A new look at hydrology in the Congo Basin, based on the study of multi-decadal chronicles

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Abstract

The latest work on the main African rivers on the Atlantic coast has made it possible to subdivide the multi-year streamflow records into several homogeneous phases. The year 1970 seems to mark both for West and Central Africa the major hydroclimatic event of the 20th century, heralding its main period of deficit flow. For the first time, this article presents a comparative study of the hydro-rainfall records of five drainage systems (those of the Congo River and its main tributaries Lualaba, Kasai, Sangha, Oubangui) based on field data, obtained on both the left and right banks of the Congo River. A reconstitution of the Cuvette Centrale regime is proposed. The 1970 hydro-rainfall disruption is common in most tributaries of the Congo River basin, with significant reductions in flows depending on various factors (geographical location, vegetation cover, surface conditions and land use, etc.). The Oubangui is the most fragile northern tributary that continues to suffer from flow deficits, with an increase in the duration and intensity of its low flows. Since 1995, flows of the Congo River at its main station in Brazzaville/Kinshasa seem to have returned to the interannual average since 1903. However, from the same year onwards, an increase in seasonal variability and a decrease in spring flood flows can also be observed for its bimodal tributaries. This article explains some of the hydrological paradoxes specific to this basin, which illustrate the complexity of its hydrological functioning. Finally, it shows that the period of excess flow in the 1960s is the major hydrological anomaly of the Congo River over a continuous 116-year history. For the whole basin, hydrological variations are attenuated compared to those of precipitation. Finally, the hydrometric regimes reconstructed by spatial altimetry and modelling are compared with those from in situ data.

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Key Points:

- The year 1970 seems to mark for both West Africa and Central Africa the major hydroclimatic accident of the 20th century heralding its main period of deficit flow.
- The 1970 hydro-pluviometric break is common in most of the tributaries of the Congo River basin, accompanied by significant reductions in flows depending on various factors (geographical location, vegetation cover, surface conditions and land use, etc.).
- The overflow period of the 1960s is the major hydrological anomaly of the Congo River over a continuous 116 years record.

Abstract

The latest work on the main African rivers on the Atlantic coast has made it possible to subdivide the multi-year streamflow records into several homogeneous phases. The year 1970 seems to mark both for West and Central Africa the major hydroclimatic event of the 20th century, heralding its main period of deficit flow. For the first time, this article presents a comparative study of the hydro-rainfall records of five drainage systems (those of the Congo River and its main tributaries Lualaba, Kasai, Sangha, Oubangui) based on field data, obtained on both the left and right banks of the Congo River. A reconstitution of the Cuvette Centrale regime is proposed. The 1970 hydro-rainfall disruption is common in most tributaries of the Congo River basin, with significant reductions in flows depending on various factors (geographical location, vegetation cover, surface conditions and land use, etc.). The Oubangui is the most fragile northern tributary that continues to suffer from flow deficits, with an increase in the duration and intensity of its low flows. Since 1995, flows of the Congo River at its main station in Brazzaville/Kinshasa seem to have returned to the interannual average since 1903. However, from the same year onwards, an increase in seasonal variability and a decrease in spring flood flows can also be observed for its bimodal tributaries. This article explains some of the hydrological paradoxes specific to this basin, which illustrate the complexity of its hydrological functioning. Finally, it shows that the period of excess flow in the 1960s is the major hydrological anomaly of the Congo River over a continuous 116-year history. For the whole basin, hydrological variations are attenuated compared to those of precipitation. Finally, the hydrometric regimes reconstructed by spatial altimetry and modelling are compared with those from in situ data.

1 Introduction

Due to the lack of contemporary *in situ* observations, the Congo River Basin (CRB) suffers from a limited understanding of the large-scale variability in the functioning of its hydrological components and their relationship to climate. This paradoxical, dichotomous and singular basin, as described below, can be considered as the least anthropized major tropical watershed on the planet. In fact, it is still very little affected by human infrastructure and activities (roads, dams, urbanization, land clearing, etc.) compared to other large tropical watersheds such as those of the Amazon (Latrubesse et al., 2017) or the Mekong (Ellis et al., 2012; Winemiller et al., 2016).

This study was limited to the evolution of hydrological regimes. It could be used as a basis for further work on their impact on the economy of the basin by modifying, for example, the period of river navigation in the basin: this is often the only land-based vector for transporting people and goods to link the capitals and main cities of the countries drained by this vast hydrographic network.

For reasons of data availability, a study by Laraque et al. (2013a) was limited to hydrometric chronicles of only three stations in the Congo Basin, namely, Congo in Brazzaville/Kinshasa (BZV/KIN, period 1903-2010) and two of its main right bank tributaries: the Ubangui in Bangui (period 1936-2010) and the Sangha in Ouesso (period 1948-2010).

The present study complements and enriches the previous one, by *(i)* adding rainfall chronicles for a period of 60 years (from 1940 to 1999), for the Congo Basin and its sub-basins studied, knowing that for each of them, we will compare the concomitant periods between the rainfall and hydrological series concerned. In addition, it complements the previous study by Laraque et al. (2013a), by *(ii)* considering for the first time the evolution of the hydro-rainfall chronicles of two important new hydrographic features, namely, Lualaba in Kisangani and Kasai in Kutu Moke. The latter is the main tributary of the Congo River, located on its left bank. Its study will make it possible to deduce the role of the Cuvette Centrale. In total, five of the main drainage entities are studied here, including the entire Congo Basin. Finally, *(iii)* hydrometric chronicles extend until 2018 instead of 2010, for three reference stations (BZV/KIN, Ouesso, Bangui), the last two of which control the main physiographic units of the CRB.

For five of the drainage systems forming the basin and having data available, we will carry out homogeneous hydro-pluviometric period breakdowns, followed by studies of the variations in mean hydrometric regimes for each of them. Then, comparisons of hydro-pluviometric chronicles will be carried out within each sub-basin and between them. These approaches will provide a better understanding of the variability of hydrological responses across the CRB.

Thanks to the water balance between Congo at BZV/KIN and the four other hydrosystems studied, it will be possible to carry out a hydrological approach to the Cuvette Centrale, which suffers from a lack of *in situ* measurements. In addition, its results will be compared with other results from previous work using indirect approaches such as remote sensing (Alsdorf et al., 2016; Becker et al., 2014; Lee et al., 2014; Kim et al., 2017; Becker et al., 2018, ….) and modelling (BRLi, 2016; Tshimanga et al., 2011; Tshimanga et al., 2012; Tshimanga, & Hughes, 2014).

1.1 Research context on the Congo Basin

This very large basin (3.7×10^6 km^2) covers the heart of Central Africa (Figure 1a) and contributes to half of Africa's freshwater exports to the Atlantic Ocean, with an interannual module of 40 600 m^3.s^{-1} for the period 1903-2010 (Laraque et al., 2013b). It is strategically located in the heart of the African continent, where it is crossed by the equator and the Inter-Tropical Convergence Zone (ITCZ) (Bultot, 1971 & 1972 ; Mahé, 1995 ; Mahé et al., 2013 ; Nicholson, 2009). The regions closest to the equator have two annual rainy seasons. The first and lowest are between March and May and the second and highest between September and November. This basin plays a major role in energy balances, moisture flows, atmospheric circulation and exchanges between the two hemispheres. But, paradoxically, it remains unknown, forgotten and until now neglected by the international scientific community. It thus remains well behind the other major basins in terms of international treaties, even though it concerns nine Central African countries (Congo and the Democratic Republic of Congo mainly, but also Angola, Burundi, Cameroon, Central African Republic, Rwanda, Zambia and Tanzania). Certainly there are some initiatives around the Great Lakes of the East with the Lake Tanganyika Authority (https://lta-alt.org/fr/) ; but this remains small given the size and importance of this basin. This relative omission is also highlighted by a ratio of 10 in scientific publications on hydrology sensu lato at the expense of the Congo Basin compared to the Amazon (Alsdorf et al., 2016), its alter ego facing it on the other side of the intertropical Atlantic Ocean.

This can be explained by the very difficult accessibility of its huge central swampy areas, the very poor terrestrial communications infrastructure, and the distribution of the basin over many countries affected by recurrent socio-political-economic unrest, marked by various conflicts, insecurity and almost endemic health problems with multiple cleavages between its shores, inherited from its colonial history. The resulting dichotomies have served as barriers by avoiding bringing together different neighboring communities, whether linguistic or thematic.

This basin still does not benefit from operational coordinating structures for operational monitoring for observation and scientific work, essential preliminaries to its integrated management.

The singularity of this basin crossed by the equator is underlined by its physiognomy, with a shape and structure generally concentric around the famous Cuvette Centrale which is partially or totally flooded according to the hydrological cycle. The Flooded Cuvette covers 360 000 km^2 (Bwangoy et al., 2010). It looks like a gigantic plate perched at an altitude of 300 m with slight slopes in its centre (< 2 $cm.km^{-1}$) according to Laraque et al. (2009). This plate is separated from the Atlantic Ocean by the succession of the Livingstone Rapids, which prohibit any maritime connection, unlike most other major river basins on the planet (Figure 1b). Indeed, over 400 km, the Congo River has a difference in altitude of about 300m (Figure 1c).

As far as existing hydro-rainfall data are concerned, a historical breakthrough occurred in the early 1960s with the independence of the countries of the basin. Since then, its 400 hydrometric stations, which were operational during the first half of the 20th century, have been reduced to about fifteen that are still operational today. Initially, Belgian and French researchers from ORSTOM (now IRD) studied the variations in the flows of the Congo River and its tributaries, according to the colonial geographical division of the basin. Several studies, including doctoral theses, scientific articles and grey literature on sub-basin hydrology have been and continue to be carried out by universities in the Democratic Republic of the Congo (DRC), often in partnership with Belgian universities and institutes for left-bank tributaries, while those on the right bank have been and are mainly studied by the universities of the Central African Republic (CAR) and the Republic of the Congo (RC) more in collaboration with French institutions in the continuity of the work initiated by ORSTOM since the 1940s.

The latest studies presenting the spatio-temporal variations in the hydro-pluviometric regimes of the Congo River and its right bank tributaries have focused on multi-decadal flow chronicles (Mahé & Olivry, 1995; Wesselink et al., 1996; Orange et al., 1996; Orange et al., 1997; Laraque et al., 2001; Runge & Nguimalet, 2005; Mahé et al., 2013; Laraque et al., 2013a & Laraque et al., 2013b; Nguimalet, 2017; Nguimalet & Boulvert, 2006; Nguimalet & Orange 2013; Nguimalet & Orange, 2019). Ils ont mis en évidence quatre périodes homogènes successives de débits. Stables jusqu'en 1960, les débits annuels évoluent ensuite à chaque décennie. Durant celle de 1960, ils augmentent et dépassent leur moyenne sur le siècle. En général, ces études montrent d'une part que le débit du Congo a été marqué par une instabilité au cours de la seconde moitié du 20ème siècle et par une forte baisse durant sa dernière décennie.

They highlighted four successive homogeneous periods of flow. Stable until 1960, annual flows then change every decade. During the 1960s, they increased and exceeded their average over the century. In general, these studies show, on the one hand, that the flow of Congo was marked by instability in the second half of the 20th century and by a sharp decline in its last decade. On the other hand, they confirm that, while flow fluctuations are due to variations in precipitation, this influence is largely modulated by the nature of the soils drained by the river and its tributaries (Laraque et al., 2013a; Mahé et al., 2013; Nguimalet & Orange, 2013).

Despite the relatively limited in situ data for such a basin and its difficulties of access, this study identified hydro-rainfall data for its main hydrographic units, based on various sources, the most recent and complete of which come from https://.hybam.obs-mip.fr/ and www.hydrosciences.fr/sierem as well as the Bas Rhône Languedoc Ingénierie (BRLi, 2016) report.

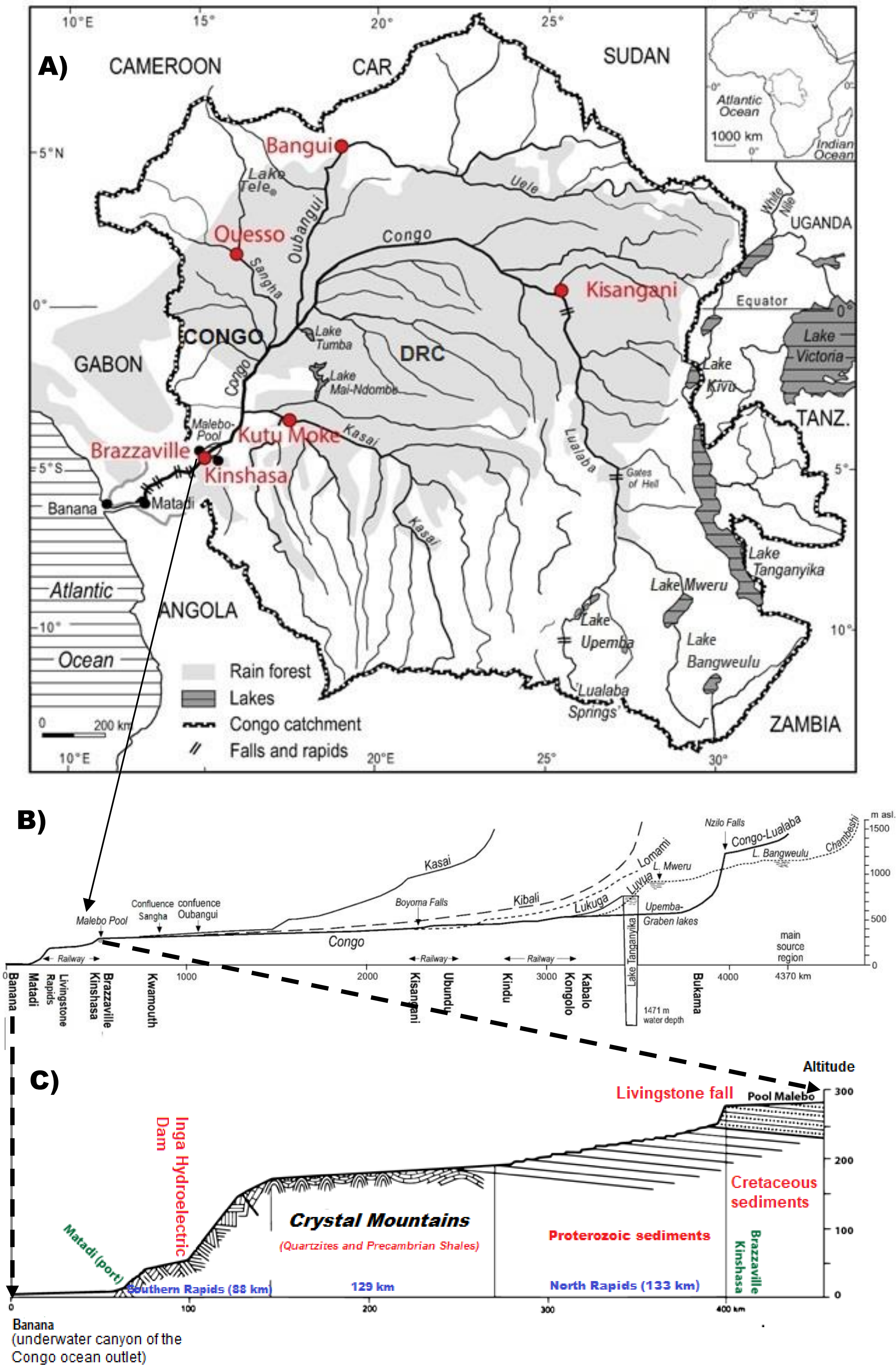
A)
CAMEROON
CAR
SUDAN
Bangui
Ouesso
Kisangani
CONGO
GABON
DRC
Brazzaville
Kinshasa
Kutu Moke
Banana
Matadi
Atlantic
Ocean
ANGOLA
ZAMBIA
UGANDA
TANZ.
Rain forest
Lakes
Congo catchment
Falls and rapids
B)
Malebo Pool
Congo
Kasai
Kibali
Lomami
Lukuga
Congo-Lualaba
Boyoma Falls
Nzilo Falls
C)
Livingstone fall
Pool Malebo
Inga Hydroelectric Dam
Crystal Mountains
(Quartzites and Precambrian Shales)
Proterozoic sediments
Cretaceous sediments
Matadi (port)
Southern Rapids (88 km)
129 km
North Rapids (133 km)
Brazzaville
Kinshasa
Altitude
Banana
(underwater canyon of the Congo ocean outlet)

Figure 1. Congo Basin; **a**) Situation of the Congo Basin and the five main hydrological stations studied; **b**) Profiles along the Congo River and its main tributaries (1a & 1b adapted from *Runge*, 2007); **c**) Zoom of the profile along the Congo River from the Malebo Pool to its ocean mouth at Banana level (adapted from Robert, 1946).

This paper presents for the first time a synthesis of the concomitant evolution over several decades of basin-wide flows and rainfall from *in situ* data, obtained on both the left and right banks of the river. It makes it possible to verify the hypothesis of Alsdorf et al. (2016) "*Despite known variations in the discharges of the Congo and Ubangui Rivers, previous rainfall amounts have varied comparatively less across the Basin*". It is a question of seeking breaks in the in situ hydrological series of the five main drainage systems of the Congo Basin (by including the latter in its entirety), in order to *(i)* highlight significant changes in flow regimes, which vary from one drainage system to another, *(ii)* estimate the average hydrological cycle of the Congolese Cuvette, *(iii)* analyze changes in hydrological regimes between periods of homogeneous flow, and finally, *(iv)* compare them with rainfall regimes.

1.2 Presentation of Congo Bassin

The Congo River and its tributaries represent the largest hydrosystem in Africa and the second largest on the planet after the Amazon.

Overall centered on the equator, its basin extends between parallels 9°N and 14°S and meridians 11°E and 34°E, with, as much by its shape, relief, geology, climate, as by its vegetation cover, a generally concentric structure around the Congolese Cuvette or central depression (Laraque et al., 2009) (Figure 1a). The presence of tropical rainforest, which represents about 44% of the basin's surface area, promotes the basin's moisture recycling capacity (de Wasseige et al., 2015). It is estimated that 75% to 95% of precipitation is recycled in the Congo Basin (Cadet and Nnoli, 1987). This basin straddling the equator covers an area of 3,660,000 km^2 at the twin stations of Brazzaville/Kinshasa, which control 98% of its total area (3,731,000 km^2) and has a 40,500 m^3s^{-1} module flows (for the period 1903-2018). The hydrological regime of Congo is bimodal due to its location in both hemispheres. Thus it has two low water levels, one low in February-March, corresponding to the dry season north of Ecuador and the other higher in July and August during the main southern dry season. These two seasons are separated by two floods, one lower in April-May, due both to equatorial equinox rains on the middle course and the other more intense in October-December under the influence of the southern part of the basin. These contributions from the various drainage units mentioned above complement each other during the hydrological cycle to ensure a relatively regular regime of the Congo River at Brazzaville/Kinshasa (or BZV/KIN) stations, both at annual and interannual scales. Thus, the seasonal (maximum monthly flow/minimum monthly flow) and interannual (maximum module/minimum module) variation indices over the last 116 years are respectively 1.86 and 1.66.

The drainage system of the entire Congo Basin is subdivided into six main drainage subsystems represented in Figure 2: Lualaba, Kasai, Sangha, Ubangui, Batékés plateaus and ''Cuvette Centrale''. The hydro-climatic characteristics of the first four and that of the entire Congo Basin analyzed in this study are presented in Tables 1 & 2. The last two drainage subsystems will not be studied here. Indeed, that of the plateaus Batékés has already been documented by Laraque et al. (1998a), and its flow chronicles are no longer available after 1994. As for the Cuvette Centrale, although there is the hydrometric station of Mbandaka with a long series of data. We did not select it because it is not representative of the said hydrosystem. It is located in the middle of this basin, and not towards its "outlet". Several tributaries located downstream of Mbandaka contribute to its functioning, such as Lake Tumba, the Likouala aux herbes, the Likouala-Mossaka and the downstream tributaries of the Oubangui (Lobaye, Lua, Ibenga, Gipi) and those of the Sangha. The hydrological behaviour of the Cuvette Centrale has thus been the subject of an indirect differential balance approach between the other subsystems and that of the entire Congo Basin, which is watered by an annual average of 1 500 mm.yr^{-1} (Mahé, 1995). This global balance integrates the vertical exchanges 'Rain-Evaporation-Evapotranspiration (ETP)' within the Central Basin, although these are not detailed and/or quantified here.

In Figure 2, the map of the watersheds and their percentages of the areas in relation to the total CRB were calculated using the ArcGIS "HydroSHEDS" and "Spatial Extension Analyst" models (except for the Cuvette Centrale, with vague and imprecise outlines).

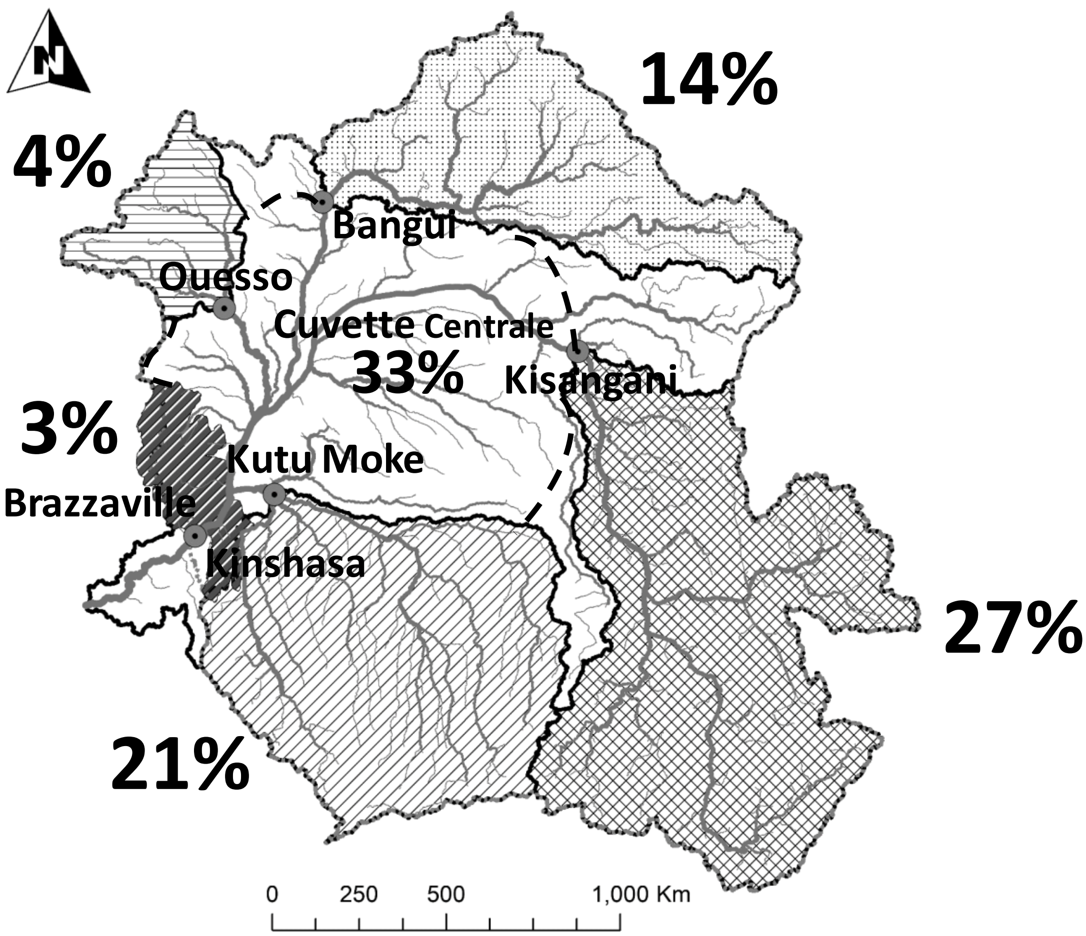

Figure 2. Congo Basin and its main drainage subsystems. The sub-basins studied are: Lualaba in Kisangani, Kasai in Kutu Moke, Sangha in Ouesso, Ubangui in Bangui and Cuvette Centrale. **Legend:** the dash encircles the Cuvette Centrale *sensu lato*. The area with inclined dark hatching is that of the Batékés plateaus.

Table 1. Hydro-climatic characteristics in the basins controlated by its main hydrological stations

		Geographical coordinates			basin area [km^2]		Hydro-climatic characteristics					
		latitude	longitude E	Altitude [m]	station	Outlet	Ratio st./ex.	% CRB at BZV/KIN	Rainfall [mm]	Interannual average discharge [m^3.s^{-1}]	Specific discharge [l.s^{-1}.km^{-2}]	Seasonal variation discharge
Lualaba	Kisangani	00°30'11"N	25°11'30"	373	974,140	974,140	1.00	26.62	1,307	7,640	7.8	1.9
Kasaï	Kutu-Moke	03°11'50"S	17°20'45"	303	750,000	897,540	0.84	20.49	1,456	8,070	10.8	1.9
Sangha	Ouesso	01°37'00"N	16°03'00"	326	159,480	213,670	0.75	4.36	1,625	1,550	9.7	2.3
Ubangui	Bangui	04°22'00"N	18°35'00"	345	494,090	650,480	0.76	13.50	1,499	3,660	7.4	2.9
Batékés Plateaus	-	-	-	305	42,570	90,000	0.47	1.16	1,900	1,330	31.24	1.1 – 1.5
Cuvette Centrale	-	-	-	305-335		1,192,190		32.57	1,700	-		-
Mambili	*Yengo*	*00°23'00"N*	*15°29'00"*	*335*	*12,080*				*1 700*	*190*	*15.73*	*2.47*
Food Cuvette	-	-	-	-	-	360,000		9.84				
Likouala aux Herbes	*Botouali*	*00°33'00"N*	*17°27'00"*	*305*	*24,800*		*0.07*	*0.68*	*1,700*	*285*	*11.49*	*5.5*
Congo	BZV/KIN	04°16'21,5"S	15°17'37,2"	314	3,659,900	3,730,740	0.98	100	1,447	40,500	11.07	1.7

The interannual modules are calculated at the different periods studied : [1] : 1951 à 2012 ; [2] : 1940 à 2012 ; [3] : 1948 à 2018 ; [4] :1936 à 2018 ; et [5] :1903 à 2018.

Legend: st. = (hydrometric station), ex. = outlet. The hydro-climatic characteristics of the Cuvette Centrale and the Batekés plateaus are derived from the work of de Laraque et Maziezoula (1995), Laraque et Olivry (1998) and Laraque et al. (2009), about right bank tributaries of Congo River controlated by hydrologics stations.
The coordinates X, Y, Z are those of the hydrological stations.
The Mambili in Yengo is a representative basin of the Cuvette Centrale.
The Likouala aux Herbes is a representative basin of the Flood Cuvette

Table 2. Hydro-climatic characteristics by drainage system for common rainfall and flow periods

Drainage system (basin)	Main Station	Period	Mean $m^3.s^{-1}$	Areal rainfall [$mm.yr^{-1}$]	Depth of runoff [$mm.yr^{-1}$]	Runoff deficit
Lualaba	Kisangani	1951-1999	7 742	1 308	251.1	1 056.9
Kasaï	Kutu-Moke	1948-1999	8 246	1 445	347.4	1 097.6
Sangha	Ouesso	1948-1999	1 596	1 638	316.2	1 321.8
Ubangui	Bangui	1940-1999	3 809	1 499	243.6	1 255.4
Congo	Brazzaville/Kinshasa	1940-1999	41 301	1 447	356.6	1 090.4

Note: The available rainfall cover the period 1940 to 1999

Below are the characteristics of the six drainage subsystems:

1. The Lualaba basin receives rainfall ranging from 1,370 to 1,458 mm yr^{-1} (Mahé, 1995) and is drained by the Lualaba (name of the upper Congo River) which originates at the borders of Zambia and the DRC, at the border between the Congo and Zambezi basins (Charlier, 1955). It is often narrow, winding, and cut off by falls or rapids (such as Boyoma Falls or Stanley Falls) because of the mountains and high plateaus it crosses. It drains an area of 974,140 km^2 and covers 27% of the total area of the Congo River basin. Its basin is characterized by the presence of many lakes and wetlands (Figure 1a), such as the large tectonic lakes of the East African rift (Tanganyika, Kivu, Mweru, Bangweulu, Upemba). It flows in a general direction from south to north to Kisangani, located 2,142 km from its source.

2. The Kasai basin belongs to the Kwango geological series (Cahen, 1954) with rainfall ranging from 1,431 to 1,515 mm yr^{-1} (Mahé, 1995). The Kasai River originates in Angola where the basin shares the ridge line with the Zambezi River (Tshimanga, 2012). This tributary is the main tributary of the Congo River. It drains the rivers of the southern Congo Basin, including the Angolan highlands, over an area of 897,500 km^2 at its outlet. Its main hydrometric station, Kutu-Moke, controls an area of 750,000 km^2 or 21% of the total area of the Congo River basin. The length of its course is 2,361 km from its source in Munyango (Figure 1a).

3. The Sangha basin, mainly covered by dense and humid rainforest, under equatorial climate receives rainfall ranging from 2,000 to 2,300 mm yr^{-1} (Laraque et al., 1998a). It consists of the Precambrian schisto-quartzitic complex with intrusions of various natures (intrusive dolerites, tillitic complexes, etc.), according to Censier (1995). This drainage subsystem covers an area of 213,670 km^2 at its outlet and 159,480 km^2 at its main hydrometric station at Ouesso, which controls almost 4% of the total area of the Congo River basin. The Sangha River runs 781 km to the confluence with Congo.

4. The Ubangui basin is made up of a set of armored plateaus covered from north to south with shrubby savannahs to trees and then with forests. It benefits from a transitional humid tropical climate with total rainfall between 1,600 and 1,800 mm yr^{-1} (Laraque et al., 2009). It drains the rivers of the northeastern Congo Basin, from the watershed with those of the Nile and Chari rivers. The Ubangui is the second largest tributary of the Congo River and the first on the right bank. It takes its name from the junction of two rivers: the Uele (also called Ouellé or Makoua) and the Mbomou (also called Bomu or Kengou), between Ouango and Limassa. At this point, the Ubangui is 1,100 km from its confluence with the Congo and the Uele-Ubangui complex is over 2,200 km long. Its basin has an area of 650,480 km^2 at the outlet and 494,090 km^2 at Bangui station, which controls almost 14% of the Congo River basin.

5. The drainage system of the Congo Basin helds in its centre a depression called the ''Centrale Cuvette'', which covers about 33% of the surface area (1 192 190 km^2) of the Congo Basin according to de Wasseige et al, (2009). It is covered by dense low-level humid forests. The Mambili at Yengo is a basin that can be considered representative of the dry periphery of this basin, knowing that its core area of about 360,000 km^2 (i.e. 10% of the surface area of the basin) (Table 1) consists of swamps, floating meadows and rainforest partially flooded during the flood period, revealing rare areas of solid earth. The Likouala aux Herbes is can be considered representative of this flood Cuvette in part or in whole depending on the hydro-pluviometric cycle (Pouyaud, 1970; Laraque et al., 1998b). Watered by 1,600 to 1,800 mm.yr^{-1} (BRLi, 2016), the Central Basin is made up of quaternary fluvial, clayey or sandy alluvial deposits where rivers wander in a very sinuous manner, and are sometimes anastomosed near their confluence, often being linked together by numerous natural or anthropogenic channels that promote flooding of the plains, according to Laraque et al. (1998b). In the Cuvette Centrale, the main lakes are Tumba and Maï Ndombe, very shallow (3 m – 8 m) which extend over more than 3,000 km^2 on the left bank of the Congo River (Molliex et al., 2019) and Télé Lake on the right bank of the Congo. Elliptical in shape, it covers 23 km^2 for a circumference of 18 km and its origin could come from a meteorite impact (Laraque et al., 1998b). The lowest point of the depression, at an altitude of about 300 m, is at the multiple confluences of the Congo River with the Ubangui, Likouala aux Herbes, Sangha and Likouala Mossaka in the heart of the flooded Cuvette Centrale (Figure 3).

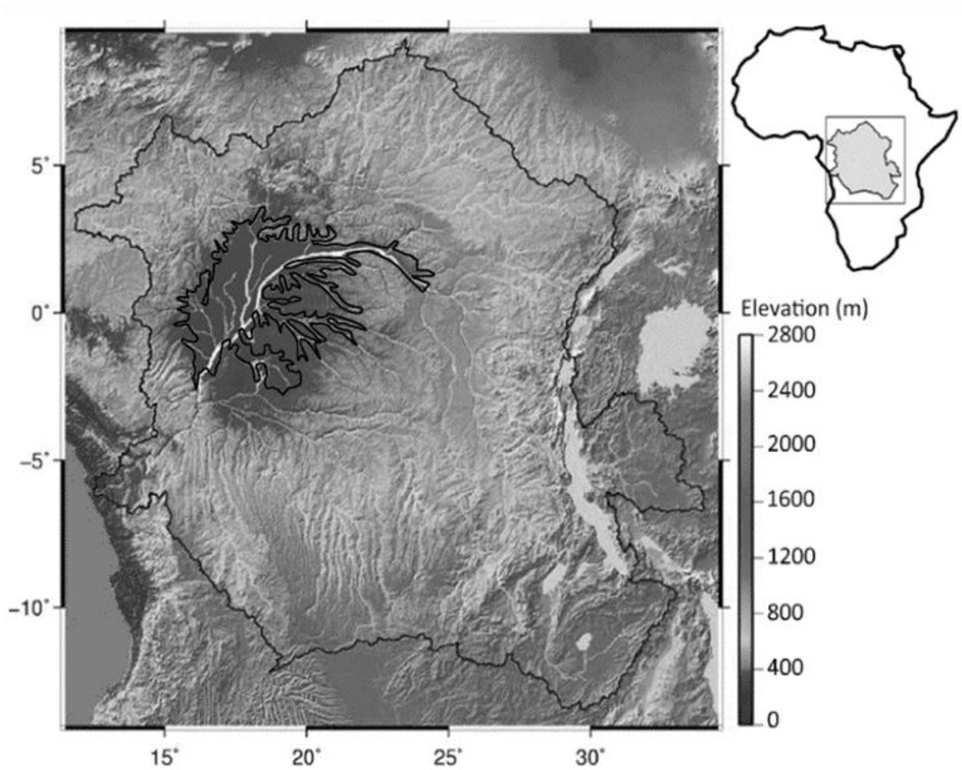

Figure 3. Topography of the Congo Basin and the flooded portion of the Central Basin. The topography comes from the SRTM (Farr et al., 2007) and the flooded portion of the Central Basin (the black polygon) is generalized by Bwangoy et al. (2010).

However, this Central Basin has a singular hydrological functioning that challenges our scientific communities. For example, Lee et al. (2011, 2014) found that the variations in wetland levels between the dry and wet seasons were subtle, ranging from only about 0.5 to 1.0 m. It is interesting to note that water levels in the main stream around the Central Basin are consistently lower than water levels in adjacent wetlands (less than 0.5 m to 3.0 m).

6. The Batékés Plateaus, located in the western part of the basin, are made up of sandy-sandstone formations 200 m to 400 m thick. These formations, which cover more than 100 000 km^2 , contribute to the support of Congo's flows by regularly generating about 3 000 $m^3.s^{-1}.yr^{-1}$. The Batékés rivers flowing at the bottom of deep and steep valleys, are very regular, and the contrast is striking between the aridity of the plateaus and the importance of their flows in the dry season (Molinier et al., 1974). Even in the rainy season, runoff is almost non-existent, following an almost instantaneous infiltration that feeds a powerful aquifer. In this drainage subsystem, annual rainfall is high (1,900 mm) and there is a hydrological paradox already highlighted by Laraque et al. (1998c), where almost stable hydrological regimes do not reflect the highly contrasted rainfall with a well-marked dry season from June to August.

1.3 Problem and hypothesis

The last segmentation of the flow time series from Congo to Brazzaville/Kinshasa (Laraque et al., 2013a) is for the period 1903-2010. From 1960 onwards, it showed alternating excess and approximately-decadal deficit phases, for which several explanations had been given as to their origins. Among these, Sanga-Ngoie & Fukuyama (1996 related them to solar activity at 11-year intervals. But if this were the case, then one can question the absence of similar approximately-decadal flow phases during the first half of the 20th century.

The remarkable change in the Congo Basin is that of 1970, which is also found on right bank tributaries by indicating a period of deficit flows, also noted in West Africa and the Sahel (Servat et al., 1998 ; Paturel et al., 1998 ; Mahé, 1995 ; Mahé & Olivry ; 1995).

However, Laraque et al. (2013a) noted *(i)* that a return to average flows seemed to be underway since 1995 for the Congo in Brazzaville/Kinshasa and that *(ii)* if the flows of the right bank tributaries decreased, it could then be deduced that they were offset by increases in those of Kasai and/or Lualaba and/or Cuvette Centrale.

To respond to this hypothesis and to shed new light on the water conditions in the basin in recent years, and in particular on the hydrological regime of the Cuvette, this study presents in turn *(i)* the significant changes in the hydro-rainfall series of the above-mentioned drainage systems, *(ii)* their trends, by *(iii)* highlighting the case of the Ubangui, which is the most sensitive tributary to regime changes.

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2 Data and methods

2.1 Availables Data

Although they control only 66% of the basin, the only four hydrological stations selected represent the main hydro-climatic regions of the BRC and have long multi-decadal chronicles of hydro-climatic data. They encircle the Cuvette Centrale, whose unique hydrological functioning is of interest to our scientific communities.

Any hydrological study requires the characterization of rainfall patterns and the calculation of spatialized precipitation by watershed. This required prior criticism of data quality and analysis of long histories to determine regime variability, trends, and relationships with major regional climate signals. The available rainfall and flowmeter periods are presented in Table 3, and the available modules of the 5 hydrological stations studied are in Annex 1.

Table 3. Available Data: Monthly rainfall (R) and Daily Discharge (Q)

		R (mm)			Q ($m^3.s^{-1}$)		
River	Station	Periods	Years	Gaps	Periods	Years	Gaps
Lualaba	Kisangani	1940-1999	60	-	1951-2012	62	
Kasaï	Kutu-Moke	1940-1999	60	-	1948-2012	65	
Sangha	Ouesso	1940-1999	60	-	1948-2018	71	1952, 1997 et 1998
Ubangui	Bangui	1940-1999	60	-	1936-2018	83	
Congo	Brazzaville/Kinshasa	1940-1999	60	-	1903-2018	116	

At the sub-basin level, rainfall chronicles have been established by the regional vector method, which is an automatic method of rainfall analysis, developed at ORSTOM-IRD by Hiez (1977). It consists of a chronological series of annual or monthly indices, representative of the evolution of precipitation within a climate-homogeneous region and whose stations show approximately-proportional variability between them (Singla et al., 2010). It was applied over the same 60-year period, from 1940 to 1999 (Boyer et al., 2006).

The flow records of the Kisangani stations on the Lualaba (which controls 100% of the surface area of its basin) and of Kutu Moke on the Kasaï (which controls 84% of the surface area of its basin) were obtained thanks to the International Commission of the Congo-Ubangui-Sangha Basin (CICOS). They have been compiled, completed and homogenized for the common period 1951-2012 by BRLi (2016). Data from the Ouesso stations on the Sangha (which controls 75% of the surface area of its basin), Bangui on the Ubangui (which controls 76% of the surface area of its basin) and the twin stations Brazzaville/Kinshasa, which control 98% of the CRB, were obtained via the HYBAM Observation Service database (www.so-hybam.org) (Table 2), which compiled the data collected by ORSTOM-IRD and then the Joint Waterway Maintenance Service (SCEVN). Hydrological data management was carried out using the Hydraccess software (www.mpl.ird.fr/hybam/outils/hydraccess.htm).

2.1 Methodologies used

For the whole period 1940 to 1999 and for each of the stations studied, an annual rainfall index was calculated. It is defined as a reduced centered variable (Lamb, 1982) : $(\mathbf{x}-\bar{\mathbf{x}})/\boldsymbol{\sigma}$, with $\mathbf{x_i}$**:** is rainfall in year i ; $\bar{x}$: is mean interannual rainfall over the reference period; σ: is standard deviation of annual rainfall over the reference period. This index reflects a rainfall surplus or deficit for the year in question compared to the chosen reference period (Ardoin et al., 2003).

The same procedure was applied to the flows for the entire length of the available chronicles per station in order to assign them an annual hydrological index. For the Congo River in Brazzaville/Kinshasa, the annual flows from 1903 to 1947 were studied, followed by daily flows from 1948 to 2018, and finally daily flows for both Ubangui in Bangui (1936 to 2018), Sangha in Ouesso (1948 to 2018), Luabala in Kisangani (1948-1992) and Kasai in Kutu-Moke (1951 to 1992).

These index chronicles were subjected to various statistical tests included in the Khronostat software (Lubès-Niel et al., 1998, www.hydrosciences.org/spip.php?article239). The literature on the statistical approach to time series of hydrometeorological variables is particularly extensive. The tests selected in the software are largely extracted from the technical note of the World Meteorological Organization (WMO, 1966) and from the book by Kendall & Stuart (1943).

The first category of tests concerns the random nature of the series. In the event that the series is declared non-random, a second category of tests is required to attempt to characterize the "non-random" nature present in the series, such as tests relating to the detection of an *a priori* breaking point at an unknown date. A break is understood to be a change in the probability law of the time series at a given time, most often unknown. The statistical tests used make it possible to determine whether there is a change in the behavior of a variable over time. These tests are:

- The rank correlation test (Kendall & Stuart, 1943; WMO, 1966) is a non-parametric test that controls the homogeneity of a time series with the alternative assumption of a trend. The null hypothesis of the test is: "the series of (xi), i=1, N, is random".
- Pettitt's test (1979),], also non-parametric, examines the existence of a break at an unknown time in the series from a formulation derived from that of the Mann-Whitney test (Dagnélie, 1970). The null hypothesis of the test is the absence of a break in the series. This test is particularly sensitive to a change in the mean and, if the null hypothesis of homogeneity of the series is rejected, it provides an estimate of the break date.
- The non-parametric segmentation procedure of hydrometeorological series (Hubert & Carbonnel, 1987; Hubert et al., 1989) is adapted to the search for multiple mean changes in the series. According to the authors (Hubert et al., 1989 this segmentation procedure can be considered as a stationarity test but is not a rigorous test: no level of significance is assigned to this "pseudo-test". Its principle is to "divide" the series into several segments so that the average calculated on any segment is significantly different from the average of the neighboring segment(s) by applying the Scheffé test (Kendall & Stuart, 1943) which is based on the concept of contrast (Dagnélie, 1970). If the procedure does not produce an acceptable segmentation of order greater than or equal to 2, then the null hypothesis of stationarity is accepted.

3 Results and discussion

For the five stations with long multi-year series, we present the results of the statistical analysis on the different hydro-pluviometric chronicles available (Table 4), before studying the variations in their mean hydrometric regimes by homogeneous period. This preliminary study by catchment area will then make it possible to compare their hydro-rainfall behavior with each other in an attempt to better understand hydrological responses within the CRB.

3.1 Hydro-rainfall statistical analysis

A literature review on rainfall and runoff trends in West and Central Africa shows that the 20th century, the period over which most rainfall data began to be observed (the vast majority of hydrological data date back to the 1950s), saw alternating dry and wet periods without any clear frequency of these alternating periods. Thus, during the decades of 1910, 1970 and 1980, a high level of rainfall drought (and hydrological drought when data were available) was observed. Similarly, the 1950s and 1960s, and in particular the latter and its early years, were very much in excess in terms of rainfall and runoff. However, these temporal developments have not been spatially homogeneous. Droughts recorded appear to have been more severe in West Africa, particularly from 1970 onwards, with a peak during the 1980s and 1983-1984, which generally record the lowest observed rainfall and annual moduli. In contrast, the 1960s were heavily rainy in Central Africa with probably flows rarely observed before.

Taking into account this “global” information on the knowledge of hydro-rainfall evolution in the West and Central African regions and the availability of data on the Congo Basin, this work has multiplied hydro-rainfall time series analyses over different periods in order to highlight the important points that statistical tests reveal to us and not to bias the results of these analyses (Table 4).

Statistical analyses of rainfall series show that between 1940 and 1999, rainfall decreased overall in the Ubangui, Kasai and Congo catchment areas in Brazzaville. This trend results in a break (change in the mean of the probability law of the time series at a given time) around 1970 (Figures 4a). The 1950s and 1960s are wetter but are not detected by statistical tests. Upstream of Brazzaville, the Lualaba catchment area in Kisangani only feels the heavy rainfall of the early 1960s but not the decrease in rainfall from 1970 onwards. On the Sangha alone, annual rainfall has hardly changed. It should be noted that of all the basins analyzed, the end of the 1980s and the beginning of the 1990s seem to have been relatively rainier. They partly mitigate the visual trends towards a sharp decrease in rainfall since 1970.

Statistical analyses of hydrological series show that since 1950, two break-up dates have emerged for all the basins analysed: 1970 or 1980 (with the exception of the Lualaba River in Kisangani), while for rainfall, the only common break-up date is that of 1970 (Figures 4b). The later break in 1980 for the Lualaba can be explained by flows mainly of an underground nature.
For the Lualaba in Kisangani, statistical tests do not reveal any trends or breaks, although the pseudo-segmentation test highlights the early 1960s as having very high flows.

When rainfall and runoff analyses are combined, rainfall trends/break-ups are found on runoff with a delay of sometimes about ten years. The exception is the Sangha River, where rainfall did not change much during the end of the 20th century, while flows have fallen sharply since 1970.

The results of the analysis of the long hydrological series from the Ubangui to Bangui (1936-2018) and from Congo to Brazzaville/Kinshasa (1903-2018), which lead to very contrasting results, should not be forgotten. Indeed, while significant changes were detected in the Ubangui around 1970, this is not the case for Congo in BZV/KIN.

These preliminary results are in agreement with those of Servat et al. (1998) who pointed out a clearly perceptible hydroclimatic change in tropical basins, such as the Ubangui and much less perceptible in African equatorial basins (the case of the entire Congo basin). For hydro-climatology, They mentioned in Central Africa a simple interannual variability over the last few decades.

By analyzing the results of the segmentation procedure, the study of the complete chronicle until the end of 2018 for the Congo River in Brazzaville/Kinshasa makes it possible to qualify the previous conclusions, by offering us a more distant perspective, since the sequencing evolves according to the duration of the available chronicles. As a result, the persistence of the recovery in flows since 1995 brings back a balance between the period before the wet decade of

1960 and the one that follows it. In fact, this wet decade of 1960 became the major anomaly in the river's hydraulicity over the past 116 years.

This anomaly is consistent with an increase in rainfall in the basin in the early 1960s, although it is less marked than that of the discharges. From 1970 to 1999, rains decreased by -3.5% compared to the previous period and flow decreased by almost -1.9% over the same period. It should be noted that the recovery in flows since 1995 suggests a more sustained rainfall over the last two decades. This should be verified when a long compilation of more up-to-date rainfall data is possible.

By studying the spatial and temporal variability of the specific flows, which constitute the best index for comparing the evolution of the behavior of the different components of a hydrosystem, we can see that among all of the sub-basins and for all the periods combined, it is those of the Ubangui that are the lowest. They have reached 5.9 l s^{-1} km^{-2} over the entire current dry period since 1982.

By homogeneous period, the specific flows of the Sangha and Kasai are of the same intensity for their respective first periods (1948-1970 with 11.3 l s^{-1} km^{-2} and 1948-1991 with 11.5 l s^{-1} km^{-2}). They decreased in the same way for their second period, after their only rupture, respectively from (1971-2018 with 9.0 l s^{-1} km^{-2} and (1992-2012 with 9.3 l s^{-1} km^{-2}).

After their increase during the wet period, those of Lualaba remain intermediate to the others, with 7.8 l s^{-1} km^{-2}.

Those from Congo to Brazzaville/Kinshasa show a balance at 10.9 l s^{-1} km^{-2} on either side of the wet period of the 1960s, which plays the role of pivot on the chronicle studied. Of course, these specific flows include those of the Congolese Cuvette, but also those of the Batékés plateaus, which are one of the major hydrogeological singularities of this basin, which are high (> 30 l s^{-1} km^{-2}).

3.2 Average hydrological regimes by periods of homogeneous flows

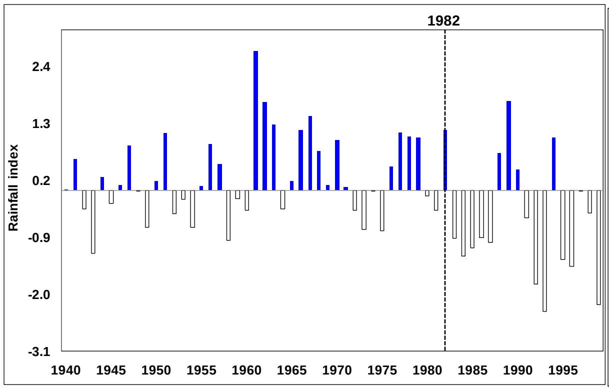
The evolution of mean hydrological regimes by homogeneous flow periods for the main stations of the drainage systems studied shows that:

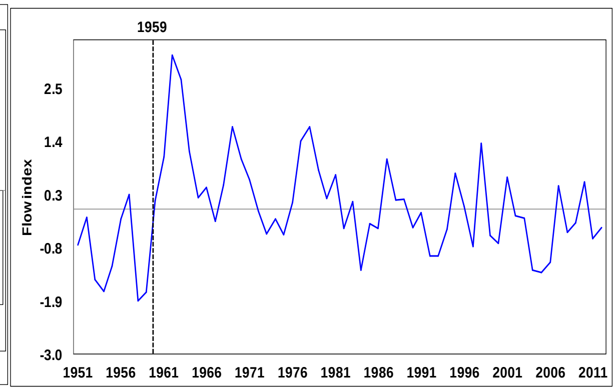
- The Lualaba in Kisangani is generally characterized by two periods of flooding from November to February and from April to June, separated by a level (in March) often above the interannual average. The low water level is from July to October (Figure 5a). The period of homogeneous flows from 1951 to 1959 shows that the amplitude of low flows was higher and the volumes of floods and low flows lower during this phase. The mean hydrograph of the period of homogeneous flows from 1960 to 2012 has the same morphology as that of the entire series studied.
- The Kasai in Kutu Moke, whose flood period extends from November to May, has a plateau flood followed by a dome peak from April to May, which precedes a low water level from June to November (Figure 5b) marked by a rapid drop in flows between May and June. Mean hydrographs by homogeneous flow periods show that the amplitude and duration of floods decrease considerably between the two periods 1948-1991 and 1992-2012. The duration of low water levels increases, the amplitude remains stable and the volume decreases during the last phase of the decade 1992 - 2012.

Table 4. Synthesis of statistical results on multi-year Rainfall (R) and Discharge (Q) time series

	Station			Correlation on the rank			Pettitt test				Segmentation							
	River at Station	beginning obs.	end obs.	99%	95%	90%	99%	95%	90%	date	date seg1	Avera. Seg1	date seg2	Avera. Seg2	date seg3	Avera. Seg3	date seg4	Avera. Seg4
Annual Rainfall (mm)	Lualaba at Kisangani	1940	1999	R	R	NR	NB	B	B	1982	1940; 1982	1337	1983; 1999	1231				
	Kasaï at Kutu Moke	1940	1999	NR	NR	NR	B	B	B	1969	1940; 1969	1525	1970; 1999	1388				
	Sangha at Ouesso	1940	1999	R	R	R	NB	NB	NB		1940; 1999	1625						
	Ubangui at Bangui	1940	1999	NR	NR	NR	B	B	B	1969	1940; 1970	1545	1971; 1999	1449				
	Congo at BZV/KIN	1940	1999	NR	NR	NR	B	B	B	1970	1940; 1970	1494	1971; 1999	1396				
	Lualaba at Kisangani	1950	1999	NR	NR	NR	NB	B	B	1982	1950; 1982	1348	1983; 1999	1231				
	Kasaï at KutuMoke	1950	1999	NR	NR	NR	B	B	B	1969	1950; 1969	1541	1970; 1999	1388				
	Sangha at Ouesso	1950	1999	R	R	NR	NB	NB	B	1971	1950; 1999	1638						
	Ubangui at Bangui	1950	1999	NR	NR	NR	B	B	B	1970	1950; 1969	1562	1970; 1999	1451				
	Congo at BZV/KIN	1950	1999	NR	NR	NR	B	B	B	1970	1950; 1970	1513	1971; 1999	1396				
Average Annual Discharge ($m^3.s^{-1}$)	Lualaba at Kisangani	1951	2012	R	R	R	NB	NB	NB		1951; 1959	6626	1960; 2012	7814				
	Kasai at Kutu Moke	1948	2012	NR	NR	NR	B	B	B	1979	1948; 1991	8606	1992; 2012	6943				
	Sangha at Ouesso	1948	2018	NR	NR	NR	B	B	B	1971	1948; 1970	1800	1971; 2018	1429				
	Ubangui/Bangui	1936	2018	NR	NR	NR	B	B	B	1981	1936; 1959	4220	1960; 1970	4886	1971; 1981	3615	1982; 2018	2919
	Congo at BZV/KIN	1903	2018	R	R	R	NB	NB	NB		1903; 1959	39691	1960; 1970	48022	1971; 2018	39755		
	Oubangui at Bangui	1948	2018	NR	NR	NR	B	B	B	1981	1948; 1959	4119	1960; 1970	4886	1971; 1981	3515	1982; 2018	2919
	Congo at BZV/KIN	1948	2018	R	NR	NR	B	B	B	1981	1948; 1959	40132	1960; 1970	48022	1971; 2018	39755		
	Lualaba at Kisangani	1951	1999	R	R	R	NB	NB	B	1959	1951; 1960	6745	1961; 1964	9762	1965; 1999	7797		
	Kasai at Kutu Moke	1950	1999	NR	NR	NR	B	B	B	1979	1950; 1991	8597	1992; 1999	6266				
	Sangha at Ouesso	1950	1999	NR	NR	NR	B	B	B	1971	1950; 1970	1808	1971; 1999	1430				
	Ubangui at Bangui	1950	1999	NR	NR	NR	B	B	B	1970	1950; 1959	4068	1960; 1970	4886	1971; 1981	3615	1982; 1999	2877
	Congo at BZV/KIN	1950	1999	R	NR	NR	B	B	B	1980	1950; 1959	39776	1960; 1970	48022	1971; 1999	39556		

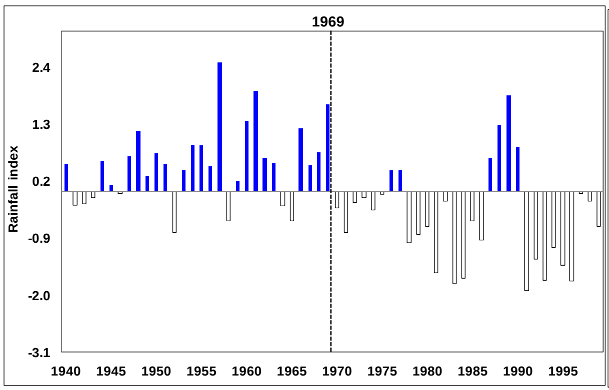
Legend : R : Random ; NR : no Random; B : Break; NB : no Break

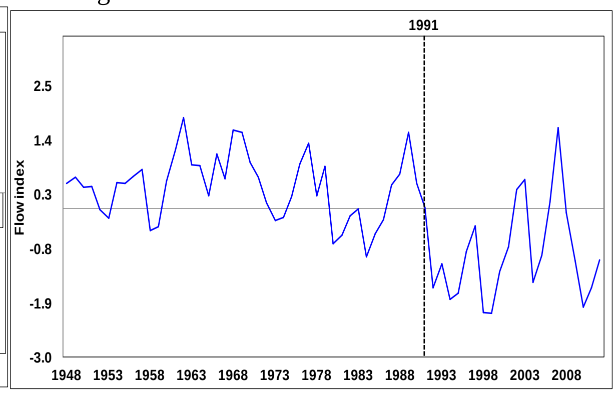




(a) (b)

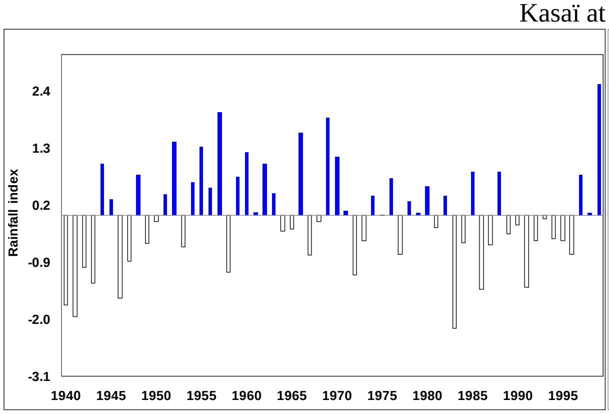
Lualaba at Kisangani

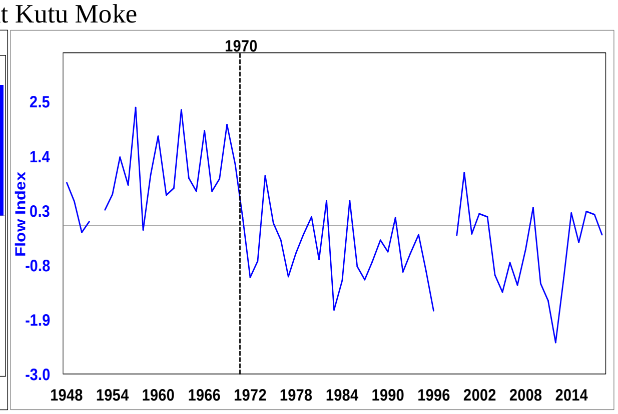




(a) (b)

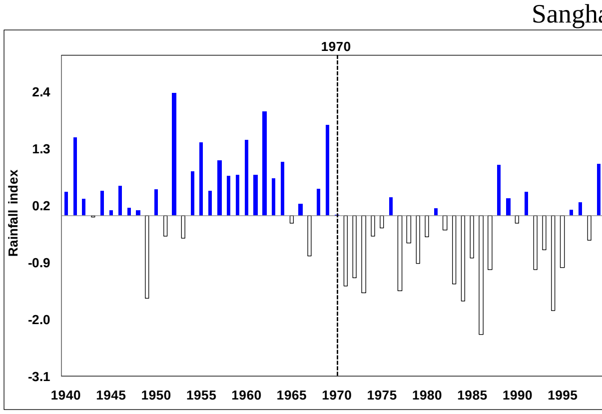
Kasaï at Kutu Moke

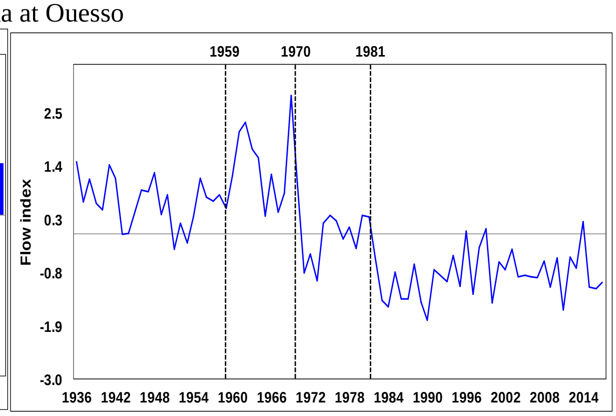




(a) (b)

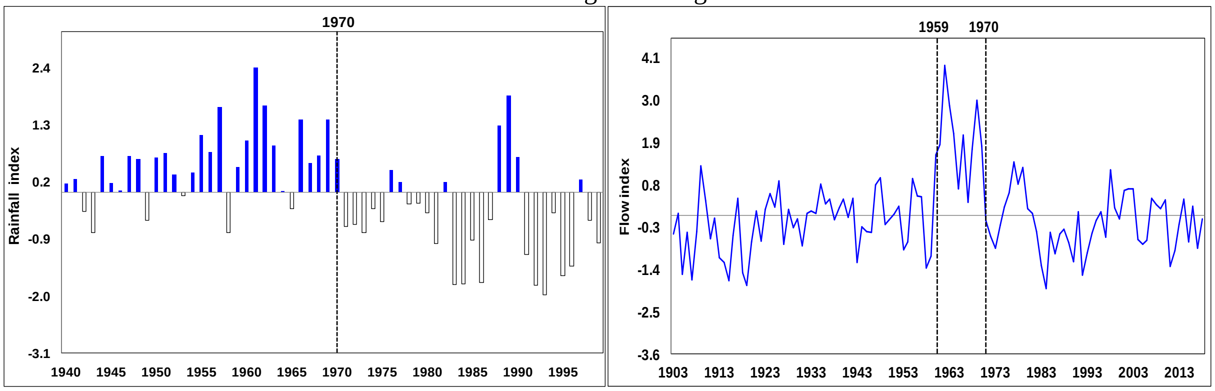
Sangha at Ouesso





(a) (b)

Ubangui at Bangui



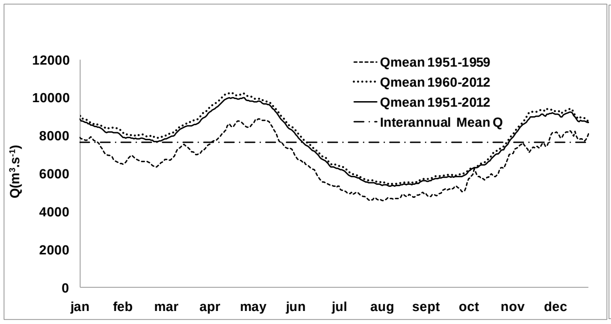
(a) (b)

Congo Basin at BZV/KIN

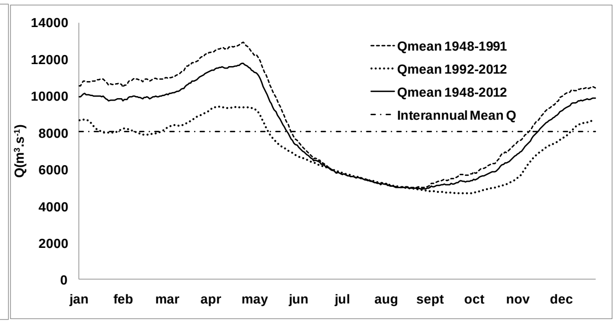
Figure 4. Sequencing of the reduced centered variables (a) rainfall for the period 1940 to 1999 and (b) runoff for the different time series available, respectively for the Lualaba to Kisangani (1951 - 2012), Kasai to Kutu Moke (1948 - 2012), Sangha to Ouesso, (1948 - 2018) Ubangui to Bangui (1936 - 2018), Congo to BZV/KIN (1903-2018).

- The Sangha in Ouesso (Figure 5c), shows an intermediate regime between uni and bimodal with a low water level from January to June, a small level flood from July to August and a well marked main flood from September to mid-December. It can also be considered that the low water level occupies about nine months from January to September with various small floods in July-August that are smoothed by the average hydrographs. The volumes flowing from the Sangha River decrease over time, as a result of the decrease in flood amplitude and the increase in the duration of low water levels. From 1971 to 2018, the secondary flood is replaced by a plateau; consequently, the low water level becomes more intense and longer. The volumes of low water levels are decreasing much faster than those of floods.
- The annual flooding of the Ubangui River in Bangui (Figure .d) begins in mid-July and ends in mid-December. The low water level occupies the rest of the year and lasts seven months. The volumes flowing from the Ubangui fell by almost half from 1936 to 2018. This is due rather to the decrease in amplitude because flood and low-water levels tend to remain stable, except for the current dry phase from 1982 to the present day, which sees the duration of low-water levels increase and that of high-water levels decrease. According to the homogeneous period hydrographs of the Ubangui in Bangui in Figure 5d, the amplitude ratios over both flood and low water duration decrease over the period 1936-2018.
- The Congo in Brazzaville/Kinshasa (Figure 5e), has a bimodal regime with its main flood, which generally begins in October and ends in February. Then begins a large low water level that ends in October. During this low water level a secondary flood appears with its slightly rounded peak in May. Since 1970, it has been under the interannual module calculated since 1903. The amplitude of the Congo's floods tends to increase while their duration decreases, but their volumes remain stable. On the other hand, the volumes flowing from low water levels tend to decrease while their duration increases and their amplitudes remain stable. Mean hydrographs per homogeneous flow period show that

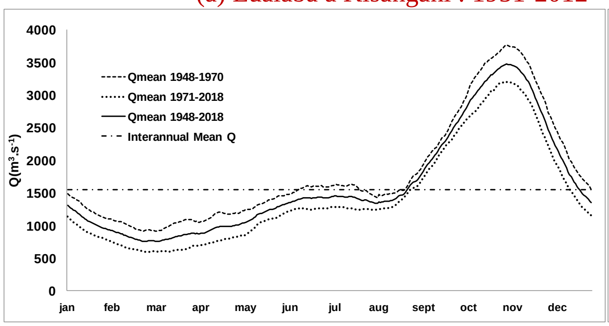
during the wet phase from 1960 to 1970 the secondary flood far exceeded the interannual module.



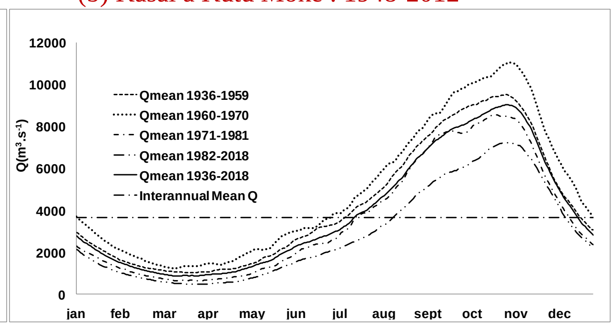
(a) Lualaba à Kisangani : 1951-2012



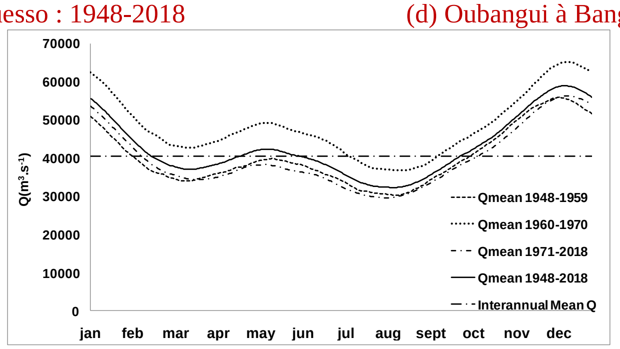
(b) Kasaï à Kutu Moke : 1948-2012



(c) Sangha à Ouesso : 1948-2018



(d) Oubangui à Bangui : 1936-2018



(e) Congo à BZV/KIN: 1947-2018

Figure 5. Changes in mean daily hydrological regimes by homogeneous flow periods for Lualaba in Kisangani (a), Kasai in Kutu Moke (b), Sangha in Ouesso, (c), Ubangui in Bangui (d), Congo in BZV/KIN (e). The total periods of available daily data are indicated for each station.

This hydrograph is not simply a transposition of the climate regime, as hydrological mechanisms assign a completely different origin to the high waters observed in Brazzaville/Kinshasa. These come from soil precipitation watering, during the boreal summer, the northern part of the basin drained mainly by the Ubangui and Sangha, and during the southern summer, the southern part tributary of the Lualaba and Upper Kasai. Given the time it takes for the high water in one or the other part of the basin to reach the downstream, this regime actually depends on two floods of different geographical origins, superimposed on the more regular contributions from the equatorial strip (Bricquet, 1993).

If this mechanism is disrupted (rains falling early or late compared to their usual schedule) in any part of the basin, normally out of phase inflows will then combine when they arrive in the main collector, both upward and downward in flow. The case of the 1960s of the highest flows corresponds to this type of conjunction of flood inflows from different sources.

3.3 Régime hydrologique de la Cuvette Centrale

Finally, the differential study of these hydrological chronicles allows us to deduce the hydrological regime of the Central Basin (Figure 6) : a bimodal regime as characterized by the areas closest to the Equator. Its hydrological regime is modelled on the rainfall regime of this forest region, but the flows show higher and more contrasted seasonal variability than those of the rains. A large part of the Cuvette's water exchanges are vertical, i.e. controlled by the Rain-Evaporation-Evaporation-PET (Evapotranspiration) balance (Alsdorf et al., 2016 ; BRLi, 2016 ; Lee et al., 2014). Laraque et al. (1998b) had already pointed this out and quantified it for its floodable part with the water balance of Lac Télé.

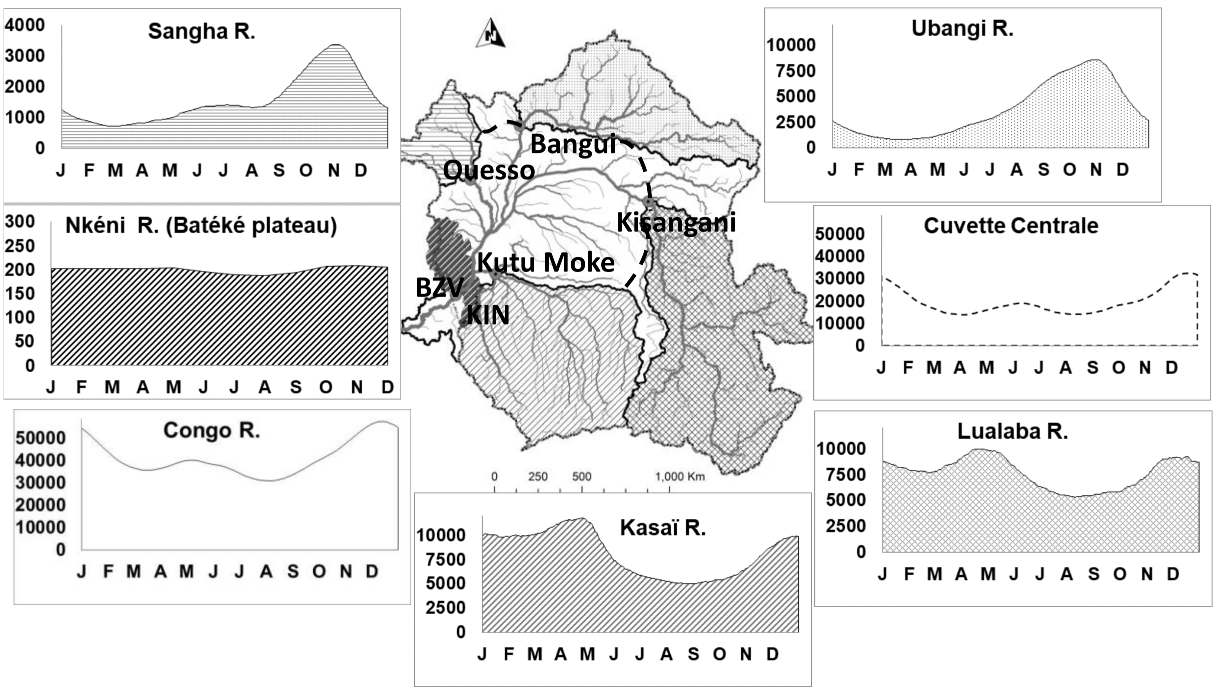


Figure 6. Comparison of hydrological regimes of the 7 main drainage entities of the Congo Basin. **Legend:** the dash encircles the Cuvette Centrale *sensu lato*. The area with inclined dark hatching is that of the Batékés plateaus.

Two seasons of high water at which around the important "crossroads" of confluences with the Congo, the Oubangui, the Sangha, the Likouala aux Herbes, the Likouala Mossaka, Lake Tumba, the Ruki..., the rivers are anastomosed and create a floodplain (see Figure 3). The first and weakest floods occur between May and July and the second and largest between September and January. The results for this are compared with other results from previous work using indirect approaches such as remote sensing (see Figure 3). The first and weakest floods occur between May and July and the second and largest between September and January. The results for this are compared with other results from previous work using indirect approaches such as remote sensing (Alsdorf et al., 2016; Becker et al., 2014; Lee et al., 2014; Kim et al., 2017; Becker et al., 2018, ….) and modelling (BRLi, 2016; Tshimanga et al., 2011; Tshimanga et al., 2012;

Tshimanga, & Hughes, 2014). The latter, which is not measured in situ, contributes to drawing the one of the river in Brazzaville/Kinshasa.

4 Conclusions

This large-scale work on a scale of the entire Congo Basin is the first of its kind, to compare hydro-rainfall behavior, both in the left and right bank basins of the river, on multi-decadal chronicles dating back to the beginning of the observations. In the absence of a truly operational supranational entity, it is still difficult and risky to compile such data in real time for the entire basin. This is an aberration at a time when remote sensing is freeing it from national borders and fears. This work is nevertheless a first step towards Integrated Water Resources Management (IWRM) and allows a renewed and more complete vision of the hydro-pluviometric functioning of the Congo Basin.

It highlights the hydro-climatic rupture of 1970 that affected West and Central Africa. This rupture affected the tributaries on the right bank of the Congo and was also felt at the main twin stations of Brazzaville/Kinshasa. But it does not affect the entire Congo Basin. The wet decade of 1960 remains the major hydrological anomaly of the river for the past 116 years. However, in view of the great regularity of its flows, the apparent hydrological inertia of the river at its outlet masks significant spatial and temporal heterogeneities, which must be taken into account in any development project. The main floods of the Congo River at the outlet come from soil precipitation, which in the boreal summer waters the northern part of the basin drained mainly by the Ubangui and Upper Sangha, and in the southern summer waters the southern part of the Lualaba and Upper Kasai. Given the time it takes for the high water in one or other part of the basin to reach the downstream, this regime actually depends on two floods of different geographical origins, superimposed on the more regular contributions from the equatorial strip.

At the basin scale, discharges variations are in fact greater than those of rainfall. But it is above all, the Ubangui basin that is the most sensitive and affected by climate change, with flows declining since 1970. This poses a problem for inland navigation, whose annual duration is reduced because of a longer period of low water, whereas it is the preferred route for the exchange of both people and goods between the countries of the basin. Similarly, attention to changes in water conditions is crucial at a time when we are once again talking about linking the Congo Basin to the Chari Basin through a canal to compensate for the water deficit in Lake Chad (Pham-Duc et al., 2020). Finally, current hydro-climatic changes are leading to a revision of hydrological standards in West and Central Africa, which have been established on the basis of concepts of discharges stationarity.

This concept perfectly illustrates our temporal myopia, since hydro-climatology has always varied over time in a more or less cyclical way. The relativity of our conclusions on the current one is in line with the work of Molliex et al. (2019) who carried out a reconstruction of liquid and solid flows during the 155 ka BP. This attempt was made by crossing the evolutions of various proxies (geochemical and isotopic evolutions of the sedimentary cores of the underwater canyon of the Congo Ocean Outlet) and by using the HydroTrend model calibrated in particular on hydrological data from the last 116 years. This model is based on morphological, climatic, hydrological, lithological, vegetation cover and anthropogenic impact criteria and gives an idea of the variations in Congo's flows, according to the glacial and interglacial cycles that have affected our planet.

This work also highlights the opposition of hydro-pluviometric phases between the northern and southern sub-basins. Finally, a first approach of the Central Basin regime is proposed thanks to hydrological balances between the stations located on its periphery.

By studying the spatial and temporal variability of specific flows, which constitute the best index for comparing the evolution of the behavior of the different components of a hydrosystem, we can see that among all sub-basins and for all periods combined, it is those of the Ubangui that are the lowest. They reached 5.9 l s^{-1} km^{-2} over the current dry period. By homogeneous period, the specific flows of the Sangha and Kasai are of the same intensity. They decreased in the same way, after their only break-up, in 1970 and 1991 respectively.

After their increase during the wet period, those of Lualaba remain intermediate to the others (7.8 l s^{-1} km^{-2}). Those from Congo to Brazzaville/Kinshasa show a balance at 10.8 l s^{-1} km^{-2} on either side of the wet period of the 1960s, which plays the role of pivot on the chronicle studied. Of course, these specific flows include those of the Congolese Cuvette, but also those of the Batékés plateaus, which are high (> 30 l s^{-1} km^{-2}) and constitute a major hydro-rainfall paradox of this basin and cover more than a hundred thousand km^2. This huge aquifer contributes to sustaining Congo’s flows by reducing the contrasting rainfall regime it receives (Laraque et al., 1998a).

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Appendix 1. Table of Modules (in m^3s^{-1}) available at the 5 hydrological stations studied

Rivière Années\Station	Lualaba Kisangani	Kasaï Kutu Muke	Sangha Ouesso	Oubangui Bangui	Congo BZV/KIN
1903					38670
1904					40680
1905					34710
1906					38820
1907					34190
1908					38950
1909					45330
1910					41920
1911					38220
1912					40240
1913					36380
1914					35860
1915					34090
1916					38500
1917					42200
1918					34850
1919					33650
1920					37880
1921					40940
1922					37980
1923					41080
1924					42620
1925					41330
1926					43920
1927					37710
1928					41120
1929					39280
1930					40130
1931					37480
1932					40700
1933					40950
1934					40700
1935				5178	43560
1936				4958	41650
1937				4227	42120
1938				4625	40060
1939				4206	41260
1940				4089	42110
1941				4886	40320

1942				4655	42150
1943				3638	35920
1944				3665	39360
1945				4062	38890
1946				4438	38820
1947			1413	4412	43470
1948		8716		4753	44210
1949		8870		4001	39610
1950		8619		4355	42140
1951	6868	8640	1606	3380	
1952	7469	8046	1911	3853	40360
1953	6127	7837	1620	3486	37100
1954	5873	8735	1704	3957	37870
1955	6416	8717	1894	4652	44130
1956	7429	8882	1768	4310	42420
1957	7948	9060	2147	4234	42300
1958	5665	7552	1511	4350	35330
1959	5844	7638	1800	4119	36500
1960	7821	8764	1998	4698	46450
1961	8767	9543	1697	5488	47410
1962	10970	10360	2014	5657	55240
1963	10440	9173	2138	5168	51230
1964	8888	9167	1792	5024	48510
1965	7887	8417	1715	3967	43100
1966	8108	9466	2115	4723	48380
1967	7369	8832	1718	4039	41770
1968	8162	10050	1784	4378	46960
1969	9431	9986	2059	6134	51830
1970	8722	9232	1858	4565	47290
1971	8278	8880	1578	2959	40040
1972	7595	8236	1271	3297	38470
1973	7120	7796	1357	2821	37290
1974	7422	7878	1793	3834	39560
1975	7092	8383	1549	3981	41340
1976	7795	9194	1458	3889	42710
1977	9119	9731	1359	3552	45760
1978	9421	8385	1396	3769	43550
1979	8486	9153	1490	3388	45180
1980	7861	7213	1582	3991	41150
1981	8379	7427	1360	3953	40710
1982	7227	7897	1670	3228	38930
1983	7805	8084	1103	2466	35560
1984	6325	6879	1256	2352	33310
1985	7332	7463	1669	2962	38810
1986	7232	7804	1325	2492	36740

1987	8726	8694	1257	2490	38700
1988	7836	8953	1347	3117	39110
1989	7849	9988	1460	2437	37830
1990	7244	8717	1402	2115	35970
1991	7577	8136	1583	3016	40880
1992	6625	6089	1122	2914	34640
1993	6636	6705	1392	2800	36790
1994	7195	5810	1499	3268	38730
1995	8426	5960	1306	2720	39970
1996	7710	7000	1112	3711	40860
1997	6827	7659		2576	38370
1998	9089	5480		3410	45000
1999	7069	5463	1499	3751	41230
2000	6900	6496	1818	2429	40120
2001	8341	7125	1502	3155	42960
2002	7506	8552	1605	3020	43070
2003	7460	8837	1588	3374	43120
2004	6337	6235	1292	2889	38150
2005	6275	6917	1204	2908	37640
2006	6489	8236	1357	2892	38090
2007	8157	10110	1238	2872	42160
2008	7142	7976	1423	3168	41590
2009	7356	6764	1638	2712	41160
2010	8237	5614	1247	3211	42010
2011	6992	6093	1163	2300	35480
2012	7242	6800	948.9	3597	37070
2013			1280	3044	39660
2014			1611	3874	42080
2015			1461	2712	37860
2016			1618	2671	41360
2017			1601	2845	37260
2018			1500	2562	40130