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Nouveau regard sur l'hydrologie dans le bassin du Congo, à partir de l'étude des chroniques hydro-pluviométrique pluri-décennales

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

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Summary: The latest work on the main African rivers on the Atlantic coast has made it possible to subdivide the multi-year chronicles of their flows 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 chronicles 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, which is problematic because it reduces the period of river navigation. 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, these results obtained show similarities between *in situ* hydrometric chronicles and those reconstructed by spatial altimetry and modelling.

Keywords: Rupture, Hydrology, Rainfall, Congo River Basin

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 we will see 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].

Here, particular attention has been paid to the evolution of the hydrological regimes on which inland navigation depends. Indeed, it is often the only land vehicle for transporting people and goods to connect the capitals and main cities of the countries drained by this vast hydrographic network.

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

54 This study complements and enriches the previous one, by (i) adding rainfall chronicles for a period of
55 60 years (from 1940 to 1999), for the Congo Basin and its sub-basins studied, knowing that for each of
56 them, we will compare the concomitant periods between the rainfall and hydrological series
57 concerned. In addition, it complements the previous study by [Laraque et al.\[2013a\]](#), by (ii) considering
58 for the first time the evolution of the hydro-rainfall chronicles of two important new hydrographic
59 features, namely, Lualaba in Kisangani and Kasai in Kutu Moke. The latter is the main tributary of the
60 Congo River, located on its left bank. Its study will make it possible to deduce the role of the Cuvette
61 Centrale. In total, five of the main drainage entities are studied here, including the entire Congo Basin.
62 Finally, (iii) hydrometric chronicles extend until 2018 instead of 2010, for three reference stations
63 (BZV/KIN, Ouesso, Bangui), the last two of which control the main physiographic units of the CRB.

64 For the five drainage systems with data, we will divide them into homogeneous hydro-pluviometric
65 periods and then study the variations in the mean hydrometric regimes for each of them. Then,
66 comparisons of hydro-pluviometric chronicles will be carried out within each sub-basin and between
67 them. These approaches will provide a better understanding of the variability of hydrological
68 responses across the CRB.

69 Thanks to the water balance between Congo at BZV/KIN and the four other hydrosystems studied, it
70 will be possible to carry out a hydrological approach to the Cuvette Centrale, which suffers from a
71 lack of *in situ* measurements. In addition, the results will be compared with other indirect approaches
72 such as remote sensing.

73 **Research context on the Congo Basin**

74 This very large basin (3.7×10^6 km²) covers the heart of Central Africa and contributes to half of
75 Africa's freshwater exports to the Atlantic Ocean, with an interannual module of $40,600 \text{ m}^3 \text{ s}^{-1}$ for the
76 period 1903-2010 [[Laraque et al., 2013b](#)]. It is strategically located in the heart of the African
77 continent, where it is crossed by the equator and the Inter-Tropical Convergence Zone (ITCZ) [[Bultot,](#)
78 [1971 & 1972](#); [Mahé, 1995](#); [Mahé et al., 2012](#); [Nicholson, 2009](#)]. The regions closest to the equator
79 have two annual rainy seasons. The first and lowest are between March and May and the second and
80 highest between September and November. This basin plays a major role in energy balances, moisture
81 flows, atmospheric circulation and exchanges between the two hemispheres. But, paradoxically, it
82 remains unknown, forgotten and until now neglected by the international scientific community. In fact,
83 it remains well behind the others in terms of international treaties, even though it concerns ten Central
84 African countries (mainly Congo and the Democratic Republic of Congo, but also Angola, Burundi,
85 Cameroon, Gabon, Central African Republic, Rwanda, Zambia and Tanzania). Certainly there are
86 some initiatives around the Great Lakes of the East with the Lake Tanganyika Authority [[https://ita-](https://ita-alt.org/fr/)
87 [alt.org/fr/](https://ita-alt.org/fr/)]; but this remains small given the size and importance of this basin. This relative omission is
88 also highlighted by a ratio of 10 in scientific publications on hydrology *sensu lato* at the expense of the
89 Congo Basin compared to the Amazon [[Als Dorf et al., 2016](#)], its alter ego facing it on the other side of
90 the intertropical Atlantic Ocean.

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

97 This basin still does not benefit from operational coordinating structures for its scientific monitoring,
98 an essential prelude to its integrated management.

99 The singularity of this basin crossed by the equator is underlined by its physiognomy, with a shape and
100 structure generally concentric around the famous Cuvette Centrale which is partially or totally flooded

101 according to the hydrological cycle. The latter covers 360,000 km² (see Figure 7). It looks like a
102 gigantic plate perched at an altitude of 300 m with slight slopes in its centre (< 2 cm km⁻¹) according
103 to [Laraque et al., \[2009\]](#). This plate is separated from the Atlantic Ocean by the succession of the
104 Livingstone Rapids, which prohibit any maritime connection, unlike most other major river basins on
105 the planet (Figure 1b). Indeed, over 400 km, the Congo River has a difference in altitude of about
106 300m (Figure 1c).

107 As far as existing hydro-rainfall data are concerned, a historical breakthrough occurred in the early
108 1960s with the independence of the countries of the basin. Since then, its 400 hydrometric stations,
109 which were operational during the first half of the 20th century, have been reduced to about fifteen
110 that are still operational today. Initially, Belgian and French researchers from ORSTOM (now IRD)
111 studied the variations in the flows of the Congo River and its tributaries, according to the colonial
112 geographical division of the basin. Several studies, including doctoral theses, scientific articles and
113 grey literature on sub-basin hydrology have been and continue to be carried out by universities in the
114 Democratic Republic of the Congo (DRC), often in partnership with Belgian universities and institutes
115 for left-bank tributaries, while those on the right bank have been and are mainly studied by the
116 universities of the Central African Republic (CAR) and the Republic of the Congo (RC) more in
117 collaboration with French institutions in the continuity of the work initiated by ORSTOM since the
118 1940s.

119 The latest major studies presenting the spatio-temporal variations in the hydro-pluviometric regimes of
120 the Congo River and its right bank tributaries have focused on multi-decadal flow chronicles [[Mahé &
121 Olivry, 1995](#); [Wesselink et al., 1996](#); [Orange et al., 1996](#); [Orange et al., 1997](#); [Laraque et al., 2001](#);
122 [Runge & Nguimalet, 2005](#); [Mahé et al., 2013](#); [Laraque et al., 2013a](#) & [Laraque et al., 2013b](#);
123 [Nguimalet & Boulvert, 2017](#); [Nguimalet & Boulvert, 2006](#); [Nguimalet & Orange 2013](#); [Nguimalet &
124 Orange, 2019](#)]. They highlighted four successive homogeneous periods of flow. Stable until 1960,
125 annual flows then change every decade. During the 1960s, they increased and exceeded their average
126 over the century. In general, these studies show, on the one hand, that the flow of Congo was marked
127 by instability in the second half of the century and by a sharp decline in its last decade. On the other
128 hand, they reveal that, while flow fluctuations are due to variations in precipitation, this influence is
129 largely modulated by the nature of the soils drained by the river and its tributaries [[Laraque et al.,
130 2013a](#); [Mahé et al., 2013](#); [Nguimalet & Orange, 2013](#)].

131 Despite the relatively limited data available for such a basin and its difficulties of access, this study
132 identified hydro-rainfall data for its main hydrographic units, based on various sources, the most
133 recent and complete of which come from [www.so-hybam.org](#) and [www.hydrosiences.fr/sierem](#) as
134 well as the [BRLi \[2016\]](#) report.

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

145 **Presentation of the Congo Basin**

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

148 Overall centered on the equator, its basin extends between parallels 9°N and 14°S and meridians 11°E
149 and 34°E, with, as much by its shape, relief, geology, climate, as by its vegetation cover, a generally
150 concentric structure around the Congolese Cuvette or central depression [[Laraque et al., 2009](#)] (Figure
151 1a). The presence of tropical rainforest, which represents about 44% of the basin's surface area,

152 promotes the basin's moisture recycling capacity [Wasseige (de) C., et al., 2015]. It is estimated that
153 75% to 95% of precipitation is recycled in the Congo Basin [Cadet and Nnoli, 1987]. This basin
154 straddling the equator covers an area of 3,660,000 km² at the twin stations of Brazzaville/Kinshasa,
155 which control 98% of its total area (3,731,000 km²) and has a 40,500 m³s⁻¹ module flows (for the
156 period 1903-2018). The hydrological regime of Congo is bimodal due to its location in both
157 hemispheres. Thus it has two low water levels, one low in February-March, corresponding to the dry
158 season north of Ecuador and the other higher in July and August during the main southern dry season.
159 These two seasons are separated by two floods, one lower in April-May, due both to equatorial
160 equinox rains on the middle course and the other more intense in October-December under the
161 influence of the southern part of the basin. These contributions from the various drainage units
162 mentioned above complement each other during the hydrological cycle to ensure a relatively regular
163 regime of the Congo River at Brazzaville/Kinshasa (or BZV/KIN) stations, both at annual and
164 interannual scales. Thus, the seasonal (maximum monthly flow/minimum monthly flow) and
165 interannual (maximum module/minimum module) variation indices over the last 116 years are
166 respectively 1.86 and 1.66.

167 The drainage system of the entire Congo Basin is subdivided into six main drainage subsystems
168 represented in **Figure 2**: Lualaba, Kasai, Sangha, Oubangui, Plateaux Batékés and Cuvette Centrale.
169 The hydro-climatic characteristics of the first four and that of the entire Congo Basin analyzed in this
170 study are presented in **Tables 1 & 2**. The last two drainage subsystems will not be studied here.
171 Indeed, that of the Batékés Plateaux has already been documented by **Laraque et al. [1998a]**, and its
172 flow chronicles are no longer available after 1994. As for the Cuvette Centrale, which does not benefit
173 from in situ measurements, its hydrological behavior has been the subject of an indirect approach
174 based on a differential balance between the other subsystems and that of the Congo Basin as a whole,
175 which is irrigated by an annual average of 1,500 mm yr⁻¹ [Mahé, 1995].

176 In **Figure 2**, the map of the watersheds and their percentages of the areas in relation to the total CRB
177 were calculated using the ArcGIS “HydroSHEDS” and “Spatial Extension Analyst” models (except
178 for the Cuvette Centrale, with vague and imprecise outlines). Below are the characteristics of the six
179 drainage subsystems:

- 180 1. The **Lualaba basin** receives rainfall ranging from 1,370 to 1,458 mm yr⁻¹ [Mahé, 1995] and is
181 drained by the Lualaba (name of the upper Congo River) which originates at the borders of
182 Zambia and the DRC, at the border between the Congo and Zambezi basins [Charlier, 1955]. It is
183 often narrow, winding, and cut off by falls or rapids (such as Boyoma Falls or Stanley Falls)
184 because of the mountains and high plateaus it crosses. It drains an area of 974,140 km² and covers
185 27% of the total area of the Congo River basin. Its basin is characterized by the presence of many
186 lakes and wetlands (**Figure 1a**), such as the large tectonic lakes of the East African rift
187 (Tanganyika, Kivu, Mweru, Bangweulu, Upemba). It flows in a general direction from south to
188 north to Kisangani, located 2,142 km from its source.
- 189 2. The **Kasai basin** belongs to the Kwango geological series [Cahen, 1954] with rainfall ranging
190 from 1,431 to 1,515 mm yr⁻¹ [Mahé, 1995]. The Kasai River originates in Angola where the basin
191 shares the ridge line with the Zambezi River [Tshimanga, 2012]. This tributary is the main
192 tributary of the Congo River. It drains the rivers of the southern Congo Basin, including the
193 Angolan highlands, over an area of 897,500 km² at its outlet. Its main hydrometric station, Kutu-
194 Moke, controls an area of 750,000 km² or 21% of the total area of the Congo River basin. The
195 length of its course is 2,361 km from its source in Munyango (see **Figure 1a**).
- 196 3. The **Sangha basin**, mainly covered by dense and humid rainforest, under equatorial climate
197 receives rainfall ranging from 2,000 to 2,300 mm yr⁻¹ [Laraque et al., 1998a]. It consists of the
198 Precambrian schisto-quartzitic complex with intrusions of various natures (intrusive dolerites,
199 tillitic complexes, etc.), according to **Censier [1995]**. This drainage subsystem covers an area of
200 213,670 km² at its outlet and 159,480 km² at its main hydrometric station at Ouesso, which
201 controls almost 4% of the total area of the Congo River basin. The Sangha River runs 781 km to
202 the confluence with Congo.

- 203 4. The **Oubangui basin** is made up of a set of armored plateaus covered from north to south with
204 shrubby savannahs to trees and then with forests. It benefits from a transitional humid tropical
205 climate with total rainfall between 1,600 and 1,800 mm yr⁻¹ [Laraque et al., 2009]. It drains the
206 rivers of the northeastern Congo Basin, from the watershed with those of the Nile and Chari rivers.
207 The Oubangui is the second largest tributary of the Congo River and the first on the right bank. It
208 takes its name from the junction of two rivers: the Uele (also called Ouellé or Makoua) and the
209 Mbomou (also called Bomu or Kengou), between Ouango and Limassa. At this point, the
210 Oubangui is 1,100 km from its confluence with the Congo and the Uele-Oubangui complex is over
211 2,200 km long. Its basin has an area of 650,480 km² at the outlet and 494,090 km² at Bangui
212 station, which controls almost 14% of the Congo River basin.
- 213 5. The drainage system of the Congo Basin has in its center a depression called the **Cuvette**
214 **Centrale**, covered with swamps, floating meadows and rainforest partially flooded during flood
215 periods, revealing rare areas of land. Watered by 1,600 to 1,800 mm yr⁻¹ [BRLi, 2016], it consists
216 of quaternary fluvial, clayey or sandy alluvial deposits where rivers wander in a very sinuous
217 manner, and are sometimes anastomosed near their confluence, often being linked together by
218 numerous natural or anthropogenic channels that promote flooding of the plains, according to
219 Laraque et al.,[1998b]. In the Cuvette Centrale, the main lakes are Tumba and Maï Ndombe, very
220 shallow (3 m – 8 m) which extend over more than 3,000 km² on the left bank of the Congo River
221 [Molliex et al., 2019] and Télé Lake on the right bank of the Congo. Elliptical in shape, it covers
222 23 km² for a circumference of 18 km and its origin could come from a meteorite impact [Laraque
223 et al., 1998b]. The lowest point of the depression, at an altitude of about 350 m, is at the multiple
224 confluences of the Congo River with the Oubangui, Likouala aux Herbes, Sangha and Likouala
225 Mossaka in the heart of the flooded Cuvette Centrale (see Figure 7).
- 226 6. The **Batékés Plateaux**, located in the western part of the basin, are made up of sandy-sandstone
227 formations 200 m to 400 m thick. These formations cover more than 100,000 km². The Batékés
228 rivers flowing at the bottom of deep and steep valleys, are very regular, and the contrast is striking
229 between the aridity of the plateaus and the importance of their flows in the dry season [Molinier et
230 al., 1974]. Even in the rainy season, runoff is almost non-existent, following an almost
231 instantaneous infiltration that feeds a powerful aquifer. In this drainage subsystem, annual rainfall
232 is high (1,900 mm) and there is a hydrological paradox already highlighted by Laraque et
233 al.[1998c], where almost stable hydrological regimes (see Figure 6) do not reflect the highly
234 contrasted rainfall with a well-marked dry season from June to August.

235 **Problem and hypothesis**

236 The flow data of the Congo in Brazzaville/Kinshasa [Laraque et al., 2013a] is for the period 1903-
237 2010. From 1960 onwards, it showed alternating excess and approximately-decadal deficit phases, for
238 which several explanations had been given as to their origins. Among these, Sanga-Ngoie &
239 Fukuyama, [1996] related them to solar activity at 11-year intervals. But if this were the case, then one
240 can question the absence of similar approximately-decadal flow phases during the first half of the 21st
241 century.

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

245 However, Laraque et al. [2013a] noted (i) that a return to average flows seemed to be underway since
246 1995 for the Congo in Brazzaville/Kinshasa and that (ii) if the flows of the right bank tributaries
247 decreased, it could then be deduced that they were offset by increases in those of Kasai and/or Lualaba
248 and/or Cuvette Centrale.

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

254

2- Data and methods

255

2.1- Available data

256 Although they control only 66% of the basin, the four hydrological stations mentioned above have
257 been selected because they represent the main hydro-climatic regions of the CRB and have long multi-
258 decade chronicles of hydro-climatic data. They surround the mysterious Cuvette Centrale, whose
259 unique hydrological functioning challenges our scientific communities.

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

265 At the sub-basin level, rainfall chronicles have been established by the regional vector method, which
266 is an automatic method of rainfall analysis, developed at ORSTOM-IRD by [Hiez \[1977\]](#). It consists of
267 a chronological series of annual or monthly indices, representative of the evolution of precipitation
268 within a climate-homogeneous region and whose stations show approximately-proportional variability
269 between them [[Singla et al., 2010](#)]. It was applied over the same 60-year period, from 1940 to 1999
270 [<http://www.hydrosiences.fr/sierem>].

271 The flow records of the Kisangani stations on the Lualaba (which controls 100% of the surface area of
272 its basin) and of Kutu Moke on the Kasai (which controls 84% of the surface area of its basin) were
273 obtained thanks to the International Commission of the Congo-Oubangui-Sangha Basin (CICOS).
274 They have been compiled, completed and homogenized for the common period 1951-2012 by [BRLi
275 \[2016\]](#). Data from the Ouessou stations on the Sangha (which controls 75% of the surface area of its
276 basin), Bangui on the Oubangui (which controls 76% of the surface area of its basin) and the twin
277 stations Brazzaville/Kinshasa, which control 98% of the CRB, were obtained via the HYBAM
278 Observation Service database [www.so-hybam.org] ([Table 2](#)), which compiled the data collected by
279 ORSTOM-IRD and then the Joint Waterway Maintenance Service (SCEVN). Hydrological data
280 management was carried out using the Hydraccess software [[www.mpl.ird.fr/hybam/outils/
281 hydraccess.htm](http://www.mpl.ird.fr/hybam/outils/hydraccess.htm)].

282 3.2- Methodologies used

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

288 The same procedure was applied to the flows for the entire length of the available chronicles per
289 station in order to assign them an annual hydrological index. For the Congo River in
290 Brazzaville/Kinshasa, the annual flows from 1903 to 1947 were studied, followed by daily flows from
291 1948 to 2018, and finally daily flows for both Oubangui in Bangui (1936 to 2018), Sangha in Ouessou
292 (1948 to 2018), Luabala in Kisangani (1948-1992) and Kasai in Kutu-Moke (1951 to 1992).

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

298 The first category of tests concerns the random nature of the series. In the event that the series is
299 declared non-random, a second category of tests is required to attempt to characterize the “non-
300 random” nature present in the series, such as tests relating to the detection of an *a priori* breaking

301 point at an unknown date. A break is understood to be a change in the probability law of the time
302 series at a given time, most often unknown. The statistical tests used make it possible to determine
303 whether there is a change in the behavior of a variable over time. These tests are:

- 304 - The rank correlation test [Kendall & Stuart, 1943; WMO, 1966] is a non-parametric test that
305 controls the homogeneity of a time series with the alternative assumption of a trend. The null
306 hypothesis of the test is: “the series of (x_i) , $i=1, N$, is random”.
- 307 - Pettitt's test [1979], also non-parametric, examines the existence of a break at an unknown time in
308 the series from a formulation derived from that of the Mann-Whitney test [Dagnélie, 1970]. The
309 null hypothesis of the test is the absence of a break in the series. This test is particularly sensitive
310 to a change in the mean and, if the null hypothesis of homogeneity of the series is rejected, it
311 provides an estimate of the break date.
- 312 - The non-parametric segmentation procedure of hydrometeorological series [Hubert & Carbonnel,
313 1987; Hubert et al., 1989] is adapted to the search for multiple mean changes in the series.
314 According to the authors [Hubert et al., 1989], this segmentation procedure can be considered as a
315 stationarity test but is not a rigorous test: no level of significance is assigned to this “pseudo-test”.
316 Its principle is to “divide” the series into several segments so that the average calculated on any
317 segment is significantly different from the average of the neighboring segment(s) by applying the
318 Scheffé test [Kendall & Stuart, 1943] which is based on the concept of contrast [Dagnélie, 1970].
319 If the procedure does not produce an acceptable segmentation of order greater than or equal to 2,
320 then the null hypothesis of stationarity is accepted.

321 **3- Results and discussion**

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

327 **3.1- Hydro-rainfall statistical analysis**

328 A literature review on rainfall and runoff trends in West and Central Africa shows that the 20th
329 century, the period over which most rainfall data began to be observed (the vast majority of
330 hydrological data date back to the 1950s), saw alternating dry and wet periods without any clear
331 frequency of these alternating periods. Thus, during the decades of 1910, 1970 and 1980, a high level
332 of rainfall drought (and hydrological drought when data were available) was observed. Similarly, the
333 1950s and 1960s, and in particular the latter and its early years, were very much in excess in terms of
334 rainfall and runoff. However, these temporal developments have not been spatially homogeneous.
335 Droughts recorded appear to have been more severe in West Africa, particularly from 1970 onwards,
336 with a peak during the 1980s and 1983-1984, which generally record the lowest observed rainfall and
337 annual moduli. In contrast, the 1960s were heavily rainy in Central Africa with probably flows rarely
338 observed before.

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

343 Statistical analyses of rainfall series show that between 1940 and 1999, rainfall decreased overall in
344 the Oubangui, Kasai and Congo catchment areas in Brazzaville. This trend results in a break (change
345 in the mean of the probability law of the time series at a given time) around 1970 (Figures 4(a)). The
346 1950s and 1960s are wetter but are not detected by statistical tests. Upstream of Brazzaville, the
347 Lualaba catchment area in Kisangani only feels the heavy rainfall of the early 1960s but not the
348 decrease in rainfall from 1970 onwards. On the Sangha alone, annual rainfall has hardly changed. It

349 should be noted that of all the basins analyzed, the end of the 1980s and the beginning of the 1990s
350 seem to have been relatively rainier. They partly mitigate the visual trends towards a sharp decrease in
351 rainfall since 1970.

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

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

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

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

369 By analyzing the results of the segmentation procedure, the study of the complete chronicle until the
370 end of 2018 for the Congo River in Brazzaville/Kinshasa makes it possible to qualify the previous
371 conclusions, by offering us a more distant perspective, since the sequencing evolves according to the
372 duration of the available chronicles. As a result, the persistence of the recovery in flows since 1995
373 brings back a balance between the period before the wet decade of 1960 and the one that follows it. In
374 fact, this wet decade of 1960 became the major anomaly in the river's hydraulicity over the past 116
375 years.

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

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

385 By homogeneous period, the specific flows of the Sangha and Kasai are of the same intensity for their
386 respective first periods (1948-1970 with $11.3 \text{ l s}^{-1} \text{ km}^{-2}$ and 1948-1991 with $11.5 \text{ l s}^{-1} \text{ km}^{-2}$). They
387 decreased in the same way for their second period, after their only rupture, respectively from (1971-
388 2018 with $9.0 \text{ l s}^{-1} \text{ km}^{-2}$ and (1992-2012 with $9.3 \text{ l s}^{-1} \text{ km}^{-2}$).

389 After their increase during the wet period, those of Lualaba remain intermediate to the others, with 7.8
390 $\text{ l s}^{-1} \text{ km}^{-2}$.

391 Those from Congo to Brazzaville/Kinshasa show a balance at $10.9 \text{ l s}^{-1} \text{ km}^{-2}$ on either side of the wet
392 period of the 1960s, which plays the role of pivot on the chronicle studied.

393 Of course, these specific flows include those of the Cuvette Congolaise, but also those of the Batékés
394 plateaus, which are one of the major hydrogeological singularities of this basin, which are high ($> 30 \text{ l}$

395 s⁻¹ km⁻²). This huge aquifer of more than 100,000 km² contributes to the support of the Congo's flows
396 by regularly generating about 3,000 m³s⁻¹yr⁻¹ [Laraque et al., 2009].

397 **3.2-Average hydrological regimes by periods of homogeneous flows**

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

- 400 - The **Lualaba in Kisangani** is generally characterized by two periods of flooding from
401 November to February and from April to June, separated by a level (in March) often above the
402 interannual average. The low water level is from July to October (Figure 5.a). The period of
403 homogeneous flows from 1951 to 1959 shows that the amplitude of low flows was higher and
404 the volumes of floods and low flows lower during this phase. The mean hydrograph of the
405 period of homogeneous flows from 1960 to 2012 has the same morphology as that of the
406 entire series studied.
- 407 - The **Kasai in Kutu Moke**, whose flood period extends from November to May, has a plateau
408 flood followed by a dome peak from April to May, which precedes a low water level from
409 June to November (Figure 5.b) marked by a rapid drop in flows between May and June. Mean
410 hydrographs by homogeneous flow periods show that the amplitude and duration of floods
411 decrease considerably between the two periods 1948-1991 and 1992-2012. The duration of
412 low water levels increases, the amplitude remains stable and the volume decreases during the
413 last phase of the decade 1992 - 2012.
- 414 - The **Sangha in Ouesso** (Figure 5.c), shows an intermediate regime between uni and bimodal
415 with a low water level from January to June, a small level flood from July to August and a
416 well marked main flood from September to mid-December. It can also be considered that the
417 low water level occupies about nine months from January to September with various small
418 floods in July-August that are smoothed by the average hydrographs. The volumes flowing
419 from the Sangha River decrease over time, as a result of the decrease in flood amplitude and
420 the increase in the duration of low water levels. From 1971 to 2018, the secondary flood is
421 replaced by a plateau; consequently, the low water level becomes more intense and longer.
422 The volumes of low water levels are decreasing much faster than those of floods.
- 423 - The annual flooding of the **Oubangui River in Bangui** (Figure 5.d) begins in mid-July and ends
424 in mid-December. The low water level occupies the rest of the year and lasts seven months.
425 The volumes flowing from the Oubangui fell by almost half from 1936 to 2018. This is due
426 rather to the decrease in amplitude because flood and low-water levels tend to remain stable,
427 except for the current dry phase from 1982 to the present day, which sees the duration of low-
428 water levels increase and that of high-water levels decrease. According to the homogeneous
429 period hydrographs of the Oubangui in Bangui in Figure 5.d, the amplitude ratios over both
430 flood and low water duration decrease over the period 1936-2018.
- 431 - The **Congo in Brazzaville/Kinshasa** (Figure 5.e), has a bimodal regime with its main flood,
432 which generally begins in October and ends in February. Then begins a large low water level
433 that ends in October. During this low water level a secondary flood appears with its slightly
434 rounded peak in May. Since 1970, it has been under the interannual module calculated since
435 1903. The amplitude of the Congo's floods tends to increase while their duration decreases,
436 but their volumes remain stable. On the other hand, the volumes flowing from low water
437 levels tend to decrease while their duration increases and their amplitudes remain stable. Mean
438 hydrographs per homogeneous flow period show that during the wet phase from 1960 to 1970
439 the secondary flood far exceeded the interannual module.

440
441 This hydrograph is not simply a transposition of the climate regime, as hydrological
442 mechanisms assign a completely different origin to the high waters observed in
443 Brazzaville/Kinshasa. These come from soil precipitation watering, during the boreal summer,
444 the northern part of the basin drained mainly by the Oubangui and Sangha, and during the
445 southern summer, the southern part tributary of the Lualaba and Upper Kasai. Given the time
446 it takes for the high water in one or the other part of the basin to reach the downstream, this
447 regime actually depends on two floods of different geographical origins, superimposed on the
448 more regular contributions from the equatorial strip [Bricquet, 1993].

449
450 If by chance this mechanism is disrupted (rains falling early or late compared to their usual
451 schedule) in any part of the basin, normally out of phase inflows will then combine when they
452 arrive in the main collector, both upward and downward in flow. The case of the 1960s of the
453 highest flows corresponds to this type of conjunction of flood inflows from different sources.

454 Finally, the differential study of these hydrological chronicles makes it possible to deduce the
455 hydrological regime of the Cuvette Centrale (Figure 6). The latter, which is not measured *in situ*,
456 contributes to the design of the river in Brazzaville/Kinshasa.

457 Finally, Figure 7 from Alsdorf et al, [2016], shows the outline of the flooded Cuvette (in black) in the
458 heart of the Cuvette Centrale.

459 **Conclusion**

460 This large-scale work on a scale of the entire Congo Basin is the first of its kind, to compare hydro-
461 rainfall behavior, both in the left and right bank basins of the river, on multi-decadal chronicles dating
462 back to the beginning of the observations.

463 In the absence of a truly operational supranational entity, it is still difficult and risky to compile such
464 data in real time for the entire basin. This is an aberration at a time when remote sensing is freeing
465 itself from national borders and fears. This work is nevertheless a first step towards IWRM and allows
466 a renewed and more complete vision of the hydro-pluviometric functioning of the Congo Basin.

467 It highlights the famous hydro-climatic rupture of 1970 that affected West and Central Africa. This
468 rupture affected the tributaries on the right bank of the Congo and was also felt at the main twin
469 stations of Brazzaville/Kinshasa. But it does not affect the entire Congo Basin. The wet decade of
470 1960 remains the major hydrological anomaly of the river for the past 116 years. However, in view of
471 the great regularity of its flows, the apparent hydrological inertia of the river at its outlet masks
472 significant spatial and temporal heterogeneities, which must be taken into account in any development
473 project. The main floods of the Congo River at the outlet come from soil precipitation, which in the
474 boreal summer waters the northern part of the basin drained mainly by the Oubangui and Upper
475 Sangha, and in the southern summer waters the southern part of the Lualaba and Upper Kasai. Given
476 the time it takes for the high water in one or other part of the basin to reach the downstream, this
477 regime actually depends on two floods of different geographical origins, superimposed on the more
478 regular contributions from the equatorial strip.

479 At the basin scale, flow variations are indeed higher than those of rainfall. But it is above all, the
480 Oubangui basin that is the most sensitive and affected by climate change, with flows declining since
481 1970. This poses a problem for inland navigation, whose annual duration is reduced because of a
482 longer period of low water, whereas it is the preferred route for the exchange of both people and
483 goods between the countries of the basin. Similarly, attention to changes in water conditions is crucial
484 at a time when we are once again talking about linking the Congo Basin to the Chari Basin through a
485 canal to compensate for the water deficit in Lake Chad.

486 Finally, current hydro-climatic changes are leading to a revision of hydrological standards in West
487 and Central Africa, which have been established on the basis of concepts of flow stationarity.

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

497 This work also highlights the opposition of hydro-rainfall phases between the northern and southern

498 sub-basins.

499 Finally, a first approach to the Central Basin regime is proposed. It is in agreement with other indirect
500 approaches such as those of spatial altimetry [Alsdorf et al., 2016; Becker et al., 2014; Lee et al.,
501 2014; Kim et al., 2017; Becker et al., 2018, ...] and modelling [BRLi, 2016; Tshimanga et al., 2011;
502 Tshimanga et al., 2012; Tshimanga, & Hughes, 2014].

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

507 By homogeneous period, the specific flows of the Sangha and Kasai are of the same intensity. They
508 decreased in the same way, after their only break-up, in 1970 and 1991 respectively.

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

511 Those from Congo to Brazzaville/Kinshasa show a balance at $10.8 \text{ l s}^{-1} \text{ km}^{-2}$ on either side of the wet
512 period of the 1960s, which plays the role of pivot on the chronicle studied.

513 Of course, these specific flows include those of the Cuvette Congolaise, but also those of the Batékés
514 plateaus, which are high ($> 30 \text{ l s}^{-1} \text{ km}^{-2}$) and constitute a major hydro-rainfall paradox of this basin
515 and cover more than a hundred thousand km^2 . This huge aquifer contributes to sustaining Congo's
516 flows by reducing the contrasting rainfall regime it receives [Laraque et al., 1998a].

517 **Glossary of terms**

518 AUF : Agence Universitaire de la Francophonie
519 BRLi : Bas Rhône Languedoc Ingénierie
520 BZV/KIN : Brazzaville/Kinshasa
521 CICOS : International Commission for the Congo-Oubangui-Sangha Basin
522 CNRS : National Centre for Scientific Research
523 CRB : Congo River Basin
524 ECHOBACO : Ultrasound of the Congo Basin
525 GET/UPS : Geosciences Environment Toulouse/Université Paul Sabatier
526 IWRM : Integrated Water Resources Management
527 IRD : Research Institute for Development
528 ORSTOM : Office de Recherche Scientifique d'Outre-mer
529 RVF : Régie des Voies Fluviales
530 SCEVN : Joint Waterway Maintenance Service
531 SO-HYBAM : Service d'Observation des contrôles géodynamique, hydrologique et
532 bioogéochimique de l'érosion/altération des transferts de matières dans les bassins de
533 l'Amazone, de l'Orinoque et du Congo
534 UMNG : Marien N'gouabi University
535 UNIKIN : University of Kinshasa

537 **En Français**

538 AUF : Agence Universitaire de la Francophonie
539 BRLi : Bas Rhône Languedoc Ingénierie
540 BZV/KIN : Brazzaville/Kinshasa
541 CICOS : Commission Internationale du Bassin Congo-Oubangui-Sangha
542 CNRS : Centre National pour la Recherche Scientifique
543 CRB : Congo River Basin
544 ECHOBACO : Echographie du Bassin du Congo
545 GET/UPS : Géosciences Environnement Toulouse/Université Paul Sabatier
546 GIRE : Gestion Intégrée des Ressource en Eau
547 IRD : Institut de Recherche pour le Développement
548 ORSTOM : Office de Recherche Scientifique d'Outre-mer

549 RVF : Régie des Voies Fluviales
550 SCEVN : Service Commun d'Entretien des Voies Navigable
551 SO-HYBAM : Service d'Observation des contrôles géodynamique, hydrologique et
552 biogéochimique de l'érosion/altération des transferts de matières dans les bassins de
553 l'Amazone, de l'Orinoque et du Congo
554 UMNG : Université Marien N'gouabi
555 UNIKIN : Université de Kinshasa

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