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Study of the Impact of Climate Change on Water Resources in the Sangha Watershed at Ouesso Hydrological Station, Republic of the Congo-Brazzaville (1961-2020)

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Abstract

The Sangha River basin is the largest sub-basin of the Congo River basin, which drains the northern part of the Republic of the Congo-Brazzaville. It is the most important economic zone in this part of the country, with a strong timber industry, agriculture and hydroelectricity. The catchment also boasts the country's third-largest river port, located in the town of Ouesso. Unfortunately, increasingly frequent low-water levels in recent years have led to a decline in river navigation and economic activities. So, the aim of this study is to show the effects of climate change over the last six decades in the Sangha watershed at Ouesso hydrological station, located in the north of the Republic of the Congo-Brazzaville, and elucidate its impact on water resources. To achieve this, several statistical and hydrological methods were used. The application of change-point or shift detection tests to flow series from 1961 to 2020 revealed variability in the hydrological cycle, characterized by two major phases of homogeneous flows: a wet surplus phase and a dry deficit phase. The results show one shift in flood flows in 1971 (Buishand test), one shift in yearly average flows or modules in 1971 (Pettitt test and Buishand test), and one shift in low-water flows in 1976, with all two tests. These disruptions were accompanied by a drop in flow of around 15.63%, 21.70% and 35.67%, on average, for floods, modules, and low-water, respectively, a drop in rainfall of around 9.6% and a rise in temperature of around 0.76˚C. These flows show an overall downward trend. The calculated recession coefficients show that, over the entire study period, a recession occurred in March 1985.

Keywords

Sangha Watershed, Republic of the Congo, Pettitt Test, Buishand Test, Change-Point, Recession Coefficient

1. Introduction

The Sangha watershed plays a key socio-economic role in the Central African sub-region in general, and in the Republic of the Congo-Brazzaville in particular. In addition to its considerable water resources, the basin's favorable geographical location makes it an essential link in the communication routes of the Central African sub-region. The Sangha watershed is a major source of revenue to the national budget, thanks to intensive logging and the transport of timber by river. Given the vulnerability of local economic resources to climate variability, the evolution of water resources is becoming a concern for many localities in the Republic of the Congo-Brazzaville, and more particularly for the Sangha area in Ouesso. It is, therefore, important to understand and control the functioning of this watershed.

Studies into the impact of climate change on water resources have caught the interest of the international scientific community following several major climatic events, including the drought that has affected the planet's intertropical zone since the 1970s [1]. This drought is the result of reduced rainfall, one of the consequences of which has been a drop in the flow rates of major African rivers and their main tributaries in recent decades [2] [3].

In the Sangha watershed at Ouesso hydrological station, a change-point was detected in the time series of average flows over the period 1953-2010. This occurred in 1970, separating a wet phase (1953 to 1970) from a dry phase (1971 to 2010) [3]. Other authors have clearly highlighted a major climatic shift in 1970, corresponding to a significant shift in the hydrological series [4] [5] [6]. From that date onwards, the Sangha watershed aquifer would no longer be able to maintain the flow regime of the Sangha River at Ouesso without passing on the annual rainfall deficit.

This article revisits the interannual variability of flows in the Sangha River at Ouesso station, based on discharges recorded over the last six decades (1961 to 2020). In the flow sequence, particular attention will be paid on analyzing the multiannual evolution of recession to discuss the current response of the Sangha basin aquifer.

2. Presentation of the Study Area

The study area is the Sangha watershed, located between latitudes 1˚37' and 6˚40' North and longitudes 11˚51' and 16˚44' East (**Figure 1**).

This watershed covers three countries: Congo-Brazzaville, Cameroon and Central Africa, with a total surface area of 213,670 km^2 [7]. The Sangha hydrological

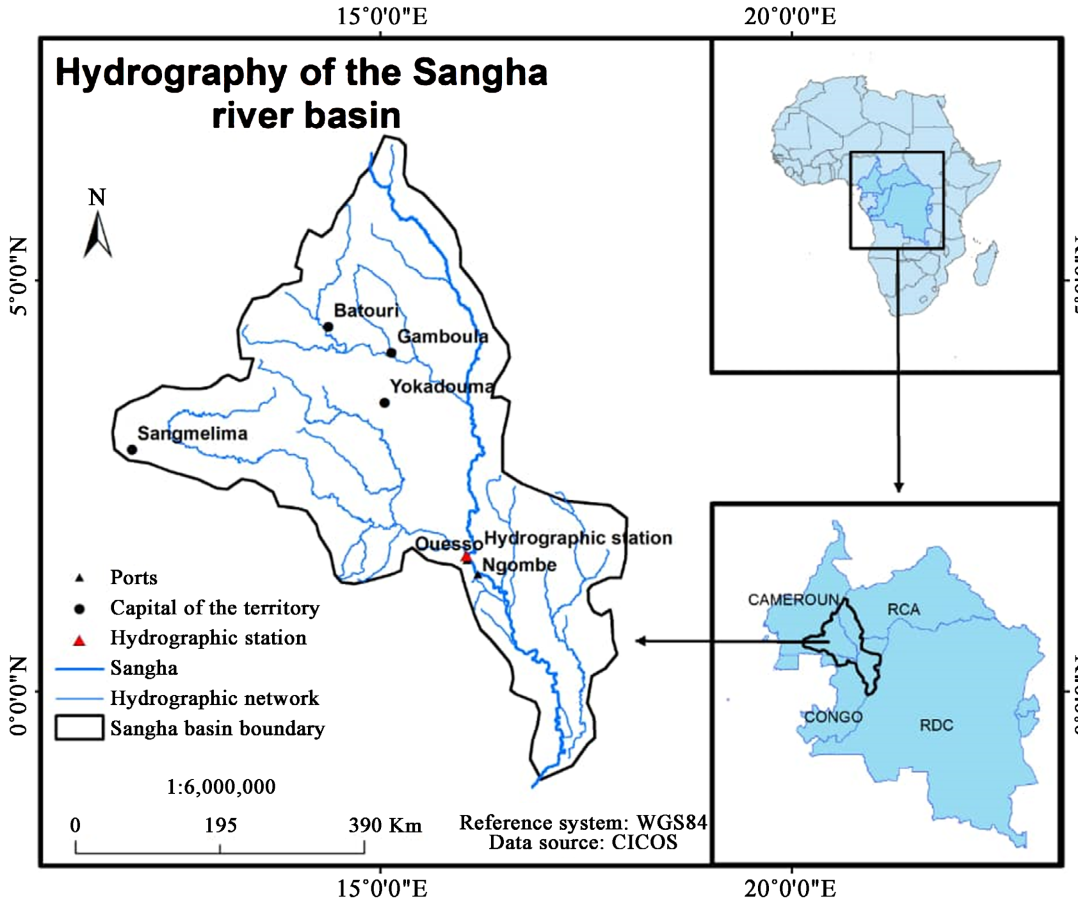

Figure 1. Location of the Sangha watershed and Ouesso hydrological station.

station at Ouesso, one of the stations in the watershed, covers an area of 159,480 km^2 [8]. The Sangha River drains 781 km from its source to its outlet on the Congo River. If one considers that Kadei is the upper branch of the Sangha River, the river has a total length of 1333 km and is the second main right-bank tributary of the Congo River after Oubangui River [9]. The Congo River is the longest river in Africa after the Nil, and the largest river in Africa in terms of water discharge and basin size (respectively 40,500 m^3/s and 3.7×10^6 km^2), second only to the Amazon River at the global level [10] [11]. The Dja is the main tributary of the Sangha River [9].

The climate of the watershed is equatorial, with rainfall ranging from 2000 to 2300 mm per year [8]. The average temperature is around 24.7˚C. The seasonal irregularity coefficient (K3 = 1.13) places the study area in a humid tropical regime [12]. The hydrological potential of the basin shows an interannual yearly average flow or module of 1534.0 m^3/s for a major flood of 4748.0 m^3/s and a minor low-water of 298.1 m^3/s during the study period (1961 to 2020).

The watershed's vegetation is mainly covered by dense, humid equatorial forest, except in the northern part, which is covered by wooded savannah [7].

Upstream of Ouesso station, the geology of the study area is essentially made up of a precambrian shale-quartzite complex with intrusions of various types (intrusive dolerites, tillite complexes, etc.). Downstream, the rocks present are the quaternary alluvium of the Congolese Cuvette [9]. Soils in the study area are ferralitic [9].

3. Data and Methods

3.1. Data of Study

The hydrological data used in this study are flows. They come from the database of the Groupement d'Intérêt Economique pour le Service Commun d'Entretien des Voies Navigables (GIE-SCEVN) Congo-République Centrafricaine (RCA). Hydrometric measurements began in 1948 on the Sangha River [13] and 1911 on the Congo River [14]. Climatic data are rainfall and temperature (average). They come from the database of the Meteorological Department of the National Civil Aviation Agency (ANAC) of the Republic of the Congo-Brazzaville. These data cover a 60-year period (1961-2020), with monthly time steps.

3.2. Methods

3.2.1. Gap Filling in Time Series

The gaps in the time series were filled using a suitable criterion to complete the missing data and provide a continuous monthly base. This is the coefficient of variation (C_V). It is defined as the ratio of the standard deviation of a variable to its mean, and is given by the relationship:

$$C_V = \frac{\sigma_X}{\overline{X}} \tag{1}$$

where σ_X is the standard deviation and $\overline{X}$ is the arithmetic mean of the series $X = (x_i)$.

When the coefficient of variation is less than 20%, the missing data for each month of the year are supplemented by the average of the available values. This assignment is made because of the low dispersion between the observed data [15]. On the other hand, for variables with a coefficient of variation greater than 20%, reflecting high variability, missing values are supplemented by the median, which is more robust than the mean. Indeed, when dispersion is very wide, the mean is an indicator biased by extreme values.

3.2.2. Tests for Change-Point or Shift Detection of Time Series

A change-point or shift in the central tendency of a time series can be defined by a change in the probability distribution of the random variables whose successive realizations define the time series under study [16].

XLSTAT software was used to detect shifts in the flow rate time series. Its various statistical tests enable us to determine whether there has been a change in the behavior of a variable over time. Changes are highlighted by a shift isolating two homogeneous flow periods. These tests are Pettitt test and Buishand test.

1) Pettitt test

Pettitt's approach is non-parametric and derives from the Mann-Whitney test.

A non-parametric test focuses on the overall distribution of data, without any hypothesis about their distribution (free distribution). The absence of a shift in the series (x_i) of size N is the Null hypothesis H_0 (no shift or no change), it is tested against the Alternative hypothesis H_1 (presence of shift or change) [17].

The test assumes that for any time between 1 and N the time series (x_i), $i = 1$ at t; $j = t + 1$ at N belong to the same population. The variable to be tested is the maximum absolute value of the variable U_t, defined by Equation (2):

$$U_{t,N} = \sum_{i=1}^{t} \sum_{j=t+1}^{N} D_{ij} \tag{2}$$

where $D_{ij} = \text{sgn}(x_i - x_j)$, with $\text{sgn}(x) = 1$ if $x > 0$; $\text{sgn}(x) = 0$ if $x = 0$; $\text{sgn}(x) = -1$ if $x < 0$.

If the H_0-hypothesis is rejected, an estimate of the shift date is given at this point, defining the absolute maximum of the variable U_t.

2) Buishand test

The Buishand test (1982) can be used on variables with any distributions (case of the U statistic). However, its properties have been particularly studied for the case of normal distribution (case of the V statistics).

In the Buishand approach, the U statistic is defined by [18] [19]:

$$U = \frac{1}{N(N+1)} \sum_{k=1}^{n-1} \left(\frac{S_k}{D_x} \right)^2 \tag{3}$$

with

$$S_k = \sum_{i=1}^{k} \left(X_i - \bar{X} \right) \tag{4}$$

where $k = 1, \cdots, n$ and D_x is the standard deviation of the time series.

The Buishand statistic U assumes a series of random variables $X_1, X_2, \cdots, X_n$ based on the following model:

$$X_i = \begin{cases} \mu + \mathcal{E}_i, i = 1, 2, \cdots, \tau \\ \mu + \delta + \mathcal{E}_i, i = \tau + 1, \cdots, n \end{cases} \tag{5}$$

The $\mathcal{E}_i$ is independent and has normal distribution, with mean value of zero and variance σ^2. The variables τ, δ and σ correspond to unknown parameters verifying:

$$1 \le \tau \le n-1, -\infty < \mu < +\infty, -\infty < \delta < +\infty, \sigma > 0 \tag{6}$$

The possible change (in position and amplitude) corresponds to the mode of the a posteriori distribution of τ (position of the shift in time) and δ (the amplitude of the change in comparison with the mean).

3.2.3. Mann Kendall Trend Test

The non-parametric Mann-Kendall test [20] [21] is recommended for identifying series trends. It is used to study the presence or absence of trend in a given time series. The Mann-Kendall test is based on the S statistic defined as follows [22]:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}\left(x_j - x_i\right) \tag{7}$$

where S is the relationship between the number of pairs of observations, n is the total number of samples and x_j represents the sequential data values:

$$\operatorname{sgn}\left(x_j - x_i\right) = \begin{cases} 1, & \text{si } \left(x_j - x_i\right) > 0 \\ 0, & \text{si } \left(x_j - x_i\right) = 0 \\ -1, & \text{si } \left(x_j - x_i\right) < 0 \end{cases} \tag{8}$$

Mann (1945) and Kendall (1975) showed that when $n \geq 8$, the statistic S has approximately a normal distribution with mean $E(S)$ and variance $Var(S)$ as follows:

$$E(S) = 0 \tag{9}$$

and

$$Var(S) = \frac{1}{18}\left[n(n+1)(2n+5) - \sum_{i=1}^{m} t_i\left(t_i - 1\right)\left(2t_i + 5\right)\right] \tag{10}$$

where n is the amount of data in the series, m is the number of linked groups and t_i is the amount of data in group of order i. The standard multivariate normal Z_{MK} is calculated as follows:

$$Z_{MK} = \begin{cases} \dfrac{S-1}{\sqrt{Var(S)}}, & \text{si } S > 0 \\ 0, & \text{si } S = 0 \\ \dfrac{S+1}{\sqrt{Var(S)}}, & \text{si } S < 0 \end{cases} \tag{11}$$

The Null hypothesis H_0 (absence of trend) is rejected when the significance level or p-value is greater than 5%. When H_0 is accepted, the slope of the trend or Sen's slope is estimated by Sen's method, where the slope is the median of all slopes calculated between each pair of points. The robustness of the test has been validated by several comparison tests [22].

3.2.4. Hydrological Deficit

The deficit of the dry period, compared to the wet period, is evaluated by applying the formula represented by Equation (12):

$$D = \frac{X_i - X_j}{X_i} \cdot 100 \tag{12}$$

with D: hydrological deficit; X_i mean before shift in the time series; X_j average after shift in the time series.

In this study, deficits were calculated using the Pettitt test. If there is no shift in a time series, the deficit is calculated in relation to the periods before and after 1970.

3.2.5. Recession Coefficient

In the absence of rainfall, a river is fed by the groundwater in its catchment area.

As a result, the volume of water released by this regulating reserve during the period of emptying under uninfluenced conditions is referred to as the recession phase. Through this relationship between surface water and groundwater, it has proved important to understand the evolution of groundwater reserves during climatic variations [1]. The variability of the recession coefficient and the volume of water mobilized by aquifers help to highlight this evolution [20]. The mathematical expression of recession is given by Equation (13):

$$Q_t = Q_0 \mathrm{e}^{-kt} \tag{13}$$

Taking the natural logarithm in the right hand side and in the left hand side, one obtains Equation (14):

$$k = -\frac{1}{t}\ln\left[\frac{Q_t}{Q_0}\right] \tag{14}$$

with Q_t: flow at time t (m^3/s); Q_0: flow at the start of recession (m^3/s); k: recession coefficient (s^{-1}) and t: elapsed or release time (s).

3.2.6. Change Detection in Time Series: Student's Test

This test is a classic test initially designed to compare two series and check whether they belong to the same data. As part of a stationarity study, this test can be used if the date of presumed shift is known. In this case, the series is subdivided into two sub-series (on both sides of this date), which are compared using this test.

- **Conditions for applying the test**

Data must have normal distribution and be independent. The variances of the two samples are assumed to be equal. This assumption can be verified using a test for equality of two variances.

- **Notations**

Let m_1 and m_2 be the theoretical averages of the two subgroups and X_1 and X_2 their arithmetic means. The two subgroups contain n_1 and n_2 values. σ_1 and σ_2 denote the theoretical standard deviations of the two samples (assumed to be equal) and S_1 and S_2 are their estimators:

$$\begin{cases} S_1 = \dfrac{1}{n_1 - 1}\displaystyle\sum_{i=1}^{t}\left(x_1 - \bar{X}_1\right)^2 \\ S_2 = \dfrac{1}{n_2 - 1}\displaystyle\sum_{i=1}^{t}\left(x_1 - \bar{X}_2\right)^2 \end{cases} \tag{15}$$

The common variance of both samples S^2 is calculated by:

$$S^2 = \frac{(n_1 - 1)S_1^2 + (n_2 - 1)S_2^2}{n_1 + n_2 - 2} \tag{16}$$

- **Assumptions**

$$\begin{cases} \mathrm{H}_0 : m_1 = m_2 \\ \mathrm{H}_1 : m_1 \neq m_2, \text{bilateral test} \\ \mathrm{H}_1 : m_1 > m_2, \text{unilateral test} \end{cases} \tag{17}$$

- **Statistic of test**

Under the assumption H_0 equality of averages, the quantity:

$$t = \frac{\bar{X}_1 - \bar{X}_2}{S} \cdot \left[\frac{1}{n_1} + \frac{1}{n_2} \right]^{-1/2} \tag{18}$$

is a t student variable with ($n_1 + n_2 - 2$) degrees of freedom.

4. Results and Discussion

4.1. Results

4.1.1. Results of Shift Detection Tests on Sangha Flow Series at Ouesso (1962-2020)

The results of the various detection tests of shifts (Pettitt and Buishand) applied to the annual flow series (floods, yearly average flows or modules, and low-water) are presented in Table 1 and Table 2.

Here, mu1 is the average before shift; mu2 the average after shift and D the hydrological deficit.

1) Results of Pettitt test

The p-values calculated on the annual flows (module and low flow) of the Sangha River at Ouesso station using the Pettitt test are below the significance level (α = 0.05), so the null hypothesis H_0 (absence of shift) is rejected. The

Table 1. Variables for detection tests of shifts on flows (m^3/s) on the Sangha River at Ouesso station (1961-2020).

Test	Test Variables	Floods	Modules	Low-water
	t	1970	1971	1976
Pettitt	p-value (bilaterale)	0.047	0.004	<0.0001
	alpha	0.05	0.05	0.05
	t	1971	1971	1976
Buishand	p-value (bilatérale)	0.035	0.000	<0.0001
	alpha	0.05	0.05	0.05

Table 2. Deficits between wet and dry periods on Sangha River flows at Ouesso station from 1961 to 2020.

Test	Parameter	Floods	Modules	Low-water
	mu1 (m^3/s)	3660	1834	872
Pettitt	mu2 (m^3/s)	3051	1436	561
	D (%)	16.64	21.70	35.67
	mu1 (m^3/s)	3614	1834	872
Buishand	mu2 (m^3/s)	3049	1436	561
	D (%)	15.63	21.70	35.67
D (means)		**16.64**	**21.70**	**35.67**

alternative hypothesis H_1 (presence of a shift date) is retained. The shift date is 1970 for floods, 1971 for modules and 1976 for low-water (**Table 1**).

The search of changes in the flow series of the Sangha River at Ouesso station shows the existence of two homogeneous flow periods: 1) a surplus period, known as the wet period, running from 1961 to 1070/1971 for floods, 1961 to 1971 for modules and from 1961 to 1976 for low-water, corresponding to an increase in flows; 2) a deficit period, known as the dry period, running from 1971/1972 to 2020 for floods, 1972 to 2020 for modules and from 1977 to 2020 for low-water, corresponding to a decrease in flows. The wet period evolves around the averages 3660 m^3/s for floods, 1859 m^3/s for modules and 871.938 m^3/s for low-water; and the dry period evolves around the averages 3051 m^3/s for floods, 1439 m^3/s for modules and 560.757 m^3/s for low-water (**Figure 2**). The deficits between the wet and dry periods are 16.64% for floods, 21.70% for modules and 35.67% for low-water, respectively. Annual maximum flows, on the other hand, do not show shift during the study period.

2) Results of Buishand test

The p-values calculated on the annual flows (modules, floods, and low-water) of the Sangha River at Ouesso station using the Buishand test are below the significance level ($\alpha = 0.05$), so the Null hypothesis H_0 (absence of shift) is rejected. The Alternative hypothesis H_1 (presence of a date showing a shift) is retained. This date is 1971 for modules and floods, and 1976 for low-water (**Table 1**). The search of changes in the flow series of the Sangha River at Ouesso station shows the existence of two homogeneous flow periods: 1) a surplus period, known as the wet period, running from 1961 to 1971 for modules and floods, and from 1961 to 1976 for low-water, corresponding to an increase in flows; 2) a deficit period, known as the dry period, running from 1972 to 2020 for modules and floods, and from 1977 to 2020 for low-water, corresponding to a decrease in flows. The wet period evolves around the averages 1834 m^3/s for modules; 3614 m^3/s for floods and 871.938 m^3/s for low-water and the dry period evolves around the averages 1436 m^3/s for modules, 3049 m^3/s for floods and 560.757 m^3/s for low-water) (**Figure 3**). The deficits between the wet and dry periods are 21.70% for modules, 15.63% for floods and 35.67% for low-water, respectively.

4.1.2. Results of the Mann-Kendall Trend Test

The results of the Mann-Kendall trend test are shown in **Table 3** and illustrated in **Figure 4**. These results show a significant downward trend in flow rates for both modules and low-water levels (**Figure 4**) from the 1970 onwards, more specifically between 1970 and 1971 for modules, and in 1976 for low-water levels. This drop in flow is more seen for low-water levels. Floods, on the other hand, show a no insignificant trend.

4.1.3. Results of Recession Coefficient for the Sangha River at Ouesso Station (1961-2020)

To elucidate the impacts of climate change on water resources in the Sangha basin at Ouesso, the recession coefficients are determined at both monthly and annual time scale over the study period (1961-2020). Over this period, one will track changes in the recession coefficient over the 1961-1990 and 1991-2020 sub-periods, and then over the entire study period. The results of the calculations are

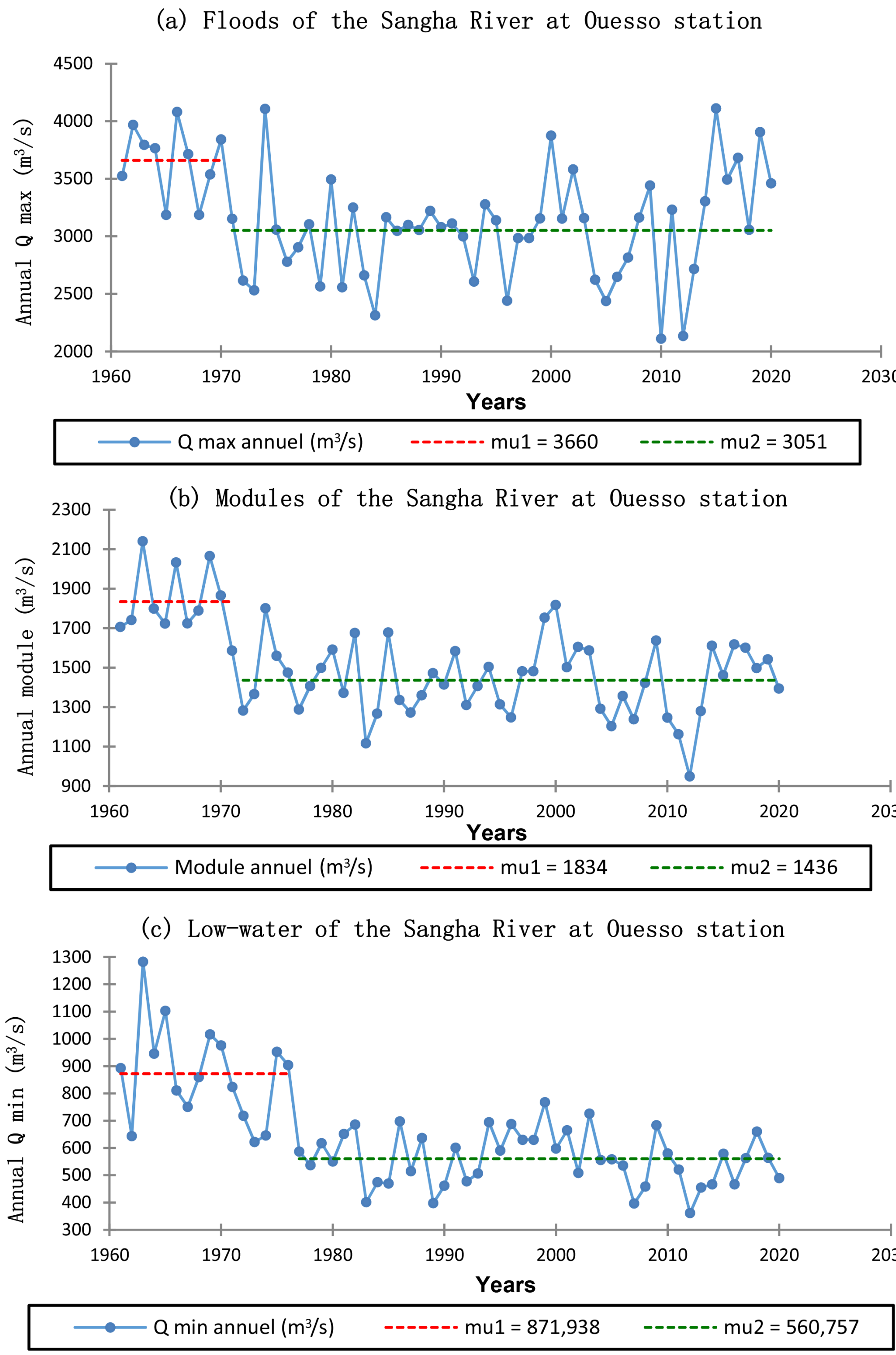

Figure 2. Detection of shifts in annual flow series using the Pettitt test from 1961 to 2020: (a) Floods, (b) Modules, and (c) Low-water.

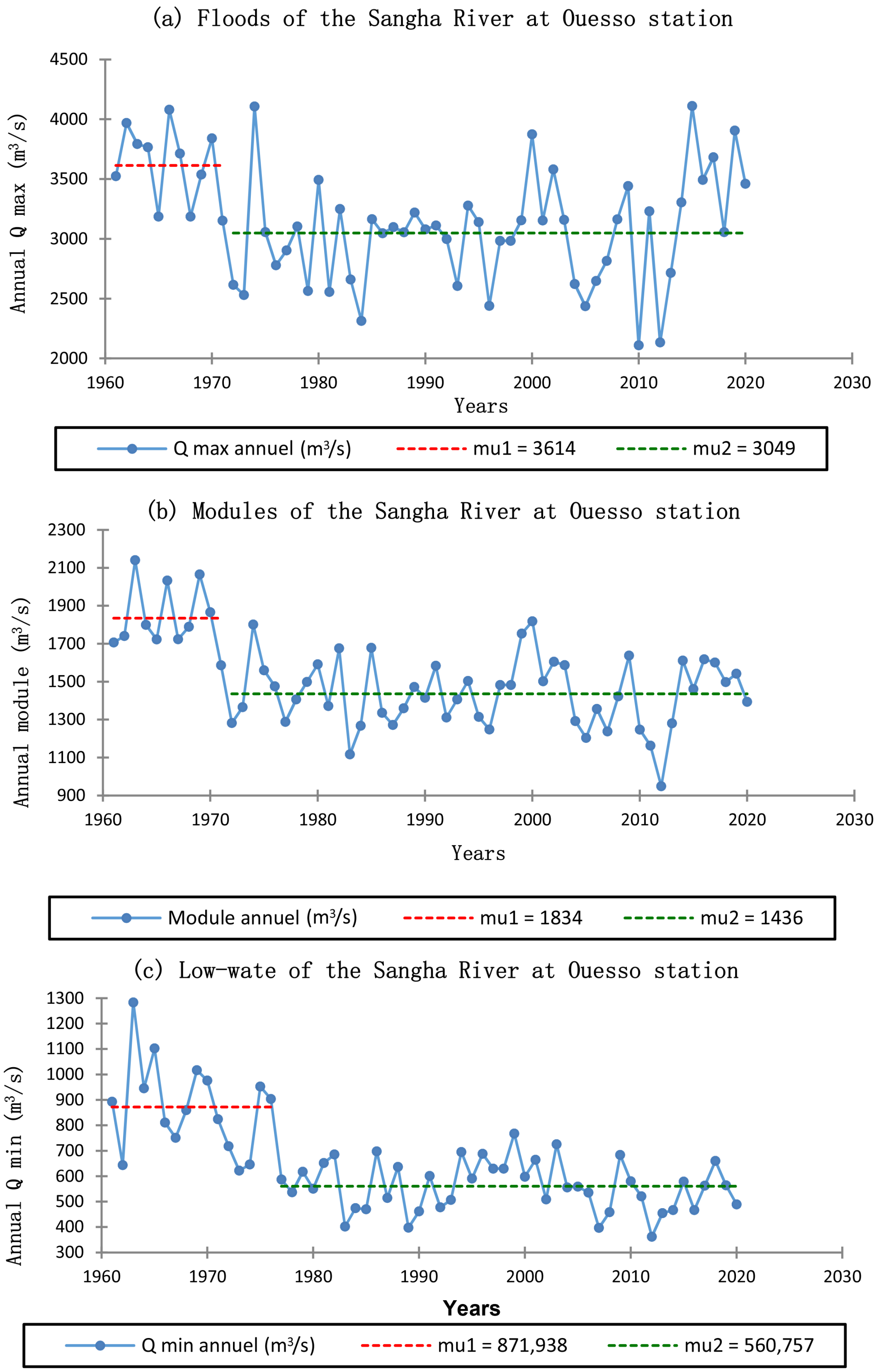

Figure 3. Detection of shifts in annual flow series using the Buishand test from 1961 to 2020: (a) Floods, (b) Modules, and (c) Low-water.

Table 3. Trends in annual flow series of the Sangha River at Ouesso station from 1961 to 2020.

Variable	Floods	Modules	Low-water
Kendall rate	−0.087	−0.268	−0.421
Probability (p-value)	0.329	0.003	<0.0001
Significance α (at 5% threshold)	Not significant	Significant	Significant
Decision	Since the calculated p-value is above the significance level $\alpha = 0.05$, the Null hypothesis H_0 can not be rejected. In other words, there is no trend in the series.	Since the calculated p-value is below the significance level $\alpha = 0.05$, one must reject the Null hypothesis H_0 and accept the Alternative hypothesis H_1. In other words, there's a trend in the series.	Since the calculated p-value is below the significance level $\alpha = 0.05$, one must reject the Null hypothesis H_0 and accept the Alternative hypothesis H_1. In other words, there's a trend in the series.

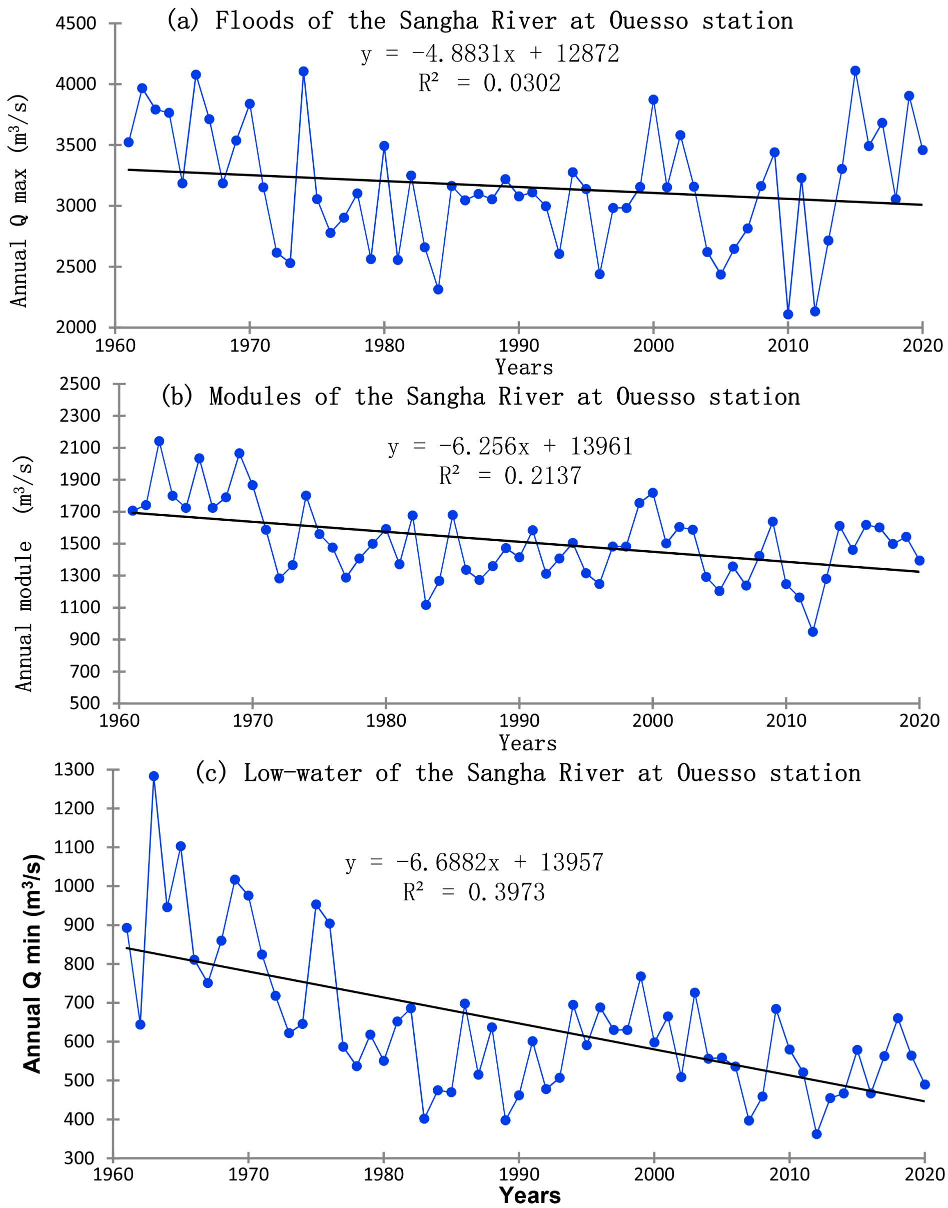

Figure 4. Trend curves of annual flow of the Sangha River at Ouesso station from 1961 to 2020: (a) Floods, (b) Modules, and (c) Low-water.

represented graphically (**Table 4**, **Figure 5** and **Figure 6**) to highlight the changes in the discharge of the basin's aquifers. This recession phenomenon did not occur in the same month throughout the two sub-periods: it occurred in March for the 1961-1990 sub-period and in April for the 1991-2020 sub-period. Over the entire study period (1961-2020), this recession corresponds to that observed during the 1961-1990 sub-period, when recession took place in March (**Figure 5** and **Table 4**).

On the other hand, at the annual time scale, recession occurred in 1985 and 2007 for the 1961-1990 and 1991-2020 sub-periods, respectively. However, over the entire study period (1961-2020), recession occurred in 1985 (**Figure 6**). The years 1985 and 2007 correspond to severe drought years in the Sangha basin at Ouesso. Similarly, the year 2011, close to recession, corresponds to the period when the basin experienced very severe low-water levels.

Table 4. Monthly recession coefficients (10^{-8}/s) of the Sangha River at Ouesso station from 1961 to 2020.

Period	1961-1990	1991-2020	1961-2020
January	16.41	10.44	13.06
February	8.56	1.39	4.28
March	0.00	2.06	0.00
April	2.70	0.00	2.70
May	13.44	5.49	8.10
June	29.83	23.15	25.85
July	34.54	20.68	23.29
August	26.02	17.52	20.14
September	31.38	31.59	31.38
October	59.65	58.21	59.65
November	67.10	51.76	54.46
December	39.31	26.26	28.87

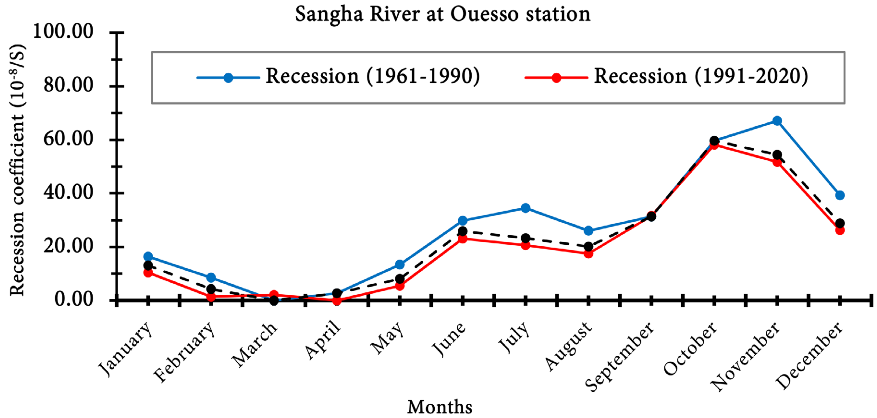

Figure 5. Monthly recession curves for the Sangha River at Ouesso station (1961-2020).

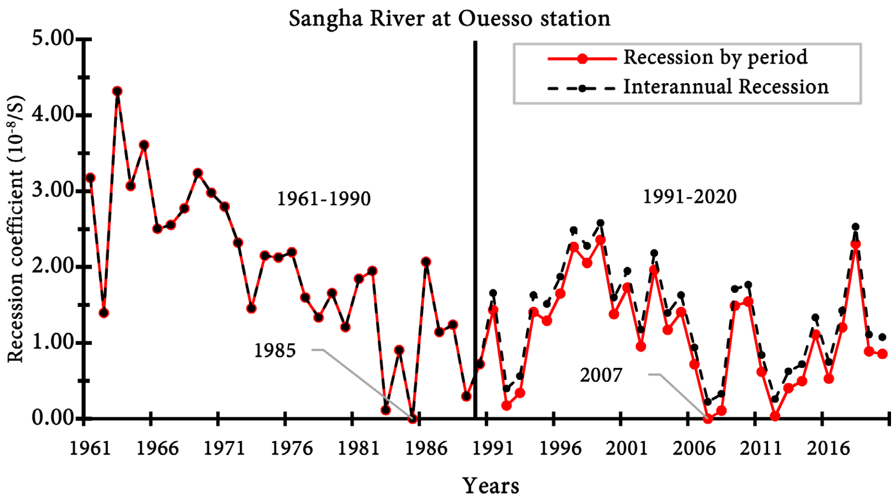

Figure 6. Annual recession curves for the Sangha River at Ouesso station (1961-2020).

4.1.4. Observed Changes in Flows of the Sangha River at Ouesso Station (1961-2020)

The results obtained from calculations of changes in Sangha River flows at Ouesso station from 1961 to 2020 are presented in **Table 5** and illustrated graphically in **Figure 7**. Trends in flood flows on the Sangha River at Ouesso station over the periods 1961-1970 and 1971-2020 show that these have been declining since 1970. This date reflects a change in flood flows. This decrease is most significant during the rainy season (September, October, and November). However, flood flows gradually increase from December to August. Similarly, trends in the modules of the Sangha River at Ouesso station over the periods 1961-1971 and 1972-2020 show that it has been declining since 1971.

These modules show a similar pattern to that of floods. In addition, low-water trends over the periods 1961-1976 and 1977-2020 show that low-water have been declining since 1976, the year in which the hydrological behavior of the Sangha River at Ouesso station changed. The decline is most observed in October. Flows gradually increase from November to September, where they reach their peak.

The changes observed in these flows (flood, modules and low-water) reflect the growing impact of climate variability on water resources in the Sangha watershed at Ouesso.

4.2. Discussion of Results

This study of the evolution of the hydrological regime of the Sangha River at Ouesso station (1961-2020) reveals the emergence of a change in the behavior of this hydrological regime.

Statistical tests for shift detection (Pettitt and Buishand) on the flow series of the Sangha River at Ouesso station, using XLSTAT software, gave the following results:

- Two shifts in flood flows in1970 and 1971, which makes it possible to isolate three homogeneous flow periods that follow one another over the course of the study period: a so-called surplus wet period (1961-1970), a transition period

Table 5. Results of calculations of observed changes (m^3/s) of Sangha River at Ouesso station.

Period	Floods			
	Average	mu1	mu2	Modification
January	1233.8	1599.2	1160.7	−438.5
February	846.5	1180.1	779.8	−400.3
March	844.4	1233.1	766.6	−466.5
April	1037.5	1439.3	957.1	−482.2
May	1333.8	1666.8	1267.2	−399.6
June	1492.2	1822.5	1426.1	−396.4
July	1613.1	1963.2	1543.1	−420.1
August	1735.1	2013.8	1679.3	−334.5
September	2580.7	2934.7	2510.0	−424.7
October	3396.9	3881.4	3300.0	−581.4
November	3514.2	4042.1	3408.6	−633.5
December	2372.8	2727.8	2301.8	−426.0
	Modules			
January	973.4	1300.0	900.1	−399.9
February	695.6	997.1	627.9	−369.2
March	672.5	1004.2	598.0	−406.1
April	805.1	1142.4	729.4	−413.0
May	1059.7	1355.3	993.3	−362.0
June	1271.8	1493.8	1222.0	−271.8
July	1385.1	1648.4	1325.9	−322.5
August	1392.2	1672.1	1329.3	−342.8
September	2083.6	2370.7	2019.2	−351.5
October	2949.6	3409.9	2846.2	−563.7
November	3049.2	3495.2	2949.0	−546.2
December	1696.0	2023.9	1622.4	−401.5
	Low-water			
January	789.9	990.8	716.9	−273.9
February	591.1	793.2	517.6	−275.5
March	555.2	760.5	480.6	−280.0
April	629.9	841.9	552.8	−289.2
May	819.7	1020.4	746.7	−273.8
June	1066.2	1219.3	1010.6	−208.8
July	1154.6	1316.8	1095.6	−221.2

Continued

August	1123.3	1300.1	1059.0	−241.2
September	1557.5	1648.8	1524.3	−124.5
October	2486.1	2707.2	2405.8	−301.4
November	2376.7	2565.1	2308.2	−256.9
December	1205.9	1387.8	1139.7	−248.1

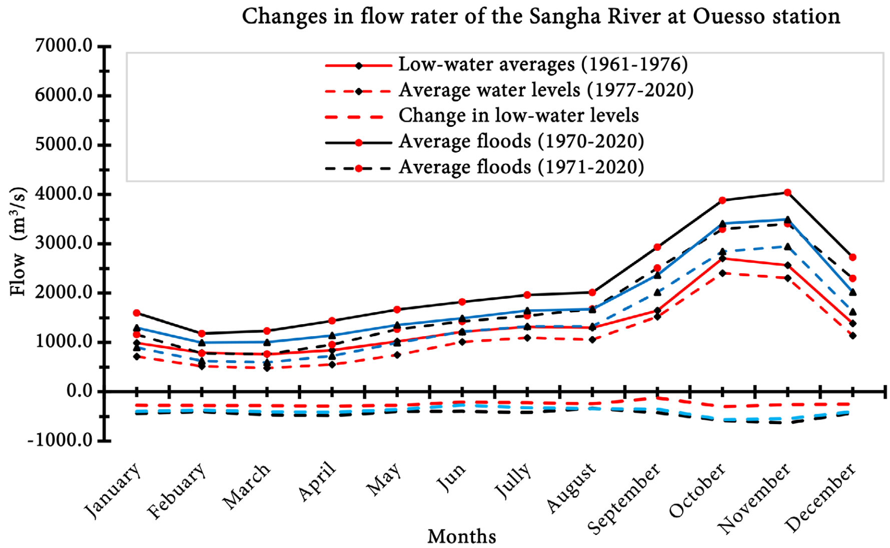

Figure 7. Changes in flow rates (m^3/s) of the Sangha River at Ouesso station from 1961 to 2020.

(1970-1971) and a deficit dry period (1972-2020). The deficit between the wet and dry periods is around 16.64%;

- One shift in modules in 1971. The flow module behaviors are like those for floods. In fact, the dates of shifts are the same as those of floods, and the different phases (wet, transitional, and dry) are concomitant. The observed deficit is of the order of 21.70%;
- One shift in low-water rates in 1976. It divides the time series into two periods of homogeneous flows: a wet period (1961-1976) and a dry period (1977-2020). The deficit between the two periods is 35.69%.

The results on trends in lows (floods, modules and low-water) of the Sangha River at Ouesso hydrological station (1961-2020) show a downward trend in flows. This trend is more perceptible for low-water. In addition, the changes observed in the flows of the Sangha River at Ouesso station from 1961 to 2020, showing a significant drop in flows from the 1970 onwards, are in line with the date of shift observed for Congo River flows by Ibiassi Mahoungou [23].

Calculation of the monthly recession coefficient shows that this coefficient has steadily increased for both the 1961-1990 and 1991-2020 sub-periods, as well as for the entire 1961-2020 period. The monthly recession curves (**Figure 7**) show that the release aquifer occurs from November to March for the 1961-1990 period, from October to April for the 1991-2020 period and from October to March for the 1961-2020 period. On the other hand, aquifer recharge occurs from April to November for the 1961-1990 period; from May to October for the 1991-2020 period and from April to October for the 1961-2020 study period.

The annual recession curves (**Figure 6**) show that the release of aquifers occurred in 1985 for the periods 1961-1990 and 1961-2020; and from 1991 to 2007 for the period 1991-2020. In contrast, aquifer recharge in the Sangha basin at Ouesso occurred from 1986 to 1990 for the 1961-1990 period; from 2008 to 2020 for the 1991-2020 period; and from 1986 to 2020 for the 1961-2020 study period.

The changes observed in the flows of the Sangha watershed at Ouesso are cyclical (ordinary) phenomena that are accentuated by the impact of the current drought, which tends either to stabilize or destabilize the hydrological regime of the river.

Comparative trends in flood and modules, on a monthly time scale, between the periods 1961-1971 and 1972-2020 for floods, 1961-1971 and 1972-2020 for modules, show a drop in flows during the months of September, October, and November, starting in 1971 for floods and modules, respectively. From December to August, these flows (floods and modules) increased slightly over the study period. However, over the 1961-1976 and 1977-2020 periods, low-water increased in the months from January to September, starting in 1976, the shift in the low-water flow series. In the months of September, October, November and December, low-water decreased, with October showing the most decrease.

5. Conclusions

Like most countries in the tropical zone, the Republic of the Congo-Brazzaville is subject to climate change. This study, carried out in the northern part of Congo-Brazzaville, specifically in the Sangha watershed at Ouesso hydrological station, has characterized the flows in the watershed from 1961 to 2020, with a view to gain a better understanding of extreme hydrological events. It illustrates these phenomena and gives an idea of their impact on water resources.

Indeed, shift detection tests on flood flows and modules indicate a shift at the beginning of the 1970s, in 1970 and 1971, and highlight the existence of two periods: a so-called wet surplus period, from 1961 to 1970 when water is abundant, and a so-called dry deficit period, from 1972 to 2020. One observes a transition period between 1970 and 1971. In addition, the low-water shift detection tests indicate a shift in 1976 that separates the time series into two homogeneous flow phases: a wet phase (before the shift) and a dry period (after the shift).

Overall, flow trends (flood, modules and low-water) in the Sangha watershed at Ouesso station show a significant drop from the shift dates onwards. These dates reflect a negative change in these trends. Indeed, from these shift dates onwards, the quantity of water in the Sangha watershed decreases. The recession coefficients calculated on monthly and annual time scales show that, during the study period, a recession occurred in March 1985.

Detection of changes in Sangha River flows at Ouesso station shows a significant drop in flood flows and modules during the September-October-November season, with the lowest level in November. Low-water declined in October and November, with the lowest level in October. Flood flows and modules reach their peak in August, and low-water is at its lowest in September.

This work should continue in the short and medium term, as according to internal publications by GIE-SCEVN, the department in charge of waterway maintenance in Congo-Brazzaville, the most severe low-water levels ever recorded in this watershed have occurred over the last two years. It would, therefore, be important to continue monitoring the evolution of water resources in the Sangha River watershed.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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