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A study on hydrological series of the Niger River

Tommaso Abrate[1], Pierre Hubert[2] and Daniel Sighomnou[3]

[1]*World Meteorological Organization, Geneva, Switzerland*

[2]*UMR Sisyphe, Université Pierre et Marie Curie, Paris, France*
pjy.hubert@free.fr

[3]*Niger-HYCOS, BP 729 Niamey, Niger*

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Abstract The Hubert segmentation procedure has been applied to historical series of annual average discharges of the Niger River at Koulikoro (Mali), Niamey (Niger) and Lokoja (Nigeria) stations. The breaks, especially those identified at Koulikoro and Niamey, match well with those identified in the Senegal River series at Bakel using the same procedure. Lokoja departs from this regional pattern, as it shows in the late 1980s a return to wetter conditions much earlier than the other three stations. The magnitudes of the variation of the inter-annual means between the alternating wet and dry periods are significant and similar. These results seem to suggest that phenomena causing non-stationarity in hydrological series can have a sub-continental impact or, in contrast, may be more limited in their spatial coverage.

Key words Niger; Hubert segmentation procedure; hydrological series; West Africa

Etude de séries chronologiques du fleuve Niger

Résumé La procédure de segmentation de Hubert a été appliquée aux séries chronologiques des débits moyens annuels du fleuve Niger à Koulikoro (Mali), Niamey (Niger) et Lokoja (Nigeria). Les ruptures détectées, en particulier celles identifiées à Koulikoro et à Niamey, correspondent bien avec celles identifiées selon la même procédure sur la série du fleuve Sénégal à Bakel. La série de Lokoja se comporte sensiblement différemment puisqu'elle montre, dès la fin des années quatre-vingts, c'est à dire beaucoup plus tôt que les trois autres stations, un retour à des conditions plus humides. Les amplitudes des variations des moyennes interannuelles entre périodes sèches et humides sont significatives et similaires. Ces résultats suggèrent que les phénomènes à l'origine de l'instationnarité des séries hydrologiques pourraient n'avoir qu'un impact subcontinental ou au contraire n'avoir qu'un champ d'action spatial limité.

Mots clefs Niger; procedure de segmentation de Hubert; series hydrologiques; Afrique de l'Ouest

1 INTRODUCTION

Hydrometeorological series in West Africa are characterized (Brunet-Moret *et al*. 1986) by a considerable persistence, as demonstrated by the frequent rejection of the hypothesis of independence, with often significant autocorrelation coefficients, and by high Hurst coefficients (Hurst 1950). Many studies conducted on pluviographic and hydrographic series in the region (Hubert and Carbonnel, 1987, 1993, Paturel *et al*. 1997) have shown the presence of a number of breaks in the series, corresponding to increases (early 1920s and late 1940s) or decreases (in the late 1930s and late 1960s) of yearly averages. Recently, higher averages in the mid-1990s have been highlighted in the hydrological series of the River Senegal at Bakel, which seems to confirm the hypothesis that the Sahelian drought could have ended in the 1990s (Ozer *et al*. 2003, Hubert *et al*. 2007). This leads one to hypothesize the non-stationarity of these series and the existence of points of discontinuity, singularities represented in particular by changes in averages, caused by a change, be it natural or man-made, in the mechanism generating discharge.

This paper presents the results obtained by applying to three long historical series of mean annual discharge of the River Niger the methodology already used by Hubert (2000) and Hubert *et al.* (1989, 2007) on other series in the same region. The goal is to look for possible breaks in the series, especially in the mid-1990s. Three stations were chosen for the study, whose data have been made available by the Niger Basin Authority. The three stations, selected on the basis of the length of their record and geographical positions in the basin, are Koulikoro (Mali) in the upper basin under the effects of the Guinean type tropical climate (peak discharge in September); Niamey in Niger, downstream of the Inner Delta and the Saharan areas of major evaporation losses, with two discharge peaks in February and September; and Lokoja in Nigeria, below the confluence with the Benué and other tributaries flowing from the Central African region, showing again a peak discharge in September.

2 GEOGRAPHY

The River Niger is the third longest river in Africa (4200 km), after the Nile and the Congo, draining a basin of about 1 100 000 km^2 (Olivry 2002). The river has its sources on the Fouta Djallon massif in Guinea and, after a long arch through the Sahelian and Saharan regions, empties in the Gulf of Guinea with a large delta. The course (Fig. 1) of the Niger can be broadly divided into four: an Upper Basin, corresponding to the Futa Djallon massif and the moderately hilly region upstream of Bamako; the Inner Delta, where the gradient suddenly decreases, resulting in a region of marshes and swamps; the middle basin ("Boucle du Niger" or Niger Bend), mainly corresponding to the northern Sahelian and Saharian parts; and the Lower Basin to the maritime delta. The main tributaries are the Bani (Inner Delta) and the Benué (Lower Basin).

3 CLIMATE

The climate of the Niger basin is governed by the seasonal movement of two air masses separated by the inter-tropical convergence zone (ITCZ); and is characterized by two distinct seasons: a rainy season in summer peaking in August, and a dry season in winter-spring. Annual rainfall ranges from 1500 mm/year in the tropical transitional area (headwaters of the Fouta Djallon massif and the maritime delta, that has peaks up to 3000 mm/year) to 250 mm/year in the most desert areas. Because of its peculiar arch-shaped course, the Niger crosses all the climatic zones twice (Fig. 1) and this has a particular influence on its hydrological regime.

The basin is characterized by intense evaporation ranging from 1200–1400 mm/year in the mountainous areas of Guinea and the lower reaches and delta of the river to 2000–2500 mm/year in the Inner Delta region and in the more arid part of basin (Olivry *et al*. 1995). The maximum temperature easily reaches 50°C in the northern Sahelian and sub-arid desert region, the annual averages range between 20 and 30°C, and minima are around 10°C in both the mountains of Fouta Djallon and the Sahara. Humidity is less than 20% in the north, but may exceed 90% near the mouth of the river in the south.

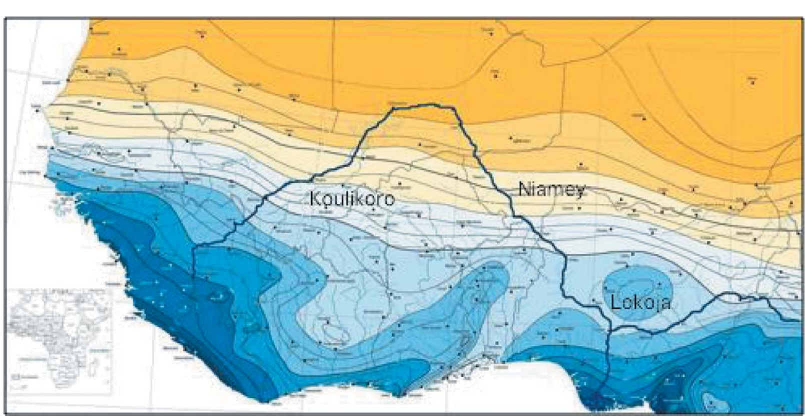

Fig. 1 The Niger River and the location of the three gauging stations, and mean inter-annual precipitation in the region (1951–1989) (after L'Hôte and Mahé 1996).

4 HYDROGRAPHY AND HYDROLOGY

As the River Niger crosses the different climatic zones twice, discharge generated by summer rains in the tropical Upper Basin undergoes significant losses by evaporation and seepage in the Inner Delta and Niger Bend zones, then is fed again, as the river heads south, by tributaries flowing from Central Africa and by more intense rainfalls in Nigeria.

At Koulikoro station (catchment of 120 000 km^2, considered the closing station of the Upper Basin) the inter-annual mean discharge is about 1348 m^3 s^{-1} for the period 1946–1992 (this period is used as it is the only period for which there is a complete series of overlapping data for the three stations studied). The maximum flood observed was 9670 m^3 s^{-1} on 5 October 1925, while the average low water flow is around 25 m^3 s^{-1}.

The Inner Delta is a vast floodable area 450 km long and of about 50 000 km^2 surface area. The very flat morphology slowing the flow, combined with very high temperature and an arid or semi-arid climate, favour considerable evaporation losses. As may be seen from Table 1, the flow at the outlet of the Inner Delta shows losses of 30–50%, depending on the year.

Since these losses are exclusively due to evaporation, they correlate very well with the extent of flooded areas, so in wet years they are greater in relative as well as absolute terms compared to a dry year (Picouet 1999). The total losses vary between 7 and 30 km^3 $year^{-1}$; the magnitude of this natural evaporation phenomenon makes almost negligible other losses due to artificial water bodies, such as irrigation areas of reservoirs.

At Niamey, representative station of the Middle Basin, the inter-annual mean discharge is around 875 m^3 s^{-1} (1946–1992). Low water levels are extremely severe (often below 10 m^3 s^{-1}) and in June 1986 the river even stopped flowing. The maximum flow was recorded on 30 January 1970, 2170 m^3 s^{-1}.

Table 1 Typical discharges upstream and downstream of the Inner Delta (based on ABN data).

Station	Mean annual discharge (m^3 s^{-1})		
	Humid year (1954)	Average year (1968)	Dry year (1985)
Ke Macina (upstream)	1951	1306	765
Tossaye (downstream)	1457	1033	574

In the Lower Basin in Nigeria, the river receives other tributaries that increase its discharge to mean values of the order of 2500 m^3 s^{-1} and annual maxima of around 9000 m^3 s^{-1}, i.e. values comparable to those observed at Koulikoro, upstream of the Inner Delta. Further downstream, at Lokoja, the Niger receives its largest tributary, the Benue flowing from Cameroon, which provides on average 3500 m^3 s^{-1}. The inter-annual mean discharge is 5589 m^3 s^{-1} (1946–1992) with a historical maximum of 27 600 m^3 s^{-1} on 16 October 1916 and low flows of around 500 m^3 s^{-1}.

5 VARIATION OF THE FLOW REGIME

The hydrological observations on the Niger River date back to the early 20th century, the oldest station being Koulikoro, established in 1907 shortly after the Bakel station on the Senegal. Lokoja followed in 1915 and Niamey in 1929 together with many others. Unfortunately, only Koulikoro can provide an almost uninterrupted series of data (only eight daily values missing in the period 1907–2005), while for many reasons, but particularly budgetary restrictions in recent decades, most of the other stations have historical series affected by large gaps.

Many syntheses, thesis papers and scientific articles have been published on the hydrology of the River Niger on the basis of these observations (Mahé 1993, Bricquet *et al*. 1995, Maiga 1998, Olivry *et al*. 1998, Servat *et al*. 1998, Ouedraogo 2001, Amani and Nguetora 2002, Ardouin-Bardin 2004). They indicate a significant variation in annual flows, with a marked reduction of the range in the last quarter of the 20th century. The inter-annual mean flow at Koulikoro, which was 1350 m^3 s^{-1} in the period 1929–1970, decreased to 1039 m^3 s^{-1} over the period 1971–2002 (–23%). At Niamey, the inter-annual mean flow between 1971 and 2000 is about 700 m^3 s^{-1}, against 1060 m^3 s^{-1} for the period 1929–1970 (–34%). At Lokoja, the average for 1929–1970 is 6055 m^3 s^{-1} against 5066 m^3 s^{-1} for the period 1971–2001 (–17%). Low-water periods with no flows have been recorded on the Bani at Douna (Mali) in 1983, 1984 and 1987, and on the Niger at Niamey in 1986.

Hubert *et al*. (1989) analysed 33 sets of rainfall data from stations in Senegal, Mali, Burkina Faso and Niger with durations of between 36 and 63 years, using the methodology used in this paper, and identified two major breaks: the first was negative (reduction of total rainfall and of the number of days of rain compared to the previous period) between 1968 and 1969, and the second positive (increased rainfall) between 1950 and 1952. In the same article, the authors also studied the series of river flow for the Senegal (at Bakel station) and Niger (at Koulikoro station) between 1907 and 1984. At Bakel, they highlighted four breaks: in 1921/22, 1936/37, 1949/50 and 1967/68, while at Koulikoro four analogous breaks were identified: in 1923/24, 1932/33, 1950/51 and 1969/70 (Hubert *et al.* 1989). The hydrological observations of the last two decades suggest that a new break has appeared in 1994/95 with a "return to the wet" (Ozer *et al*. 2003).

6 METHODOLOGY

The procedure used herein has been detailed by Hubert *et al*. (1989) and Hubert (2000). It allows one to determine whether a series is stationary or not, and divide it, should it not be stationary, into as many homogeneous series as possible. Based on the same principles, the segmentation procedure algorithm has been recently improved to deal with very long time series (Kehagias *et al*. 2004, 2006, Aksoy *et al*. 2008, 2010, Gedikli *et al*. 2008, 2010).

A series of length n is divided into m segments (segmentation of order m) whose length varies between 1 and $n-(m-1)$. Let i_k, $k = 1, 2, \ldots, m$ be the rank in the initial series of the upper end of the kth segment, whose length is $n_k = i_k - i_{k-1}$ and the average $\bar{x}_k$ (local average):

$$\bar{x}_k = \frac{\sum_{i=i_{k-1}+1}^{i=i_k} x_i}{n} \tag{1}$$

We define

$$d_k = \sum_{i=i_{k-1}+1}^{i=i_k} (x_i - \bar{x}_k)^2 \tag{2}$$

and

$$D_m = D(i_1, i_2, \ldots, i_m)$$
$$\sum_{k=1}^{k=m} \sum_{i=i_{k-1}+1}^{i=i_k} (x_i - \bar{x}_k)^2 = \sum_{k=1}^{k=m} d_k \tag{3}$$

as the squared difference between the series and the segmentation considered, allowing the closeness between the series and the segmentation considered to be estimated. In equation (3), D_m is indeed the sum of the squared difference with respect to the local average for all the terms of the initial series and depends only on the segmentation adopted. The optimum segmentation of order m would minimize D_m (equation (3)) with respect to all the other possible segmentations of the same order.

For $m = 1$ and $m = n$, there is only one possible segmentation:

$$D_1 = D(i_1) = n\sigma^2 \tag{4}$$

where σ is the standard deviation of the initial series, and

$$D_n = D(i_1, i_2, \ldots, i_n) = 0 \tag{5}$$

For all the segmentations whose order m is between 1 and n, several possible segmentations exist. The end of the mth segment coincides with the nth element of the series, while the end of the other $(m-1)$ segments can be arbitrarily placed on all the $(n-1)$ values of the original series. The number of possible segmentations of order m is given by:

$$c_{n-1}^{m-1} = \frac{(n-1)!}{(m-1)!(n-m)!} \tag{6}$$

The number of possible segmentations becomes rapidly unmanageable (7.9×10^{28} for a series of 97 elements) and, therefore, a search algorithm was developed to find the optimal segmentation (Hubert *et al*. 1989).

The procedure described allows optimal segmentation to be achieved in the sense of least squares. However, this procedure must be completed by introducing a constraint, as a particular segmentation cannot be accepted unless the means of two contiguous segments are significantly different. Hubert *et al.* (1989) used for this purpose the concept of contrast, ψ, introduced by Scheffé (1959). Segmentation of order m will be acceptable only if all contrasts ψ_k, $k = 1, 2, \ldots, m-1$ are different from zero at significance level α. This test is also included in the search algorithm. A new segmentation whose standard deviation is lower than the lowest standard deviation already obtained, can be accepted as the new optimal segmentation only if the null hypothesis of the Scheffé test is rejected at the chosen confidence level. This test also allows one to limit the order of the segmentation.

As the standard deviation of a $(m+1)$-order segmentation is lower than, or equal to the standard deviation of the optimal m-order segmentation, there is the risk of continuing the segmentation up to the order n, with $D_n = 0$, which is not useful for the interpretation of the series. By applying the Sheffé test to the optimal segmentation of any order, if any of the segmentations of order $m+1$ do not satisfy the test, the optimal segmentation of order m is retained and the process is halted.

Hubert *et al.* (2007) introduced a further refinement in the process by analysing not only the series from n_1 to n_n, but also all the possible subseries from year n_1 to year n_i $(n_1 < n_i \le n_n)$, as well as all the subseries from year n_i to year n_n $(n_1 \le n_i < n_n)$. This refinement allows verification of the stability of the segmentation obtained and identification of breaks in the neighbourhood of the end of each segment that could not be detected on the complete series, as breaks in the stationarity of time series are not absolute but are relative to the scales of observation.

Finally, the Wald-Wolfowitz (1943) independence test was performed on the residuals (the differences between values and local average) to estimate whether the values above or below the local average alternated randomly or not. The test was conducted at 0.01 and 0.05 significance levels.

7 APPLICATION OF THE SEGMENTATION PROCEDURE TO THE HISTORICAL SERIES OF KOULIKORO, NIAMEY AND LOKOJA

Among the 100 stations listed in the database of the Niger Basin Authority, Koulikoro (Mali), Niamey (Niger) and Lokoja (Nigeria) were used for this study on the basis of the length of the historical series (1907–2005 Koulikoro, 1929–2006 Niamey, 1915–2005 Lokoja) and their locations, which represent the various parts of the basin. These data were collected by the French “Institut de recherche pour le développement” (IRD formerly ORSTOM) in the framework of the activities of the Regional Hydrological Observatory in West and Central Africa (OHRAOC) and AOC-HYCOS project, supported by the French Cooperation and the World Meteorological Organization.

However, with the exception of Koulikoro, the stations present significant gaps in the series that could not be interpolated with confidence. Therefore, the periods retained for analysis are Koulikoro: 1907–2005; Niamey: 1944–2005; and Lokoja: 1946–1992. In these periods some further short gaps (a few days during low-water period) have been linearly interpolated, but this did not affect the total annual discharge.

The results of the application of the segmentation procedure are represented in Figs 2, 3 and 4. On the abscissas is indicated the initial or final year n_i of the sub-series, on the ordinates are the years where a break could be identified for each sub-series. Breaks in the sub-series n_1–n_i lie below the diagonal of the diagram, while breaks identified in the sub-series n_i–n_n lie above. A “+” sign indicates a positive break with flow increase, and the “–” sign a negative break with decrease. The dashed square indicates the range of years used for segmentation.

All segmentations were conducted at the 0.01 significance level for the Scheffé test. For the Wald-Wolfowitz independence test on the residuals, the vast majority of segmentation was accepted

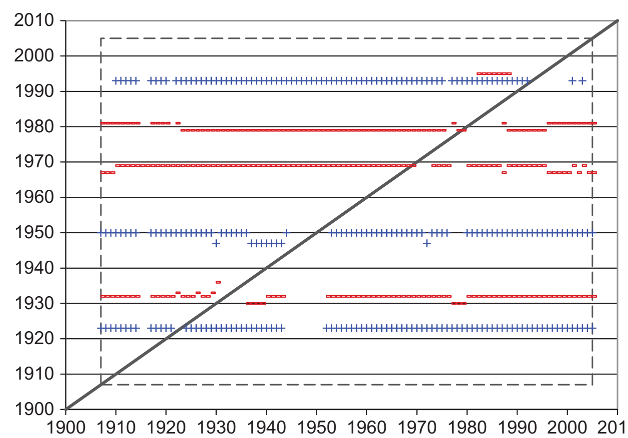

Fig. 2 Results of the segmentations of the Koulikoro series (1907–2006).

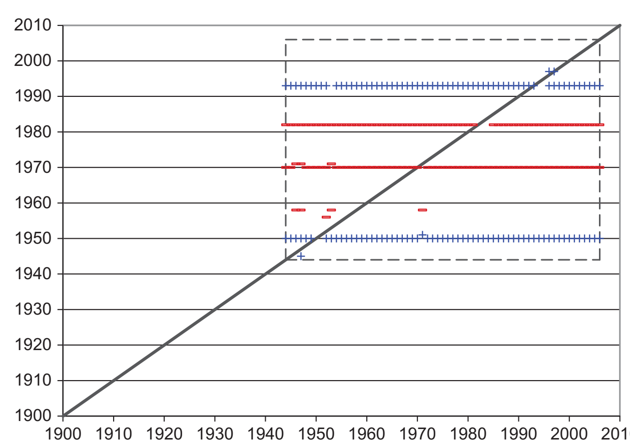

Fig. 3 Results of the segmentations of the Niamey series (1944–2006).

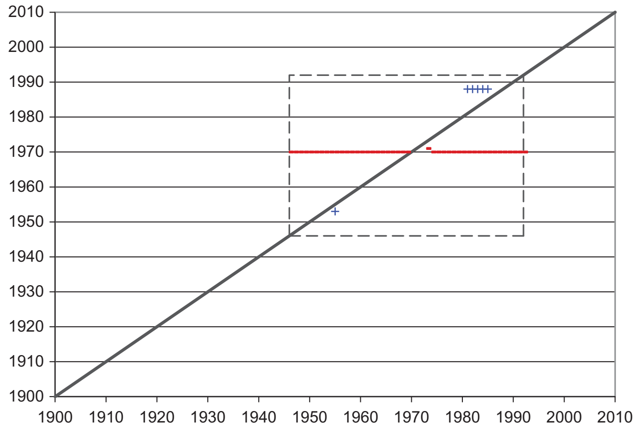

Fig. 4 Results of the segmentation of the Lokoja series (1946–1992).

at the 0.05 level. However, there are 16 cases in which the independence of the residuals was rejected at the 0.05 level and 25 were rejected at the 0.01 significance level.

Breaks are well aligned, confirming the stability and robustness of the procedure. All breaks for the three stations are almost always around the same years and with the same sense of variation (increase or decrease), as follows:

– At Koulikoro (Fig. 2): 1923/24 (positive), 1932/33 (negative), 1950/51 (positive), 1969/70 (negative), 1979/80 (negative again) and 1993/94 (positive). A further negative break in 1995/96 appears only in a few sub-series ending in 2005.
– At Niamey (Fig. 3): 1950/51 (positive), 1970/71 (negative), 1982/83 (negative again) and 1993/94 (positive).
– At Lokoja (Fig. 4): 1970/71 (negative), 1988/89 (positive, and close to 1992). A positive break was also identified in 1953/54, but only in one sub-series. It could well correspond to similar breaks detected in Koulikoro and Niamey; however, the data gaps prior to 1946 do not allow us to confirm this interpretation.

The breaks correspond well with those identified at Bakel on the Senegal River (Fig. 5) by Hubert *et al.* (2007), namely 1921/22 (positive), 1938/39 (negative), 1949/50 (positive) and 1967/68 (negative), 1976/77 (negative again) and 1993/94 (positive), although the last two are less evident and appear only in the sub-series starting after 1945 and ending in 2003 (last year examined in the analysis).

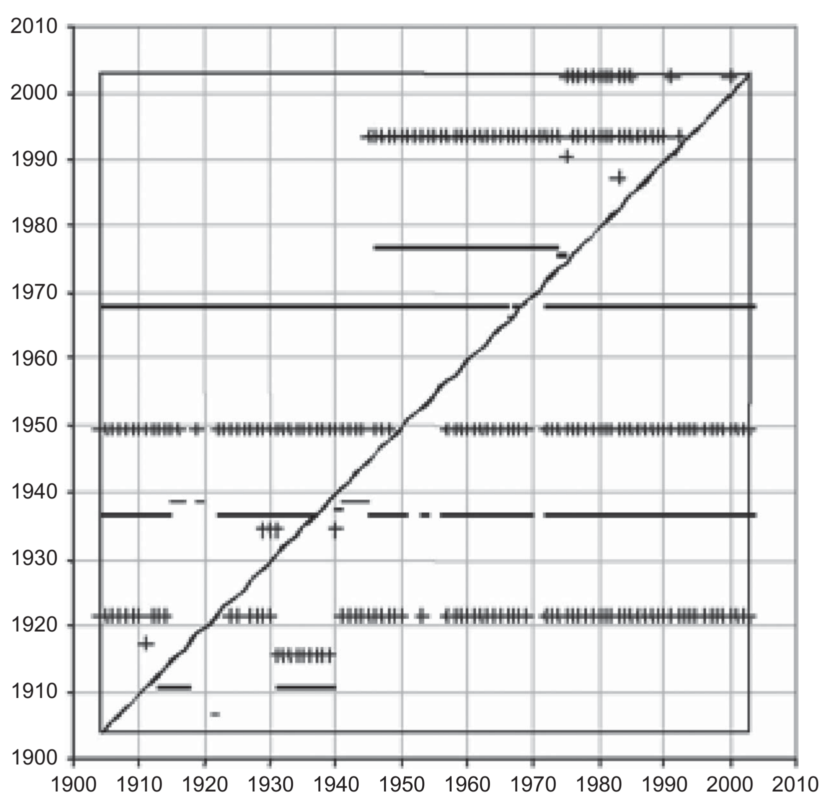

Fig. 5 Results of the Senegal series (1904–2003) segmentations at Bakel (from Hubert *et al*. 2007).

Table 2 Comparison of the inter-annual averages (discharge and percentage difference, Δ).

Koulikoro			Niamey			Lokoja		
Period	Average ($m^3 s^{-1}$)	Δ (%)	Period	Average ($m^3 s^{-1}$)	Δ (%)	Period	Average ($m^3 s^{-1}$)	Δ (%)
1907–1923	1323							
1924–1932	1980	+49.7						
1933–1950	1358	−31.4	1944–1950	807				
1951–1969	1727	+27.2	1951–1970	1111	+37.6	1946–1970	6266	
1970–1979	1272	−26.3	1971–1982	778	−30.0	1971–1988	4637	−26.0
1980–1993	803	−36.9	1983–1993	530	−31.9	1989–1992	5643	+21.7
1994–2005	1144	+42.0	1994–2006	843	+59.0			

At Lokoja, because of the relative shortness of the series, only the negative break 1970/71 could be identified with certainty. It should be noted also that around 1988, in sub-series starting in 1981, a positive break was identified, against the trend observed for Koulikoro and Niamey, where the early 1980s were characterized by a worsening of the drought.

The percentage changes in the inter-annual average of each period relative to the previous one are significant, in the order of 30–50% and, in general, are of a comparable magnitude at Koulikoro and Niamey stations when considering breaks occurring at around the same time (see Table 2).

The years where breaks were identified, and the percentage change between two consecutive periods, suggest that there is an analogy in the hydrological behaviour between the series of Koulikoro and Niamey and possibly dependence in the discharge of the two stations. Therefore, the correlation between average annual discharges at Koulikoro and at Niamey was calculated using a simple linear relationship throughout the overlap period (1946–2005) for these two stations; the correlation coefficient obtained equalled 0.6.

8 CONCLUSIONS

The analysis of the historical series of Koulikoro, Niamey and Lokoja using the segmentation procedure allowed us to explore at the basin scale the phenomena of non-stationarity of hydrological series that several other authors have already identified in West Africa. This was done within the limits imposed by the gaps affecting almost every series. The inclusion in the study of data from Lokoja has broadened the investigation area to Central Africa and therefore introduced the possibility of assessing the spatial extent of these events at the sub-continental scale.

Since the breaks identified occur in a narrow range of up to three years, as compared to a duration of 10 years or more for the periods they define, and with the same direction and roughly the same magnitude of change, this indicates that they reflect processes of regional scale, a fact confirmed by the good synchronization between the breaks identified on the Niger, especially at Niamey and in Koulikoro, and those on the Senegal at Bakel (Hubert *et al*. 2007). Particularly conspicuous at the three stations studied, as well as at Bakel, is the negative break in 1969–1971, which corresponds with the onset of drought in the Sahel. Koulikoro, Niamey (and Bakel) also share a net positive break in 1950/51. The analysis also highlighted with good certainty the presence of a positive break in 1993/94 at Koulikoro and Niamey with a return to wetter conditions, although still far from the values of the wet periods of the 1920s and 1950–1960s.

At Lokoja, despite a series ending in 1992, there is a fairly clear positive break in 1988/89, while the break of the early 1980s, which was very clear at Koulikoro and Niamey, marking a further worsening of drought conditions, does not appear at all. One might attribute this difference in behaviour to the influence of inputs from Central Africa in the formation of the Niger flow at Lokoja: in fact, the Benue, which joins the Niger just upstream Lokoja, contributes about 50% of the discharge measured at this station. This therefore suggests that the phenomena that cause nonstationarity in hydrological series can be of variable geographical extent, sometimes of sub-continental scale, such as in 1950/51 and 1970/71, sometimes more local, and also of opposite direction, such as in 1988/89 and 1993/94.

The fact that the inter-annual average in each segment identified by the segmentation are very well correlated between Koulikoro and Niamey, while within each segment the annual averages show no correlation, may indicate that large-scale phenomena in space and time govern the non-stationarity, overlapping with other local phenomena of lesser spatial extent and with higher temporal frequencies that control annual discharge.

The application of the segmentation procedure to other Central African data sets, possibly longer and more complete, could clarify the differences in behaviour with West Africa, while an extensive analysis of several historical series, such as those contained in the database of the Niger Basin Authority, would identify the different spatial scales, if any, at which breaks in stationarity occur.

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