regime of the Volta River.

The water deficit index (*WDI*) is expressed on the basis of the discontinuity detected periods. It is given by:

$$WDI(\%) = 100.\left[\frac{A_1}{A_0} - 1\right] \quad (2)$$

where A_0 and A_1 are the mean hydroclimatic variables respectively after and before the discontinuity years.

The base flow index (*BFI*), helps to define the influence of geological patterns of the basin on the base flow (Humbert & Kaden, 1994), especially for the drought or low-water level period. It is a function of the base flow volume (*BFV*) and the total flow volume (*TFV*):

$$BFI(\%) = 100.\frac{BFV}{TFV} \quad (3)$$

The seasonal irregularity index (*SII*) is used (Tangana, 2005; Totin *et al.*, 2010) to analyse flow and flow regime variation while Perrin (2000) applied it in the study concerning the rainfall. This index is calculed on the sub-basin of Pendjari and Magou by:

$$SII(\%) = 100.\frac{Q_{hfm} - Q_{lfm}}{Q_{ym}} \quad (4)$$

where Q_{hfm} and Q_{lfm} are the average of higher flow and lower flow months, respectively; and Q_{ym} is the annual average flow.

RESULTS AND DISCUSSION

Climatic and aridity context on the Volta River basin in Benin

In the Volta River basin of Benin, monthly average rainfall is 97.3 ± 98 mm against a potential evapotranspiration of 124.2 ± 17.3 mm over the period 1961–2010. The induced monthly mean climate balance (P-PET) is –27 ± 80 mm. Inter-annual rainfall variation (Fig. 2) highlighted by the

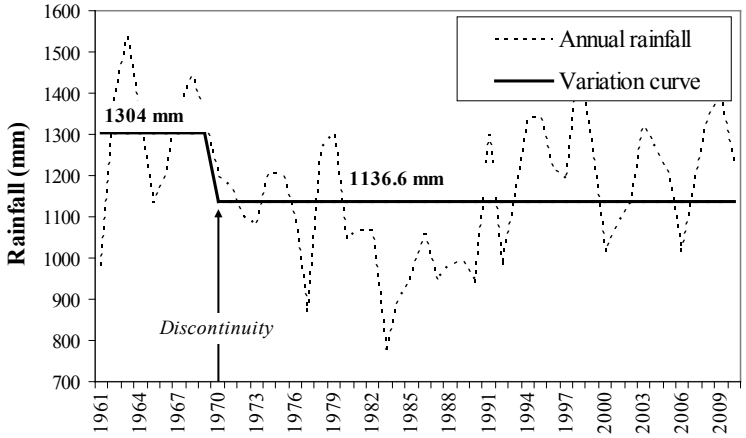

Fig. 2 Inter-annual rainfall variation on the Volta River basin in Benin.

homogeneity tests of Pettitt for time series leads to a decrease of 13% and drought persistence since 1970. According to Totin *et al.* (2009) the occurrence of the dry climatic conditions is due to the influence of the Sahelian climate from the north on the basin.

This annual rainfall trend is evidence of change in the monthly precipitations over the study period, as shown in Fig. 3. At the monthly scale, except January with increasing rain (6%) but negligible rainfall anyway, the Volta basin registered decreasing rainfall from 1% (May) to 58% (November). There is a clear link between drought in the Sahel, sea surface temperature (SST) and upwellings in the Gulf of Guinea (Le Houérou, 1996) and the climate of the study area.

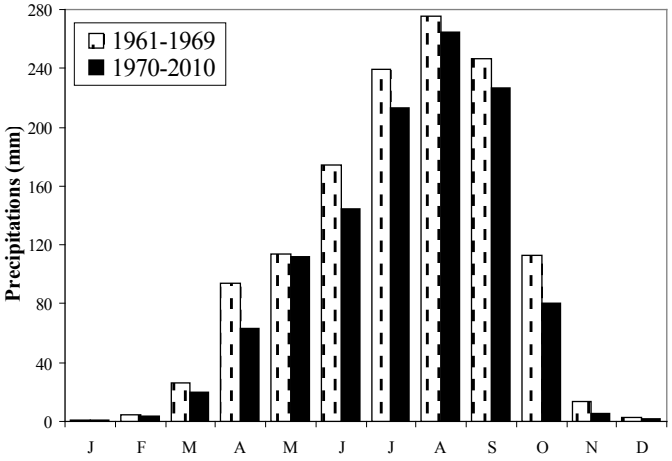

Fig. 3 Variation of the mean precipitations regime on the Volta River basin in Benin (1961–2010).

Table 1 Evolution of the mean aridity index over the period 1961–2010 on the Volta River basin in Benin.

	J	F	M	A	M	J	J	A	S	O	N	D
1961–1969	0.01	0.03	0.16	0.64	0.84	1.62	2.39	3.13	2.72	1.03	0.12	0.02
1970–2010	0.01	0.03	0.13	0.43	0.81	1.21	2.00	2.60	2.17	0.68	0.05	0.01
1961–2010	0.01	0.03	0.14	0.47	0.82	1.27	2.06	2.66	2.24	0.74	0.06	0.02

Moreover, seasonal rainfall variation (1970–2010 compared to 1961–1969) is –12% and –32% for the rainy season and the dry season, respectively. Indeed, this signature of the drying climate postulates that the Volta River basin in Benin faces drought conditions and certainly increasing aridity.

Aridity indicators (Table 1) show that the Benin basin of the Volta River experienced within each year six climate contexts such as hyperarid climate (December to February), arid (March and November), semi-arid (April over 1970–2010), dry sub-humid (April over 1961–1969 and 1961–2010), sub-humid (October) and humid/hyper-humid (May to September).

The aridity index variation over 1961–2010 (0.01 to 2.66) illustrates a slide of the hyper-humid climate context (JAS) to that of hyperarid climate (DJF). This index of the period 1970–2010 compared to 1961–1969 (Table 1) decreased by 20%, explaining the drying climate. This is related to the fact that the Volta River basin in Benin, near southwestern Burkina Faso is more and more influenced by the Sahelian dry climate. Furthermore, change of temperature (IPCC, 2007), however moderate, would correspond with a significant increase in climatic aridity (Le Houérou, 1996) in this basin.

Hydrological regime sensitivity to drying climate

The year 1975 is the break point in the hydrological time series stationarity, six years after that of the heavy rainfall of 1969. The observed increasing level of aridity affects hydrological processes

in the Volta River basin. Indeed, variation in the hydrological regime (Fig. 4) shows a decrease in mean annual flow by 41% in the sub-basin of Porga and by 32% in that of Tiele 71 to 41.5 m^3/s and 5.5 to 3.7 m^3/s, respectively, from the period 1961–1975 to 1975–2010.

Correlation between the aridity index (Table 1) and monthly flow (Fig. 4) highlights the effects of the dry climate on the Volta River. The hydrological change is marked at the monthly scale by higher variability and decreasing flow (8–47% at Porga and 31–62% at Tiele). This hydrological variation certainly results from a spatiotemporal slide of the humid climate to the arid climate on the basin.

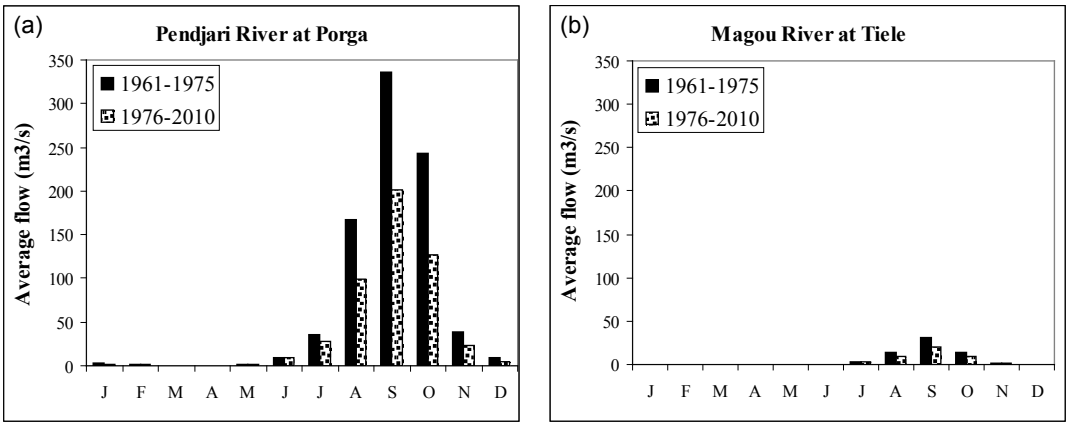

Fig. 4 Variation of the mean hydrological regime on the Volta River basin of Benin (1961–2010): (a) River Pendjari and (b) River Magou.

Table 2 Variation of the base flow index (BFI) and the seasonal irregularity index (SII).

Sub-basins	Magou River (Tiele)			Pendjari River (Porga)		
Periods	1961–1975	1976–2010	1961–2010	1961–1975	1976–2010	1961–2010
BFI (%)	0.00	0.06	0.03	0.64	0.85	0.81
SII (%)	575.7	543.0	555.6	476.0	483.0	480.2

Analysis of other hydrological indicators such as the base flow index and the seasonal irregularity index (Table 2) reveals the sensitivity of the Volta basin to its progressive aridification.

Within the context of the hyperarid climate (December to February) and of the arid climate (March and November) and over the period 1976–2010 compared with 1961–1975, the base flow index increase from 0.6 to 0.8% at Porga and 0 to 0.1% at Tiele. This pattern of the hydrological recession and the surface water scarcity is supported by a very marked seasonal irregularity linking the aridity severity, as shown by the environmental state in Fig. 5.

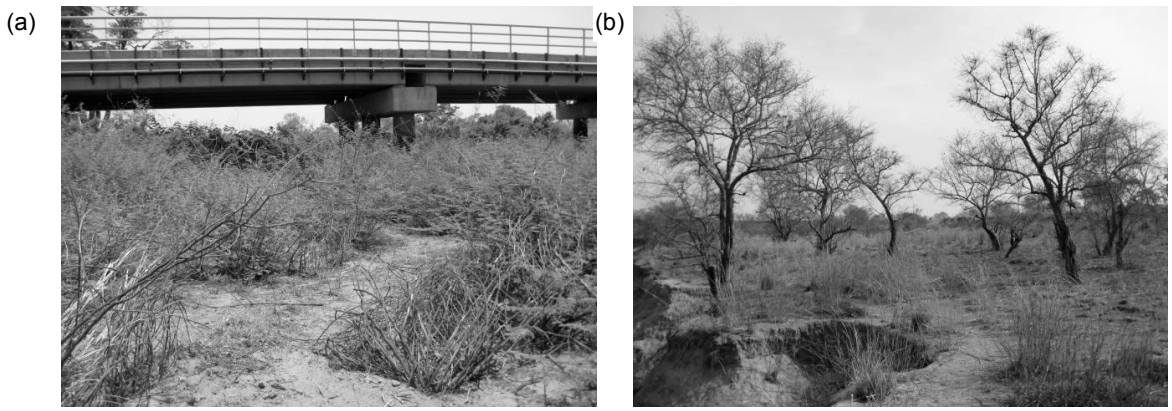

Fig. 5 State of the Volta River basin in time of the hyperarid climate: (a) on the Magou sub-basin and (b) on the Pendjari sub-basin in Benin.

Reduction or destruction of the perennial plant cover also decreases the rugosity of the landscape resulting in higher wind speeds at the soil surface and hence higher rates of evapotranspiration and increased aridity (Le Houérou, 1996) as observed on the Volta River basin in Benin.

CONCLUSIONS

Since 1970 on the Volta River basin in Benin, annual rainfall and flow have changed by –13%, and –30% to –40%, respectively, leading to the climatic and hydrological droughts persistence. Indeed increase in climatic aridity (20%) results from the precipitation and flow regimes sensitivity to the effects of the dry Sahelian climate.

As the monthly aridity index showed, it is evident that the Volta basin in Benin is affected and faces problems of water supply.

Hydrological regime sensitivity to the increasing aridity, in the Volta basin, should be an indicator to develop adequate and sustainable environment protection and water management strategies in the Sudano-Sahelian area of Africa.

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