Freshwater Yields to the Atlantic Ocean: Local and Regional Variations from Senegal to Angola

Gil Mahé
ORSTOM
BP 2528
Bamako
Mali

Abstract

The total annual yield of freshwater flowing into the Atlantic Ocean from West and Central Africa is computed over the 1951-1989 period. Interannual variations are presented for 34 rivers. Water yields are computed by decades using a data base composed of 57 rivers, and also considers water originating from coastal areas. These coastal areas represent 20% of the 7.7 million km^2 of total surface area studied and contribute approximately 25% of the water yield to the sea, due to high runoff coefficients. The total annual water yield to the Atlantic Ocean is about 2700 billion m^3. The study of the interannual variations of water yield shows two periods, namely wetter before 1970 and drier afterwards. During the period 1981-1989, total yield fell by 28% as compared to the mean during the period 1951-1980.

Résumé

Le débit total d'eau douce arrivant dans l'océan Atlantique de l'Afrique de l'Ouest et Central est calculé pendant une période allant de 1951 à 1989. Les variations d'une année sur l'autre sont présentées pour 34 rivières. Les débits sont calculés par décennie en utilisant une base de données composée de 57 rivières, mais aussi en utilisant les débits des stations côtières.

Ces zones côtières représentent 20 % des 7,7 millions de km^2 de la surface totale étudiée, et en raison de leurs forts coefficients de débit, contribuent à 25 % des débits partant en mer. Le débit total arrivant dans l'océan Atlantique est de 2 700 milliards de m^3. L'étude des variations interannuelles des débits montre l'existence de deux périodes, humide avant 1970 et plus sèche après. Pendant la période 1981-1989, les débits ont chuté de 28 % par rapport à ceux de 1951-1980.

INTRODUCTION

On the coasts of the Atlantic Ocean from Senegal to Angola, and in particular along the coast of the Guinea Gulf, fishing is an important social and economic activity for the region's populations. For many years researchers have sought to understand the reasons for stock variations of coastal fishes. Studies have focused on environmental factors such as salinity, wind, and coastal freshwater yields.

From the mouth of the Senegal River, at the Senegalese-Mauritanian border, to the mouth of the Cunene River, at the Angolan-Namibian border, tributary rivers which flow into the Atlantic Ocean drain a basin of about 7.7 million km^2 (Fig. 1). Data regarding this runoff have been recorded for 57 rivers. For 33 of these rivers, it is possible to use or extrapolate from annual series for the period 1951 to 1989, which will be studied. The surface area drained by these 33 rivers occupies 81% of the total surface area considered here, with the Congo river basin alone contributing 46% (Table 1).

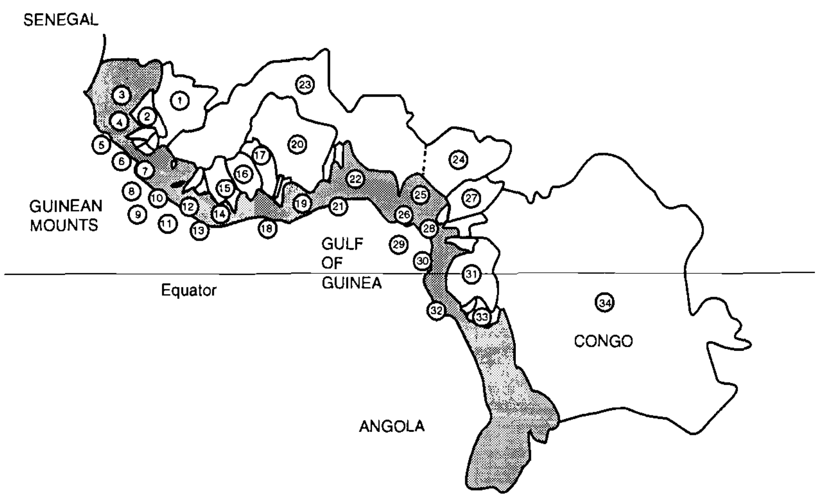

Fig. 1: Contours of the 34 basins studied in West and Central Africa, with numbers presented in Table 1. The non-controlled zones are shaded in grey.

N°	RIVER	STATION	BASIN SURFACE KM^2	% OF TOTAL SURFACE
1	SENEGAL	Bakel	218 000	2.83
2	GAMBIE	Gouloumbo	42 200	0.55
3	CASAMANCE	Kolda	3 700	0.05
4	CORUBAL	Saltinho Amont	23 800	0.31
5	FATALA	Bindan	5 100	0.07
6	KONKOURE	Amaria	16 200	0.21
7	KOLENTE	Tassin	6 600	0.09
8	ROKEL	Bumbuna	4 000	0.05
9	PAMPANA	Matatota	2 400	0.03
10	SEWA	Jaïama	6 900	0.09
11	MANO	Mano Mines	5 500	0.07
12	ST PAUL	Mount Coffe	21 400	0.28
13	ST JOHN	St John Falls	11 400	0.15
14	CESTOS	Sawolo	4 600	0.06
15	SASSANDRA	Gaoulou	70 600	0.92
16	BANDAMA	Daboitié	60 000	0.78
17	COMOE	Mbasso	70 500	0.92
18	BIA	Ayamé	10 000	0.13
19	TANO	Alenda	16 000	0.21
20	VOLTA	Senchi Halcrow	394 000	5.11
21	MONO	Tététou	20 500	0.27
22	OUEME	Pont de Savé	23 600	0.31
23	NIGER	Onitsha	1 100 000	14.28
24	BENOUE (NIGER)	Makurdi	300 000	(3.89)
25	WOURI	Yabassi	8 200	0.11
26	MUNGO	Mundame	2 400	0.03
27	SANAGA	Edéa	132 000	1.71
28	NYONG	Dehane	26 400	0.34
29	KIENKE	Kribi	1 100	0.01
30	NTEM	Nyabessan	26 300	0.34
31	OGOOUE	Lambaréné	203 000	2.64
32	NYANGA	Tchibanga	12 400	0.16
33	KOUILOU	Sounda	56 600	0.73
34	CONGO	Brazzaville	3 550 000	46.08

Table 1: The 34 rivers studied during the period 1951-1989: stations, surface areas, and percent of basin surface compared to total surface area of 7.7 million km^2 (see Fig. 1 for location of river basins, by number).

Thus, it appears that for the 19% of the total surface, the 'non-controlled zones' of about 1.5 million km^2, it is impossible to generate time series of annual runoff values for the period 1951-1989. The non-controlled zones are found particularly along the coastal bands (Fig. 1), where gauging stations are rarely located due to the anomalies of water height measurements caused by tides and sedimentation near river mouths. However, in coastal regions, rainfall is often more abundant than on the continent. With only few exceptions, such rain exceeds 1500 mm per year, and even reaches 10 meters on average at the foot of Mount Cameroon at Debundsha Station. Using the example of the rivers of Cameroon, Olivry (1986) showed that in the zones of average annual rainfall greater than 1500 mm the runoff coefficients rapidly increase up to 70% for rains of 3.5 meters per year. Due to these higher runoff coefficients, as compared to continental regions, these non-controlled zones represent a considerable yield of freshwater, which must be included in estimates to total yields.

For Angola, we have not been able to gather information more detailed than the average runoffs presented in a reference book (Angola, 1974) published for the international decade of hydrology. Hence, for Angola, we only present water yields variations by decades.

The freshwater yields to coastal marine waters directly influence salinity and retention of nutrients. Hence, variations of freshwater yields impact marine life. Numerous authors (e.g., Binet, 1983; Caverivière, 1991) have reported correlations between variations in coastal fish stock sizes and the variations of freshwater yields.

Since the creation of ORSTOM, 50 years ago, its Hydrologic Service, integrated today with ORSTOM's Department of Continental Waters (DEC), has been at the forefront of developing networks of runoff measures for numerous African rivers. Not surprisingly, results regarding freshwater yields were collected and compiled at ORSTOM, by the former Research Unit A7, now UR22. Thus, we can benefit from ORSTOM's extensive experience in Africa, most notably from runoff results that represent years of uninterrupted work by generations of hydrologists working in Africa. However, in the interest of thoroughness, in addition to the data from ORSTOM, we have gathered runoff data from non-francophone countries, namely Nigeria, Angola, Equatorial Guinea, Guinea Bissau, Ghana, Sierra Leone and Liberia.

1. Background and data

The runoff values used in this study come from different sources. For most of the rivers the yearly runoff values are taken from daily or monthly runoffs measured at gauging stations. Some gaps in certain series have forced us to reconstruct or extrapolate certain daily, monthly, or yearly values, or even to establish correlations between data from several stations or several rivers near the stations, for periods greater than ten years. In certain cases, we have been unable to establish correlations between different runoff data, and, thus, have had to establish rainfall/runoff correlations both on a monthly basis (at Saint John, Saint Paul, and Ogooue) or, more generally, on an annual basis. Details regarding such calculations are found in Mahé (1993). Time series are analyzed in two ways. First an annual representation is given for the period 1951-1989 (Fig.2 and 3). This concerns 33 rivers (Fig. 1, Table 1) as well as the Benoue, the principal tributary of the Niger River. This tributary represents the runoff of a vast hydroclimatic region which is very different from the rest of the Niger River basin. Secondly a decadal representation is given for the four decades studied, 1951-1960, 1961-1970, 1971-1980, 1981-1989 (only nine years). By chance, these decades correspond to four different climatic periods. Space is used in the same way as time. First, regarding the interannual study, the hydrologic units used are individual basins. Second, regarding the study by decades, we have grouped the rivers, as well as the non-controlled zones, into eight regional entities (Fig. 2, Table 2). Among these eight zones, two are individual basins of the largest rivers in Africa, as measured by runoff, namely the Congo (second largest river in the world after the Amazon) and the Niger.

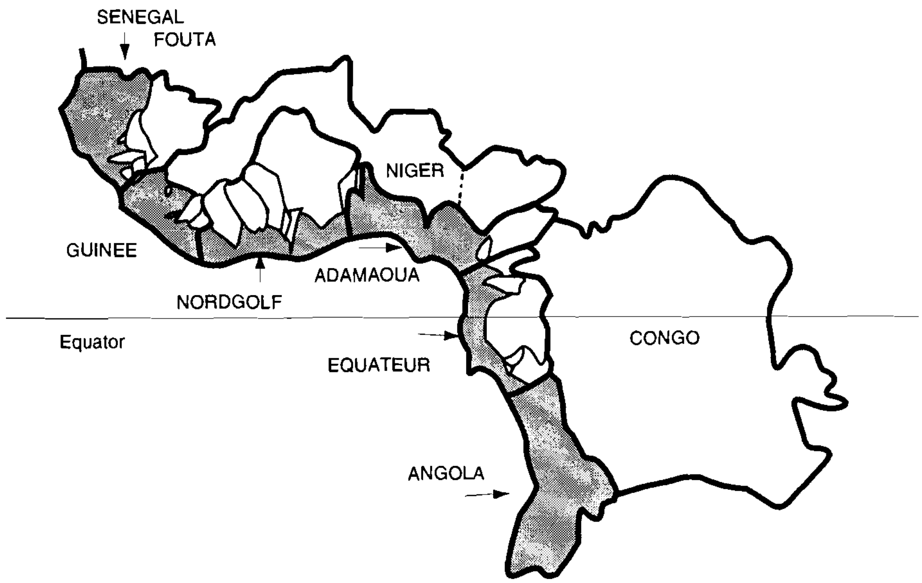

Fig. 2: French names and locations of the eight major hydroclimatic regions of Western/Central Africa. The non-controlled zones are shaded in grey.

REGION	BASIN SURFACE (10^3 KM^2)	% OF TOTAL SURFACE	NON CONTROLLED SURFACE (10^3 KM^2)	% OF TOTAL SURFACE
SENEGAL-FOUTA	590	7.7	230	3.0
GUINEE	182	2.4	120	1.6
NORDGOLF	900	11.7	210	2.7
NIGER	1 100	14.3	0	0
ADAMAOUA	355	4.6	215	2.8
EQUATEUR	475	6.2	150	2.0
CONGO	3 550	46.1	0	0
ANGOLA	551	7.0	551	7.0

Table 2: The eight hydroclimatic regions of Western/Central Africa: surface area of each region, non-controlled surface area of each region, and each region's area compared to total surface area.

2. VARIATIONS IN FRESHWATER YIELDS TO THE ATLANTIC OCEAN

2.1. Interannual variations

2.1.1- Normalized runoffs

Figure 3 illustrates variations of normalized runoffs (= yearly/total runoff) of 34 rivers for the period 1951-1989, following from left-to-right the geographic location of the river's mouths as one moves northward from the Equator. The black rectangles correspond to a normalized runoff greater than 1.05. The white rectangles correspond to a normalized runoff less than 0.95. The rectangles with a dash indicate a normalized runoff between 0.95 and 1.05. The choice of rivers depended on the length of the original data series, as well as on the size of the basins, and on their location on the coast. Runoff of small coastal rivers were not reconstructed; it can be assumed that their runoff variations are similar to the overvall pattern presented here.

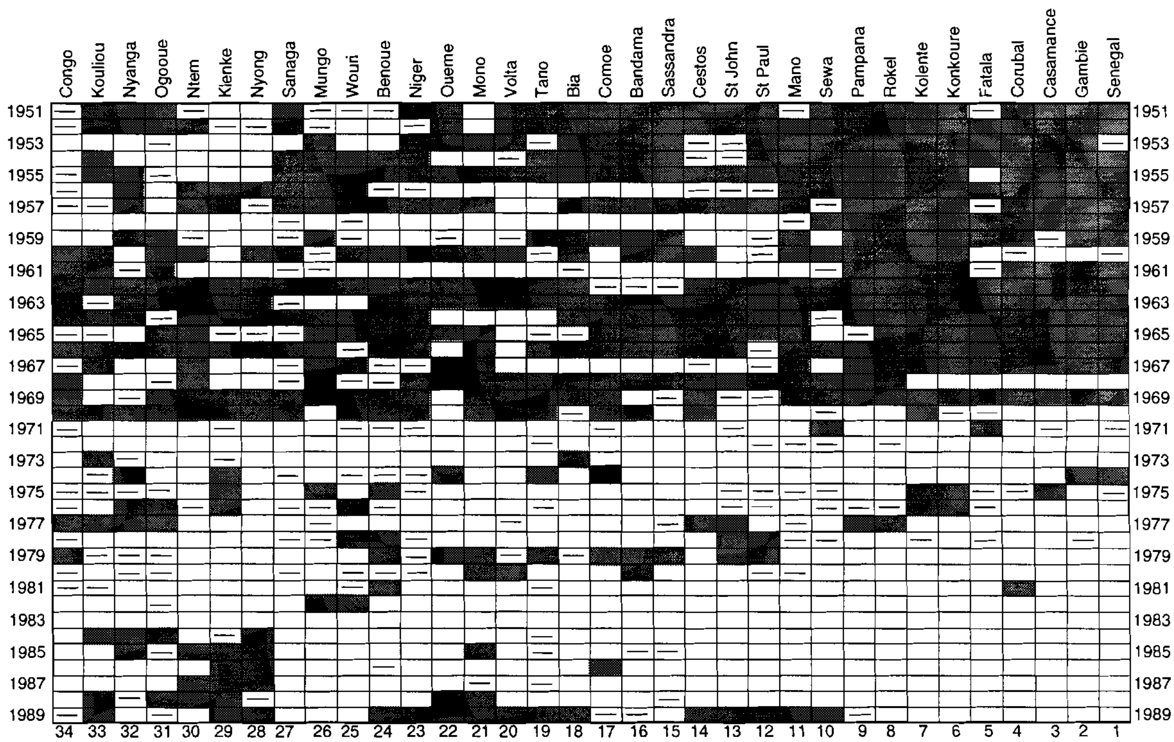

Fig. 3: Normalized runoffs of the 34 rivers studied from 1951-1989, and corresponding hydroclimatic regions. The black rectangles correspond to H > 1.05; the white rectangles correspond to H < 0.95; and the dashes mean that H is between 0.95 and 1.05.

Two periods are distinguishable in Figure 3: before 1970, with high values and after 1970, with low values. This pattern is very visible to the west of the mouth of the Niger River, but becomes less clear to the south of the Sanaga River. In this regard, it is appropriate to mention that runoff variations are rarely the same for all rivers at the same time. In fact, 1983 is the only year where every values of normalized runoff are negative, while 1962 is the only year where all normalised runoffs are positive. Likewise, all rivers experienced a runoff minimum between 1972 and 1973. Also, during the last decade, the rivers in the Adamaoua (Sanaga, Mungo, and Wouri) region here displayed different normalized runoffs than other rivers in the same area. Runoff variations are more similar to those of rivers in more tropical climates which flow from the Pampana River of the Guinean Mountains, to Senegal.

Figure 3 also presents contrasts between rivers in the north and coastal rivers of the littoral of the Gulf of Guinea. For example, in 1958, runoff deficits were only observed to the northward of the Sewa River in northern Sierra Leone, at 10°N latitude. An almost completely opposite case occurred in 1968. In 1989 numerous regions displayed greater-than-average runoffs, except for the Mungo, Wouri and Sanaga River basins in Cameroon, the Senegal-Fouta region, and the northern Guinea region. Since 1970, the only rivers which have experienced at least four years of greater-than-average runoffs were the Kouilou, the Nyanga, the Ogooue, the Kienke, and the Nyong in the Equator region; and more northwards, the Benoue, the Oueme, the Mono, the Comoe, and the St. John Rivers. Finally, during the last decade, the only rivers which have not been in continual deficit have been the equatorial rivers the Nyong and the Kouilou, as illustrated in Figure 4.

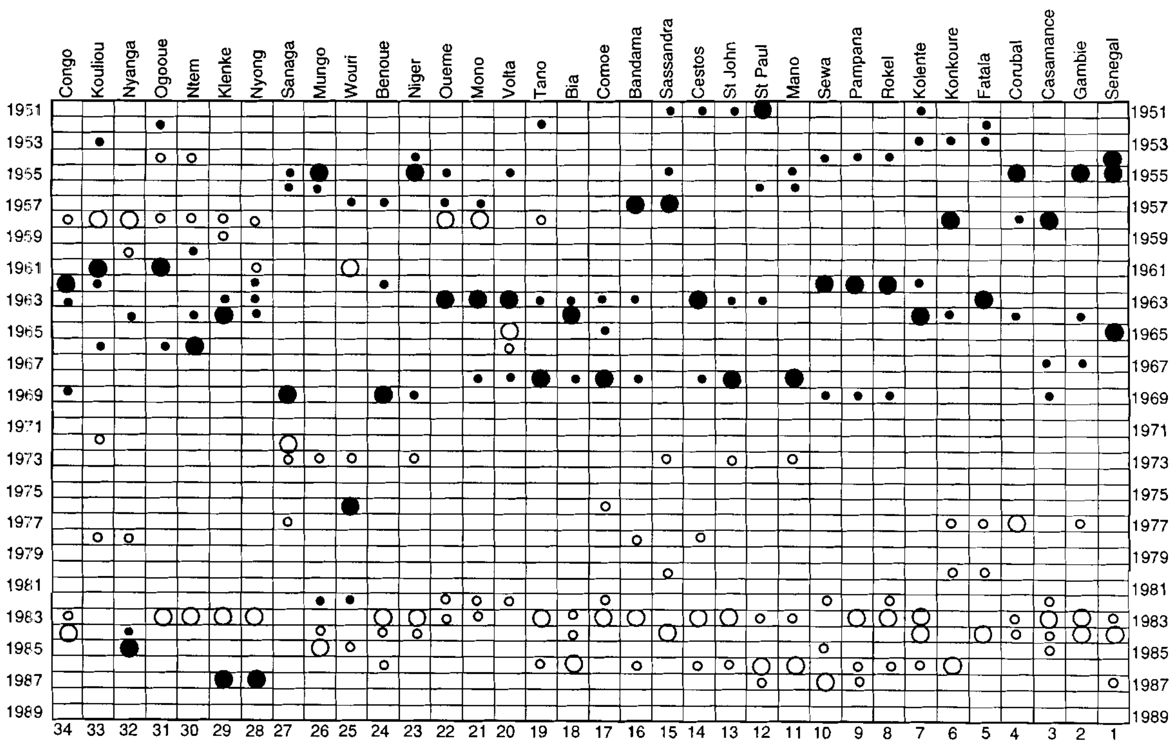

Fig. 4: Years of occurrence of maximum and minimum annual runoffs for each of the 34 rivers studied from 1951-1989. Primary maximum and secondary maximum are represented by big and small black circles, respectively; primary minimum and secondary minimum are represented by large and small white circles, respectively.

2.1.2- Extreme runoffs

As illustrated in Figure 4, years of maximum and minimum runoffs for the period 1951-1989 are indicated respectively by black dots and white circles.

In the Equator region, primary maxima are observed during 1980-1989 only for the Nyanga, the Kienke, and the Nyong. The Mungo and the Wouri present secondary maxima in 1982. Almost all rivers experienced a minimum between 1982 and 1987, except the Sanaga (data extrapolated from rainfall), the Nyanga, and the Kouilou. The runoffs were so weak during the last decade in this study (1981-1989) that the minima of the 1970 decade are only secondary minima. In fact, during this last decade only the Sanaga and the Corubal experienced primary minima. From the Equator region to the Nordgolf region, 1958 is a year of marked deficits, and of occurrences of primary minima (Kouilou, Nyanga, Mono, Oueme). Finally, minima for the Volta in 1965 and 1966 coincide with the filling of the Lake Akosombo, a reservoir. The maxima are divided between two decades, 1950-1959 and 1960-1969. For the Senegal Fouta region and for the Niger, the main period for maxima is the decade 1950-1959. In contrast, for the Equator and the Nordgolf regions from the Oueme to the Comoe, the maxima are concentrated in the decade 1960-1969. The years with the greater number of maxima are 1955, 1963, and 1968.

For purely informative purposes, and without drawing any definitive conclusions, we remark finally a progressive time lag in the timing of maxima from west to east. In the middle of the period of deficits of the last twenty years, we observe that the Senegal and the Gambia have higher-than-average runoffs in 1974/75. This period of higher-than-average runoffs moves in 1975/76 to the Kolente and the Konkoure, in 1977/79 to the St. Paul and the St. John, in 1979/80 to the north coast of the Gulf of Guinea, and in 1981/82 to the Mungo and the Wouri.

2.2. Decadal freshwater yields variations

This section of the study fulfills two objectives :
- to synthesize the results from every river basins by grouping them into larger hydroclimatic regions ;
- to integrate the contribution of non-controlled zones into our calculations of freshwater yields to the Atlantic Ocean.

We do not have complete runoff data for the period 1951-1989 for the non-controlled coastal zones. Nevertheless, we can obtain information on the order of magnitude of specific runoffs for these zones from the results of studies undertaken periodically on small coastal rivers (24 in all, representing 5% of the total surface area). To estimate these runoffs from non-controlled zones, the simplest solution is to first calculate an average runoff value from known values for nearby rivers in the same zones, then apply annual coefficients of variation also derived from the same time-series of runoffs of nearby rivers. The problem with this method is that it does not consider specific coastal runoffs and rainfall variations. The solution that we have chosen for reconstructing runoff time series, taking into consideration coastal specificity, was inspired by Olivry (1986) who, after studying rainfall and runoff of the rivers of Cameroon, proposed a relationship between total annual rainfall and specific runoff values. This relation demonstrated a correlation between rainfall and specific runoffs, applicable to cases of annual rainfall of at least 1500-2000 mm/year.

The transposition of Olivry's relation to regions other than those of the Cameroon coast is problematic, due to differences in climatic conditions. On the Cameroon coast, the climate can be classified as equatorial transition, with a small dry season and significant cloudiness. We use this relationship for the coastal zones from the Guinean Mountains to the Gabonese and Congolese coasts. In these littoral zones, rains reach and often exceed 1500-2000 mm/year, with the length of the dry season as the only factor that makes such zones different from the Cameroon coast. The conditions for optimal utilization of the relation between rain and runoff are thus largely met, and specific runoffs can be deduced from the relationship described by Olivry. Then the runoff is calculated from the surface of the areas. Hence, Olivry's relationship requires calculation of average rainfall on the surface area of the non-controlled zones. The annual rainfall values for each zone during the period 1951-1989 are calculated automatically through spline interpolation, based on data on annual rainfall at about 900 rainfall stations covering the total surface of the basins under study. Details of the method are described in Mahé and L'Hôte (1992) and Mahé *et al.* (in press). Thus, we have precipitation time-series, which, with Olivry's equation, can be transposed into time-series of annual runoff, with the specific variability of coastal precipitation being preserved in the constructed data series, as well as the nuances of specific runoffs along the coast. However, the accuracy of the calculation of annual runoff from these zones obtained through graphical methods and the accuracy of the runoff coefficients (ratio of runoff to rainfall, in percentages), are not identical for the past four decades of study (Mahé, 1993). Specifically, annual runoff values from non-controlled zones are only qualitative, and runoff averages by decades are much more reliable.

For each hydroclimatic region we can present freshwater yields and estimated freshwater yields from non-controlled zones. Figure 5 displays interannual variations of annual runoff, by hydroclimatic regions, with average runoffs by decades represented with thin horizontal lines. For Angola, due to the lack of information concerning runoffs, it is not possible to reconstruct annual values. During the last decade, the runoffs of the Senegal-Fouta and the Nordgolf regions were more than half as weak than during the decade 1950-1959. For the Niger and the Guinea regions, the decrease is only one-third. It is also noticeable in the Adamaoua region, but much less perceptible in the Congo Basin and the Equator region, where, however, very strong runoffs are observed during the 1960s.

To illustrate the variations of freshwater yields, Table 4 presents the volumes of freshwater yields by decades and by region. As illustrated, each year approximately 2.7 10^{12} m^3 of freshwater enters the Atlantic Ocean between Senegal and Angola. About half of this amount comes from the Congo River. The decrease in freshwater yields during the last decade is considerable, with a 28% annual average decline during 1981-1989 as compared to 1951-1980. This decline is also not equal throughout Central and West Africa. Specifically, in Central Africa the decrease in freshwater yields is small in the Adamaoua region, and very small in the Equator region and in Angola, where periods of drought affected only slightly the runoffs. In West Africa, the decline in freshwater yields becomes greater as one advances from Cameroon to the northwest (Guinea, Mali, Senegal, Mauritania). During the decade 1981-1989, the yields from the Senegal-Fouta region fell by more than half in comparison to their average value during the 1951-1960 decade. As a result, runoff changed, with a fall in ground water reserves, and in river recharge during dry seasons. This phenomenon is the intensification of depletion, as described by Olivry *et al.* (1993).

One example should suffice to illustrate the observed magnitude of the runoff deficits. In 1983, the year of maximum rainfall decline both during the 1951-1989 period and since the beginning of the century (Sircoulon, 1989); for all regions, freshwater yields to the Atlantic Ocean have been 34% less than the average from 1951-1989, which represents a decline of about 900 billion m^3. This value corresponds to total annual runoff of all of West Africa from Senegal to the Cameroon Mountains in a normal year.

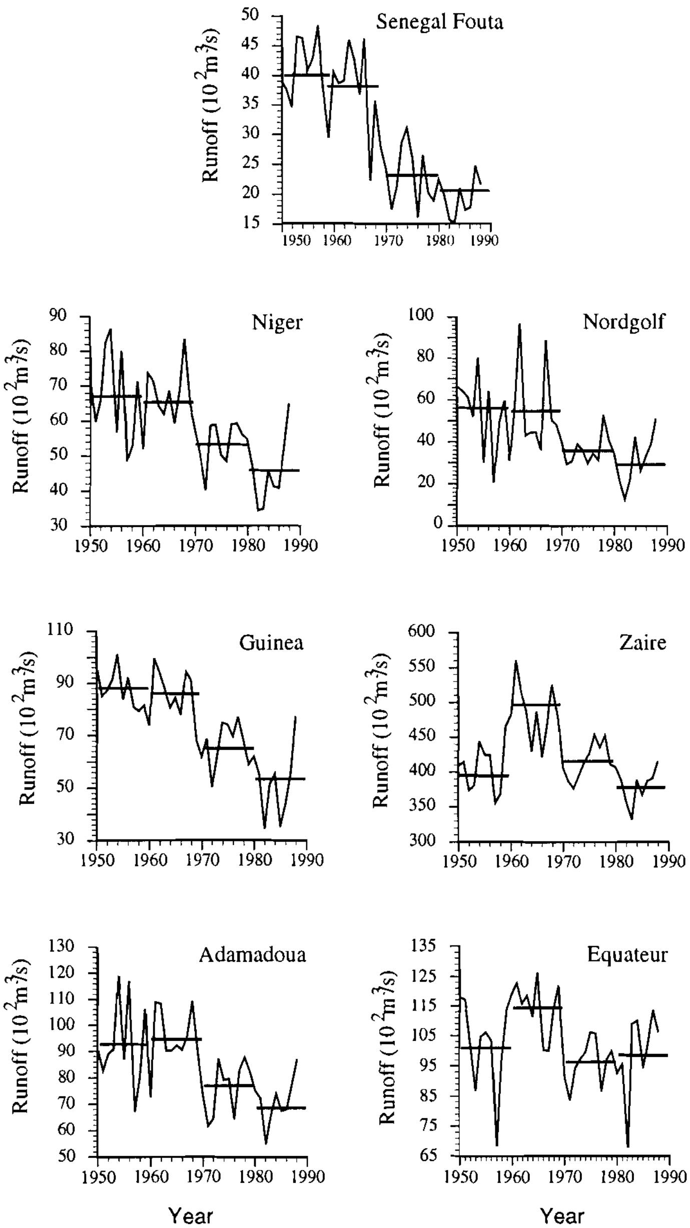

Fig. 5: Annual runoff by hydroclimatic region, in m^3s^{-1}, 1951-1989, (Angola not included). Decadal means are indicated by horizontal lines. For each region, the runoff values represent the sum of yields in controlled and non-controlled zones.

	MEAN ANNUAL YIELD (m^3 10^9), BY PERIOD				
REGION	1951 - 1960	1961 - 1970	1971 - 1980	1981 - 1989	MEAN
SENEGAL - FOUTA	127	119	73	62	96
GUINEE	278	269	211	165	233
NORDGOLF	173	171	115	98	140
NIGER	214	211	170	146	186
ADAMAOUA	294	300	241	225	266
EQUATEUR	321	362	303	312	325
CONGO	1280	1530	1310	1200	1335
ANGOLA	87	94	80	83	86
TOTAL	2780	2870	2500	2290	2670

Table 3: Volume of freshwater yield to the Atlantic Ocean, by hydroclimatic region and decade, in billions of m^3 per year. The means for 1951-1989 are presented in the right column.

Conclusion

Of the 2.7 10^{12} m^3 of freshwater reaching the Atlantic Ocean each year from West and Central Africa, approximately half, i.e., 1.34 10^{12} m^3, come from the Congo River. The freshwater yields from the non-controlled zones (19 % of the total surface) where rainfall is stronger and hydrologic studies rare, represent about 25% of total runoff to the ocean. Estimation of this part of the runoff, which has not been previously calculated, constitutes an addition to previous estimates. In relation to the average runoff for the period 1951-1989, maximum runoffs occurred between 1951 and 1970. Since 1970, freshwater yields have decreased. This study constitutes a first synthesis of freshwater yields on the Atlantic side of the African continent. Results presented, however, can be further refined. For example, complementary information on runoffs from non-francophone countries such as Angola and southern Nigeria would improve on the results of this study.

Acknowledgments

We would like to thank the National Hydrologic and Meteorological Service of West and Central Africa for assistance with the creation of our data base.

REFERENCES CITED

Angola. 1974. Collectanea de estudos hidrologicos. Direcçao-General de Obras publicas e Communicaçoes. Grupo de trabalho para o decenio hidrologico internacional. Lisboa, 400 p.

Binet D. 1983. Phytoplancton et production primaire des régions côtières à upwellings saisonniers dans le golfe de Guinée. *Océanographie tropicale*, 18 (2): 331-355.

Caverivière A. 1991. L'explosion démographique du baliste (*Balistes carolinensis*) en Afrique de l'ouest et son évolution en relation avec les tendances climatiques. *In*: P.Cury et C.Roy (eds.). Pêcheries ouest-africaines: variabilité, instabilité et changement. ORSTOM: 354-367.

Mahé G. 1993. *Les écoulements fluviaux sur la façade atlantique de l'Afrique. Etude des éléments du bilan hydrique et variabilité interannuelle, analyse de situations hydroclimatiques moyennes et extrêmes*. Thèse, Université Paris-Sud-Orsay/ORSTOM. Coll. Etudes et Thèses, ORSTOM, 438 p.

Mahé G. and Y. L'Hôte. 1992. *Utilisation de la méthode du vecteur régional pour la description des variations pluviométriques interannuelles en Afrique de l'ouest et centrale de 1951 à 1989*. Huitièmes Journées hydrologiques de l'ORSTOM, Montpellier, Septembre 1992, 14 p.

Mahé G., F. Delclaux and A. Crespy. In press. Elaboration d'une chaîne de traitement pluviométrique et application au calcul automatique de lames précipitées (bassin versant de l'Ogooué au Gabon). *Hydrologie continentale*, 9 (2).

Olivry J.C. 1986. *Fleuves et rivières du Cameroun*. Thèse d'Etat. MESRES-ORSTOM. Coll. Monographies hydrologiques ORSTOM, Paris, 9, 733 p., 360 tab., 2 cartes.

Olivry J.C., J.P. Bricquet and G. Mahé. 1993. Vers un appauvrissement durable des ressources en eau de l'Afrique humide ? *In* : J.S. Gladwell (ed.). Hydrology of warm humid regions. 4ème Assemblée AISH, Yokohama, *AISH Publ.*, 216: 67-78.

Sircoulon J. 1989. Bilan hydropluviométrique de la sécheresse 1968-84 au Sahel et comparaison avec des sécheresses des années 1910 à 1916 et 1940 à 1949. *In*: *Les hommes face aux sécheresses. Nordeste brésilien. Sahel africain*: 107-114.