The concept of rainfall and streamflow normals in West and Central Africa in a context of climatic variability

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Abstract This contribution to the debate on the revision of rainfall and streamflow normals concerns three countries of West Africa: Burkina Faso, Ivory Coast and Mali. The rainfall deficit (15–20% on average in the study area) and the river flow deficit (about 30–50% and sometimes more) observed over the past 30 years in West and Central Africa raise the problem of the reference period that must be considered in estimates of hydrological characteristics. The hypothesis of the concept of “normal” supporting these estimates is a stability of the climate. However, the effect of taking or not taking into account the data of recent years on the estimates of these characteristics can lead to very different results. This would have serious consequences for the development and management of water resources systems, as seen in two examples of dams.

Key words rainfall normal; streamflow normal; climatic variability; drought; West and Central Africa

Le concept de normales pluviométriques et hydrométriques en Afrique de l’Ouest et Centrale dans un contexte de variabilité climatique

Résumé Cette étude concerne trois pays d’Afrique de l’Ouest: le Burkina Faso, la Côte d’Ivoire et le Mali. Il s’agit d’une contribution au débat sur la révision des normes hydrologiques tant en matière de précipitations que de débits. Les déficits pluviométriques (de l’ordre de 15 à 20% en moyenne dans la région étudiée) et sur les débits (de 30 à 50% et parfois plus) observés durant ces 30 dernières années en Afrique de l’Ouest et Centrale soulèvent la question de la période de référence qu’il convient de retenir pour la définition des caractéristiques hydrologiques. Par définition, le concept de normes hydrologiques fait référence à une stabilité du climat. A l’opposé, le fait de prendre en compte, ou non, les données des années récentes pour estimer les caractéristiques hydrologiques peut conduire à des résultats très différents et à de sérieuses conséquences sur la conception et le fonctionnement des ouvrages équipant les bassins versants. Le cas de deux barrages est évoqué ici.

Mots clefs normales pluviométriques; normales hydrométriques; variabilité climatique; sécheresse; Afrique de l’Ouest et Centrale

Open for discussion until 1 August 2003
INTRODUCTION

Problems related to climatic changes are among the most important of the present century. Moreover, the assessment and control of water resources are of paramount importance in general, and in developing countries in particular. There is therefore a particular and legitimate interest of scientists to study climatic variability and its impact on water resources.

Studies of rainfall fluctuations in West and Central Africa show a tendency to aridification from 1970 onwards. Initially observed and studied in the Sahelian regions, this drought also appeared in wetter regions, near the Gulf of Guinea (Sircoulon, 1976; Nicholson, 1985; Hubert & Carbonnel, 1987; Nicholson et al., 1988; Hubert et al., 1989; Demarée, 1990; Mahé & Citeau, 1993; Mahé & Olivry, 1995; Paturel et al., 1997, 1998; Servat et al., 1997a,b; Mahé et al., 2001b; L’Hôte et al., 2002). The rainfall deficit, observed over several consecutive years, has reduced flows of the region (Sircoulon, 1987; Sutcliffe & Knot, 1987; Olivry et al., 1993; Mahé & Olivry, 1991, 1999; Aka et al., 1996; Servat et al., 1997c; Fanta et al., 2001).

These rainfall and streamflow deficits, observed over a long period of 30 years, raise the problem of the period of reference that must be considered to estimate the hydrological characteristics used by those working in the field of development projects. Indeed, what value can be given, for instance, to rainfall normals calculated over the period 1961–1980, or even over the period 1951–1980, when it is known that, in the Sahelian and the Sudanian zones, annual rainfall amounts have not exceeded the long-term annual mean since 1969?

Many authors insist on an urgent need for revising the rainfall and streamflow normals. For example, Todorov (1985) shows that, if 16 years of measurements (1968–1983) are integrated in the chronological series of Sahelian raingauge records, all the “new” rainfall averages, except one, are lower than those already established by the World Meteorological Organization. Bricquet et al. (1996) showed that, of the annual maximum flows of the River Niger at Koulikoro for the period 1971–1992, discharges are 24% lower than those for the whole period of observation (1922–1992).

These few results should have led to operational recommendations and to adjustments of methods in use. However, most of the publications used in planning and water resources management in West and Central Africa still employ information based on the periods 1941–1970 or 1951–1980, and rarely on the period 1961–1990. One can easily understand the problems brought about by this inadequacy between the observed situation and the normals used. Moreover, there are several projects in West and Central Africa which have required heavy investments, yet the expectations have not materialized as the nominal design values were different from the ones which occurred in reality. This justifies the concern about drought events and the selection of hydrological normals to be used.

DROUGHTS RECORDED OVER THE 20TH CENTURY IN WEST AND CENTRAL AFRICA

Droughts become a matter of consideration when they have a regional dimension, when they last long, and when they affect the population, the environment and the
socio-economic systems in which people live. From available data, historical research, witness reports and sayings (Sircoulon, 1976, 1987; Paturel et al., 1998), there was a significant drought resulting in severe starvation between 1913 and 1916 in West and Central Africa. According to the same sources, there was a drought in the middle of the century (1940–1944), also with dramatic consequences although it was less severe than the 1913–1916 drought and probably more localized (Nigeria). Since the beginning of the 1970s, the media have constantly reported on the successive droughts in West Africa and, to a lesser extent, in Central Africa. Several intervals with contrasting climates were thus identified over the 20th century.

VARIATIONS IN RAINFALL AND RUNOFF OVER THE SECOND HALF OF THE 20TH CENTURY

The relative inconsistencies of pluviometric and hydrometric information at the beginning of the 20th century do not always allow an objective comparison between the different climatic events that occurred during the whole of the century. During the second half of the 20th century, on the other hand, there was a marked expansion of measurement networks, particularly of the hydrometric network, which was at an embryonic stage up to 1950 with only a few big streams being measured regularly.

Most studies in West and Central Africa usually compare the rainfall levels during the 1950s and 1960s to those of the 1970s and 1980s: the former corresponding to a wet or excess period as far as rainfall and flow are concerned, whereas the latter correspond to a dry or deficit period. The drought that occurred since 1970 differs from the earlier ones in its duration, intensity and regional extent (Sircoulon, 1990). As for the 1990s, only a few regional studies of water availability have been carried out to the authors’ knowledge. Nevertheless, many people seem to agree that also during this decade a water deficit was observed.

Mahé et al. (2001b) analysed annual rainfall over 1951–1989 in West and Central Africa (Fig. 1). They identified eight climatic sectors, which could be regrouped in six large geographical areas, and calculated annual pluviometric indexes (standard deviation values): Sahel (“NWsahel”, “Central sahel” and “East sahel”), the Guinean mountains (“Guinea”), the Guinea Gulf (“North coast”), the Cameroon mountains (“East cameroon”), the western equatorial region (“Center west”) and the eastern equatorial region (“Center east”). The results obtained are confirmed by those of Servat et al. (1998). They focused on the existence of a deficit period since 1970, affecting the whole of West Africa. Central Africa seems to have been less affected by this phenomenon and the said climatic fluctuation does not seem to depart from the normal range of natural variability. Generally speaking, in West and Central Africa, after 1970, the mean annual rainfall was about 15–20% below the values for the reference period of 1950–1989.

This highest rainfall deficit observed for 30 years has had serious impacts on the river flows in West and Central Africa (Fig. 2): the mean discharge deficits are commonly greater than 30% and sometimes exceed 50% (Fig. 3).
Fig. 1 Variations in standardized annual rainfall indexes in West and Central Africa (from Mahé et al., 2001b).

VARIATIONS IN RAINFALL AND STREAMFLOW NORMALS

Methodology

The aim is to quantify the incidence of drought years in West and Central Africa. The availability of data limits the study to the period 1951–1997.
Two options are considered:

(a) to base the new normal on the most recent data, i.e. to take into consideration only the “dry” period 1971–1997; and
(b) to integrate the most recent data with the earlier data, i.e. to take the whole period 1951–1997 into consideration.

The period 1951–1980, still too frequently used to define and calculate normals, is used as the reference and comparison point. The results are shown for Ivory Coast, Burkina Faso and Mali.

Rainfall normals

Traditionally, and by agreement, the World Meteorological Organization defines normals based on periods of 30 years.

Normals based on most recent data Figure 4 shows maps of 30-year averages of annual rainfall for the periods 1951–1980, 1961–1990, and 1971–1997 for Burkina Faso, Mali and Ivory Coast. The form of the isohyets is maintained from one period to
another but a general shift of the isohyets towards the south–southwest is observed, clearly showing a rainfall deficit over the periods 1961–1990 and 1971–1997, compared with the period 1951–1980.

For the period 1961–1990 (Fig. 4), there was a southward shift in the 400 mm isohyet of about 50 km, and a similar shift in the 800 mm isohyet of about 100 km. The 1200 mm isohyet disappears completely from Burkina Faso, and covers only a small part of the south of Mali and considerably recedes towards the southern part of Ivory Coast. The zone of annual rainfall exceeding 1600 mm is located in the extreme southwestern part of Ivory Coast during 1961–1990.

The recession is even more marked for the period 1971–1997 (Fig. 4(c)). It also confirms that the 1990s was a dry decade. The difference between the mean annual isohyets of the periods 1951–1980 and 1971–1997 is presented in Fig. 5. Throughout the study area, the mean annual rainfall for 1971–1997 is lower than that for 1951–1980. The deficits mostly vary between 10 and 20% but are greater in some areas. These shifts of the normal have serious consequences for development and management of water resources systems.

**Normals based on the integration of most recent data** Because of the exceptional character of the drought that occurred since the beginning of the 1970s, it is necessary to be careful in defining the normal. Rather than use averages over a moving window of 30 year duration, it is recommended to base calculations on all the
Rainfall normals in West and Central Africa

To consider the quality and density of the information (as described above), a calculation of rainfall normals over the period 1951–1997 could be undertaken. Figure 6 presents the difference between the mean annual isohyets for the periods 1951–1980 (reference) and 1951–1997. The normal for 1951–1997 is almost systematically lower than that for the years 1951–1980 by 0–10%. The gaps are then logically weaker than when the two distinct periods 1951–1980 and 1970–1997 are considered. This illustrates that it is important to recognize the changing pattern of water availability over the recent decades.

**Fig. 4** Rainfall normals (400, 800, 1200 and 1600 mm) for the years 1951–1980, 1961–1990 and 1971–1997 for Burkina Faso, Mali and Ivory Coast (C.I.).
River flow normals

Previous studies (Aka et al., 1996; Bricquet et al., 1996, 1997; Servat et al., 1997c, 1998; Mahé & Olivry, 1999) have shown that anomalies in river flows are greater than those observed for rainfall. The nonlinearity of the rainfall–runoff relationship explains these major differences. In West and Central Africa, the economy strongly depends on the management of water resources (agricultural development projects, hydro-electricity production, infrastructures protection, water supply, etc.). The impact of the recent climatic variability on the rivers and the definition of the corresponding normal is therefore very important.

In the countries of the zone studied here, the frequency of flows greater than the average is most commonly used to evaluate the hydrological variables necessary when dimensioning infrastructures. The results presented here are the variations in flows for specific return periods. These results are obtained from adjustments of mean annual flows and high flow characteristics of the series for the rivers Kouroukele at Iradougou (a Niger tributary in Ivory Coast, 1990 km$^2$), Bandama at Bada (Ivory Coast, 24 050 km$^2$), Sassandra at Semien (Ivory Coast, 29 300 km$^2$), Mouhoun at Dapola (Burkina Faso, 70 000 km$^2$) and Bani at Douna (a Niger tributary in Mali, 101 650 km$^2$). The adjustments were made through the use of a normal law or its derivatives.
Problems with data quality precluded similar analysis of the low flow data. Moreover, for many rivers of these regions, the flows used to be perennial, but are now ephemeral. Data are available at Douna from 1951 onwards, at Semien from 1954, at Dapola from 1955, and at Iرادougou and Bada from 1962. These differences of “start” dates do not fundamentally affect the results obtained.

**Mean annual flows** The mean annual flows are widely used to characterize the availability of water resources. Table 1 regroups the values of mean annual flows obtained in the five basins for different frequencies associated with the wet return period.

*Definition of normal based on the most recent data* The estimates of mean annual flows for the period 1971–1997 are systematically lower than those for the period 1951–1980, which are often used to define river flow normals. The most significant differences are observed at Douna: the difference between estimates is more than 55% for all the return periods. As an illustration of the magnitude of the shifts, the “new” annual flow for the 100-year return period is lower than the 10-year return period value for 1951–1980.

*Definition of normal based on the integration of the most recent data* The estimates of mean annual flows for the period 1951–1997 are lower than those for the
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Table 1 Values of mean annual flows (m$^3$ s$^{-1}$) associated with wet return periods and the difference compared to 1951–1980.

<table>
<thead>
<tr>
<th>Basin</th>
<th>Return period</th>
<th>10 years:</th>
<th>20 years:</th>
<th>50 years:</th>
<th>100 years:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandama</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>at Bada</td>
<td>183</td>
<td>155</td>
<td>108</td>
<td>201</td>
<td>173</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(–15%)</td>
<td>(–41%)</td>
<td>(–14)%</td>
<td>(–40)%</td>
</tr>
<tr>
<td>Mouboun</td>
<td>161</td>
<td>152</td>
<td>113</td>
<td>176</td>
<td>167</td>
</tr>
<tr>
<td>at Dapola</td>
<td></td>
<td>(–6%)</td>
<td>(–30%)</td>
<td>(–5)%</td>
<td>(–29%)</td>
</tr>
<tr>
<td>Bani at</td>
<td>842</td>
<td>765</td>
<td>333</td>
<td>929</td>
<td>859</td>
</tr>
<tr>
<td>Douna</td>
<td></td>
<td>(–9%)</td>
<td>(–60%)</td>
<td>(–8%)</td>
<td>(–60%)</td>
</tr>
<tr>
<td>Kouroukele at Iradougou</td>
<td>27.2</td>
<td>25.1</td>
<td>19.8</td>
<td>29.4</td>
<td>28.1</td>
</tr>
<tr>
<td></td>
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<td>(–8%)</td>
<td>(–27%)</td>
<td>(–4%)</td>
<td>(–27%)</td>
</tr>
<tr>
<td>Sassandra at Semien</td>
<td>328</td>
<td>301</td>
<td>234</td>
<td>358</td>
<td>331</td>
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<tr>
<td></td>
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<td>(–8%)</td>
<td>(–29%)</td>
<td>(–8%)</td>
<td>(–30%)</td>
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</tbody>
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Table 2 Estimated values of 1-day maxima (m$^3$ s$^{-1}$) associated with wet return periods and the difference compared to 1951–1980.

<table>
<thead>
<tr>
<th>Basin</th>
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<th>10 years:</th>
<th>20 years:</th>
<th>50 years:</th>
<th>100 years:</th>
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<tr>
<td>Bandama</td>
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<tr>
<td>at Bada</td>
<td>991</td>
<td>878</td>
<td>804</td>
<td>1908</td>
<td>986</td>
</tr>
<tr>
<td></td>
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<td>(–11%)</td>
<td>(–19%)</td>
<td>(–11%)</td>
<td>(–18%)</td>
</tr>
<tr>
<td>Mouboun</td>
<td>756</td>
<td>710</td>
<td>667</td>
<td>837</td>
<td>787</td>
</tr>
<tr>
<td>at Dapola</td>
<td></td>
<td>(–6%)</td>
<td>(–12%)</td>
<td>(–6%)</td>
<td>(–12%)</td>
</tr>
<tr>
<td>Bani at</td>
<td>3405</td>
<td>3139</td>
<td>1821</td>
<td>3716</td>
<td>3507</td>
</tr>
<tr>
<td>Douna</td>
<td></td>
<td>(–8%)</td>
<td>(–47%)</td>
<td>(–6%)</td>
<td>(–45%)</td>
</tr>
<tr>
<td>Kouroukele at Iradougou</td>
<td>135</td>
<td>122</td>
<td>104</td>
<td>145</td>
<td>132</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(–10%)</td>
<td>(–23%)</td>
<td>(–9%)</td>
<td>(–23%)</td>
</tr>
<tr>
<td>Sassandra at Semien</td>
<td>1639</td>
<td>1536</td>
<td>1328</td>
<td>1763</td>
<td>1668</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(–6%)</td>
<td>(–19%)</td>
<td>(–4%)</td>
<td>(–19%)</td>
</tr>
</tbody>
</table>

Table 3 Estimated values of 30-day annual maxima (m$^3$ s$^{-1}$) associated with wet return periods and the difference compared to 1951–1980.

<table>
<thead>
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<th>Basin</th>
<th>Return period</th>
<th>10 years:</th>
<th>20 years:</th>
<th>50 years:</th>
<th>100 years:</th>
</tr>
</thead>
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<td>Bandama</td>
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<tr>
<td>at Bada</td>
<td>944</td>
<td>744</td>
<td>644</td>
<td>1056</td>
<td>838</td>
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<tr>
<td></td>
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<td>(–21%)</td>
<td>(–32%)</td>
<td>(–21%)</td>
<td>(–31%)</td>
</tr>
<tr>
<td>Mouboun</td>
<td>723</td>
<td>620</td>
<td>575</td>
<td>802</td>
<td>693</td>
</tr>
<tr>
<td>at Dapola</td>
<td></td>
<td>(–14%)</td>
<td>(–20%)</td>
<td>(–14%)</td>
<td>(–20%)</td>
</tr>
<tr>
<td>Bani at</td>
<td>3387</td>
<td>3026</td>
<td>1700</td>
<td>3698</td>
<td>3390</td>
</tr>
<tr>
<td>Douna</td>
<td></td>
<td>(–11%)</td>
<td>(–50%)</td>
<td>(–8%)</td>
<td>(–49%)</td>
</tr>
<tr>
<td>Kouroukele at Iradougou</td>
<td>124</td>
<td>102</td>
<td>88</td>
<td>133</td>
<td>110</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(–18%)</td>
<td>(–29%)</td>
<td>(–17%)</td>
<td>(–29%)</td>
</tr>
<tr>
<td>Sassandra at Semien</td>
<td>1408</td>
<td>1081</td>
<td>960</td>
<td>1510</td>
<td>1164</td>
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<tr>
<td></td>
<td></td>
<td>(–23%)</td>
<td>(–32%)</td>
<td>(–23%)</td>
<td>(–32%)</td>
</tr>
</tbody>
</table>

period 1951–1980, although they are greater than those for the period 1971–1997. The effects of drought years are partially compensated for by the high values observed in the wet decades, the 1950s and 1960s. The clearest differences are noted at Bada.
Characteristics of high flows

The study of high flows consisted of analysing series of annual maximum 1- and 30-day mean flows. The results are summarized in Tables 2 and 3.

The estimates of the 1-day maxima for the period 1971–1997 are always lower than those for the other periods. Nevertheless, the variations in the estimates of the 1-day maxima from one period to another do not reach the relative amplitude of those recorded for the annual mean flows. High flows have been probably less affected by climate change than mean flows or low flows.

The 30-day maxima for the period 1971–1997 are always lower than those over other periods. The variations in the estimates of the 30-day maxima from one period to another are greater than those recorded for the 1-day maxima.

The variations in the 30-day maxima estimates are more closely related to those observed in the annual means. They are even of the same magnitude for the Kouroukele and the Sassandra rivers.

In absolute values, deviations are still visible: at Douna, the decadal flow for the period 1951–1980 corresponds to a return period of 20 years for 1951–1997, but does not even reach the 100-year level for 1971–1997.

LIMITATIONS OF RAINFALL AND STREAMFLOW NORMALS

From the results obtained, particularly on the streamflow normals, it may be easily seen that managers or decision makers may design projects (e.g. hydraulic structures), which are technically and economically different, depending on the normals used.

For example, the big Bagre Dam in Burkina Faso, constructed in 1992, was designed using the pre-1980 data. Its spillway was dimensioned for a peak flow estimated at 1520 m$^3$ s$^{-1}$. In 1994, a flood occurred that reached a peak flow estimated at 2050 m$^3$ s$^{-1}$. This was unexpected and paradoxical because of the climatic context of drought. Analysis of the data for part of the upstream basin showed a considerable increase in the runoff coefficients since 1970. Mahé et al. (2001a) showed that, although the rainfall decreased, the flows were more marked. If this information and the most recent data were taken into consideration, one would probably estimate peak flow values that are considerably higher than those used in the design. In contrast, the Kossou Dam in Ivory Coast, designed based on a “wetter” normal and constructed during a “wet” period and inaugurated at the beginning of the drought during the 1970s, has never filled to its nominal capacity.

These examples emphasize the complexity of the phenomenon of persisting drought. Drought leads to modifications of habits, behaviours, and agricultural practices. In addition to the nonlinearity of the rainfall–runoff transformation, this set of factors emphasizes the need for hydrosystems to be stable. Taking into account the “new” normal is certainly necessary, in the light of the results presented here, but the evolution of the land use and land cover must be also considered.

In the process of design of dams (or of any other hydraulic works) in Africa, it must be taken into consideration that, during design life of structures, there may be major fluctuations in discharge due to changes in the flow regimes of the rivers concerned. The design must therefore be robust, taking into account the effects of strong variability, i.e. several years of drought or of water surplus (Hubert et al., 1989).
The problem of revision of rainfall and streamflow normals is therefore of considerable practical importance and one to which it is difficult to propose a unique and definitive solution.

Acknowledgements The authors wish to acknowledge both reviewers for their relevant comments which were helpful in the writing of the final version of this paper.

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Received 13 February 2002; accepted 31 October 2002