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Characterization of the Hydrological Drought Occurrence in Côte D'ivoire: Case of the Sassandra Watershed

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Abstract

The Sassandra watershed is increasingly marked by droughts, linked to the decline in rainfall observed in recent decades. These rainfall anomalies observed have had repercussions on river flows, causing hydrological droughts. This study proposes to study the hydrological droughts occurrence in the said basin. The methodological approach, based on the exploitation of annual flow data, has first allowed to identify the ruptures and to evaluate the hydrometric deficits. The IHN index was used to characterize the dry sequences and finally, Markov chains were used to determine the probabilities of successive dry years occurrence. It appears from this study that breaks occurred (between 1993 and 2001) with a tendency to increase the flow rates from 40.94% to 69.94% after the rupture. The most remarkable droughts in terms of intensity and duration occurred at the hydrometric stations located in the West and the North of the basin. The results of Markov chains 1 and 2 indicated that the highest probabilities of obtaining two or three successively dry years are recorded in the North and the West of the basin with probabilities of up to 79% for the first-order Markov chains and 86% for the second-order Markov chains.

Keywords: Hydrological drought, Markov chain, Sassandra watershed, Côte d'Ivoire

1. Introduction

The evolution of climate change is one of the main current and future challenges facing Africa. Climate change is detrimental to vulnerable regions such as sub-Saharan Africa **(IPCC, 2014)** as it affects water resources and many sectors of activity.

Numerous studies on climate variability at the scale of West Africa (**Ardoin, 2004; Faye, 2013**) and Côte d'Ivoire (**Irié *et al.,* 2016; Dekoula *et al.,* 2018; Kouamé *et al.,* 2019**), show that a drought trend has emerged since the end of the 1960s and intensified during the 1980s and 1990s. As a result, the flow rates of the region's major rivers have fallen by 20% to 60% **(Savané *et al.,* 2001; Goula *et al.,* 2006; Kouakou 2011; Kamagaté *et al.,* 2017),** thus causing so-called hydro-logical droughts. It is defined as the situation where water supplies become lower than normal due to prolonged periods of lack of rainfall **(Bergaoui and Alouini, 2001)**. This hydrological deficit has led to a significant drop in hydroelectric production **(Kouassi *et al.,* 2007)** etc. Drought thus implies many social-economic problems whose effects are often difficult to absorb. Thus, to characterize the magnitude and intensity of hydro-logical droughts in the Sassandra basin, the normalized hydrological index similar to meteorological drought indices has been used. This index is widely used worldwide **(Sharma and Panu, 2012; Mirabbasi *et al.,* 2013)**, has advantages in terms of statistical consistency, and has the capacity to describe short, medium and long term drought impacts across different time scales.

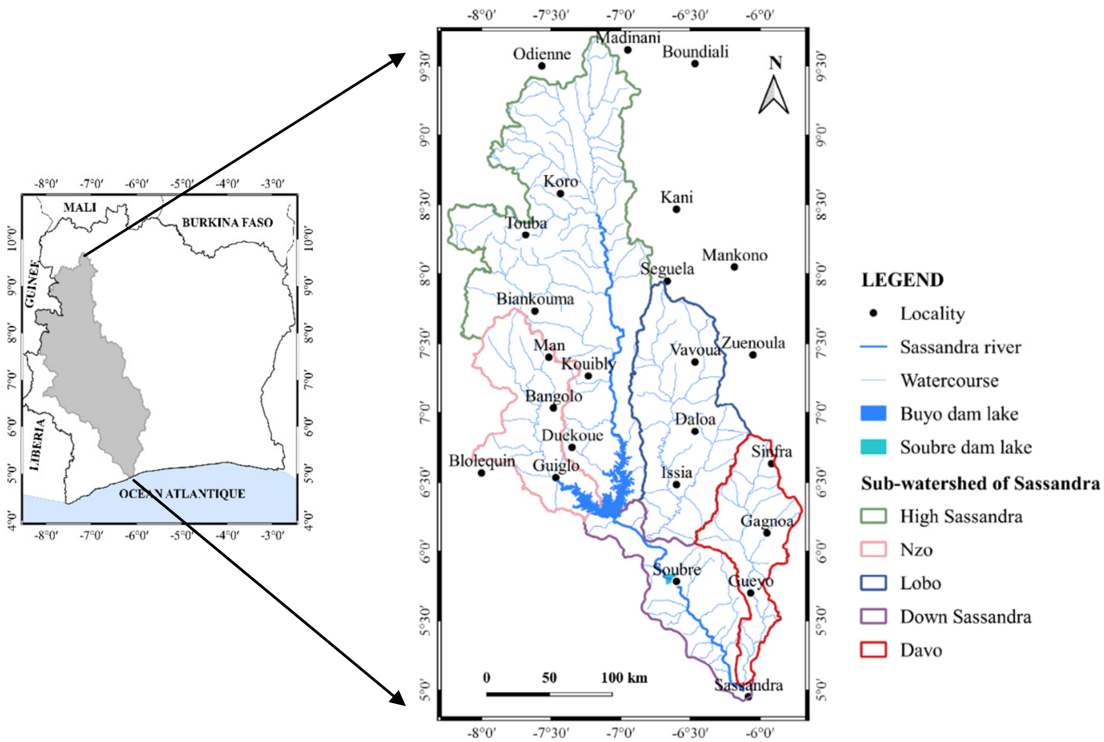
The example of the Sassandra watershed is interesting because this region has increasingly experienced a decrease in rainfall **(Santé *et al.,* 2019; Anouman, 2020).** These deficit periods have led to a disruption of cropping seasons in rural areas **(N'go *et al.,* 2013; N'Go *et al.,* 2017)**, a decrease in river flows **(N'Go, 2015; Yao *et al.,* 2015).** It is especially marked by strong anthropogenic pressures. In fact, this watershed, which is also part of the cocoa and coffee economy of Côte d'Ivoire, is undergoing a reduction in plant cover linked to systematic large-scale deforestation of the forest heritage for the creation of plantations **(Brou, 2010).** There are also social-economic infrastructures (hydroelectric dams, agricultural dams...) and this watershed is subject to numerous water-related development projects.

In a climatic context marked by a possible increase in the occurrence and impact of droughts in the years to come, it is essential to be able to analyze hydrological drought sequences in order to propose mitigation or adaptation measures to the populations.

2. Study Area

The watershed is located between longitude 5°3 and 8°4 West and latitude 5° and 9°75 North (Figure 1). It has a total area of about 75.000 km^2, of which the Ivorian part covers an area of about 67.000 km^2. This basin is subdivided into 5 sub-basins which are the Davo, Lobo, N'Zo, Upper Sassandra and Lower Sassandra. The relief is made up of plateaus (200 m to 500 m) from North to South and mountainous massifs (1100 and 1180 m) in the West. The climatic regime is subdivided into four climatic units that cover the different rivers. *The transitional equatorial climate* which covers the Davo and the lower Sassandra, is marked by four seasons (a large rainy season from April to June, a small rainy season from September to November, a large dry season from December to March and a small dry season from July to August). The interannual average is 1441.5 mm over the period 1953-2015. *The equatorial climate* of attenuated transition covers Sassandra, Lobo and Bafing. It is marked by two seasons (a great rainy season covering the months of August to October and a great dry season from November to March). The interannual average is 1305.2 mm; *the transitional tropical climate* covers the Boa. It has a unimodal regime and is characterized by a rainy season that occurs from June to October. The dry season covers the months of November to March. The interannual rainfall recorded at the Odienné station is 1473 mm; *the mountain climate* covers the N'Zo river and is characterized by an azonal type pattern. The highest rainfall peak is recorded in September (279 mm). The dry season covers the month of November to March. The average interannual rainfall is 1578.5 mm. As for vegetation, there are two types of vegetation: savannah in the north and forest in the rest of the basin.

Figure 1: Geographic localization of the study area



3. Data and Methods

3.1. Historical Time Series Data

The historical precipitation and flow data used in this work covers the entire study area on an annual scale. Precipitation data are from 10 weather stations evenly distributed throughout the watershed. These data over the period 1953-2015, were provided by the National Directorate of Meteorology (MND) of Society de Dévelopment and Exploitation, Aeroportuary, Aeronotic and Météorological (SODEXAM) of Côte d'Ivoire. As for the flow data, they were made available to us by the Direction de l'Hydraulique Humaine, subdirection of Hydrology. These data are the daily flows. The hydrometric network chosen for this study consists of 5 hydrometric stations (Vialadougou, Sémien, Kahin, Nibehibé and Dapkadou). The data used cover the period from 1970 to 2015**.** The **table 1** present the coordinates of the meteorological and hydrometric stations.

Table 1: Meteorological and hydrological stations selected

Code	Stations	Data	Latitude North	Longitude West
1090017200	Sassandra	Météorological	4°57'	6°50'
1090010300	Gagnoa		6°13'	5°95'
1090018100	Soubré		5°78'	6°60'
1090011200	Guiglo		6°53'	7°47'
1090021400	Vavoua		7°37'	6°47'
1090008200	Daloa		6°88'	6°45'
1090014200	Man		7°24'	7°31'
1090017500	Séguéla		7°95'	6°07'
1090020500	Touba		8°28'	7°68'
1090016000	Odienné		9°30'	7°34'
1092501603	Vialadougou	Hydrological	8°54'	7°22'
1092500109	Sémien		7°71'	7°07'
1092502205	Kahin		6°91'	7°63'
1092501903	Nibehibé		6°80'	6°70'
1092501503	Dapkadou		5°34'	6°08'

3.1. Methodology

3.1.2. Time Series Change Detection

Rupture is defined as a sudden change in the properties of a random process **(Renard *et al.,* 2006).** In this study, the Cumulative Gap (CS) test was used to detect possible sudden changes in hydroclimatic series. This non-parametric procedure, based on rank, analyses whether the means of the two parts of the series are different for an unknown break date **(Chiew and McMahon, 1993).** The statistic of this test is calculated from the cumulative sum of the "sign" function of the difference between the observed values and the median. This statistical processing will be performed with Hydrospect 2.0 software. The test statistic is defined as follows:

$$|TS| = (2\backslash n) \max |S_k| \text{ avec } S_k = \sum_{i=1}^{k} \text{signe } (x_i - X_m) \text{ et } (k = 1, \ldots, n) \qquad \text{(Model 1)}$$

x_i is the extreme hydrometric observation of rank *i (i=1...n)* ; X_m is the median of the extreme hydrometric series ; S_k is the statistic test.

3.2.1. Characterization of Hydrological Drought Sequences

The Normalized Hydro-logical Index (IHN) was used in this study to highlight drought sequences on an annual scale over the period 1970-2015. This index, similar to the standardized precipitation index (McKee et al., 1993; Hayes, 2004), has advantages in terms of statistical consistency, and has the capacity to describe both short- and long-term drought impacts across different time scales. Thus, it has been developed to quantify the hydro-logical deficit for multiple time scales that will reflect the impact of drought on the availability of different types of water resources for a given period **(Sharma and Panu, 2012).** It is expressed mathematically as follows:

$$IHN = (Di - Dm)/ S \qquad \text{(Model 2)}$$

Di: Total flow of one year i (m^3/s); Dm: Average flow over the period 1970-2015 (m^3/s); S: Standard deviation of precipitation over the period 1970-2015 (m^3/s).

The annual IHN values are obtained from the monthly flows recorded at the various hydrometric stations over the period 1970-2015. This index, once calculated, makes it possible to identify the various surplus and deficit sequences of the study period **(table 2).** A drought occurs when the IHN is consecutively negative and its value reaches an intensity of -1 or less and ends when the IHN becomes positive. Drought is classified according to the IHN values.

Table 2: Classification of drought sequences according to IHN (Sharma and Panu, 2012)

Value of the IHN	Drought sequence	Value of the IHN	Drought sequence
0.00< IHN <-0.99	Slightly dry	0.00< IHN <0.99	Slightly wet
-1.00< IHN<-1.49	Moderately dry	1.00< IHN <1.49	Moderately wet
-1.50<IHN<-1.99	Severely dry	1.50< IHN <1.99	Severely wet
IHN < -2.00	Extremely dry	2,00< IHN	Extremely wet

3.2.1.1. Descriptive Parameters of Drought Sequence

- ***Maximum duration of drought sequences***

Duration is important characteristic of drought. In fact, if a drought starts quickly under some weather conditions, it usually takes at least two to three months before it can spread to other regions. It can then persist for months or even years. The calculation of the duration is as follows (**Soro *et al.*, 2014**).

$$D= (A_{end} - A_{initial}) \quad \text{(Model 3)}$$

A_{end}: Year of the end of the dry period; $A_{initial}$: Year of the beginning of the dry period

- ***Intensity of drought sequences***

Intensity of drought can be defined as the magnitude and severity of the consequences for the rainfall deficit. It can be evaluated using the IHN values. In this study, the extreme value of the SPI was considered as a reference value for drought intensity.

3.2.2. Characterization of Hydrological Droughts Occurrence by Markov Chains

Several statistical techniques for analyzing precipitation data have been published in the literature. The most used technique is still the one based on the Markov chains. A Markov string is a series of random variables *(X_n, $n \in N$)* that allows to model the dynamic evolution of a random system: *X_n* represents the state of the system at time *n*. The fundamental property of Markov chains, known as "Markov property", is that its future evolution depends on the past only through its current value. In other words, conditionally to *X_n, (X_0,..., X_n)* and *(X_{n+k}, $k \in N$)* are independent **(Lazri *et al.*, 2007; Radu, 2014).**

3.2.2.1. Chaîne de Markov à Deux États D'ordre 1

For a first order Markov chain, the state of the variable *E(t)* at time *t* depends only on its state at time *(t -1)*. Thus, we have four situations:

$$P_{00} = pr(E(t+1) = 0 / (E(t)=0)) \quad \text{(Model 4)}$$
$$P_{01} = pr(E(t+1) = 1 / (E(t)=0)) \quad \text{(Model 5)}$$
$$P_{10} = pr(E(t+1) = 0 / (E(t)=1)) \quad \text{(Model 6)}$$
$$P_{11} = pr(E(t+1) = 1 / (E(t)=1)) \quad \text{(Model 7)}$$

P_{ij} is the probability of going to state *j* knowing that you are in state *i*. These probabilities were calculated using the following relationship:

$$P_{ij}= N_{ij} / N_i \text{ avec } i \text{ et } j= 0 \text{ ou } 1 \quad \text{(Model 8)}$$

N_{ij} is the transition number from state *i* to state *j* and N_i is the number of transitions from state *i* to any other state. The pairs of years *N_{ij}* are determined:

$$\begin{cases} N_0 = N_{00} + N_{01} \\ N_1 = N_{10} + N_{11} \\ N = N_0 + N_1 \end{cases} \qquad \text{(Model 9)}$$

N_0; N_1 and N are the number of dry, wet years and the total number of years of observation, respectively. N_{01} and N_{10} respectively represent the number of years of state change from a dry year to a wet year and from a wet year to a dry year. The transition matrix P of the conditional probabilities P_{ij}, is presented so that each line is equal to 1. Resulting in a set of possible P_{ij} values :

$$P = \begin{bmatrix} P_{00} & P_{01} & \cdots \\ P_{10} & P_{11} & \cdots \\ \cdots & \cdots & \cdots \\ P_{i0} & P_{i1} & \cdots \end{bmatrix} \qquad \text{(Model 10)}$$

3.2.2.2. Chaîne de Markov à deux états d'ordre 2

For a Markov string of order 2, the state of the variable *E(t)* at time t depends on its state *E(t-1)* at time *(t-1)* as well as its state *E(t-2)*. The probability of having this state can be written:

$$P_{ijk} = pr\,(E(t) = k / (E(t-1) = j,\ E(t-2) = i)) \qquad \text{(Model 11)}$$

P_{ijk} represents the conditional probability of having a state doublet *(j, k)* following the state doublet (*i, j*) and *i, j, k = 0* or *1*, calculated using the following relationship **(Lazri *et al.,* 2007)**:

$$P_{ijk} = N_{ijk} / N_{ij} \qquad \text{(Model 12)}$$

N_{ijk} is the number of transitions from the state doublet *(i, j)* to the state doublet *(j, k)*.

The process of transition of conditional probabilities with the Markov 2 chain is as follows **(Table 3):**

Table 3: Markov process of order 2 (Méledje *et al.,* 2015)

State at day k-1 and k-2	State at day k-1 and k			
	00	**01**	**10**	**11**
00	P000	P001	0	0
01	0	0	P010	P011
10	P100	P101	0	0
11	0	0	P110	P111

4. Results and Discussion

4.1. Results

4.1.1. Hydroclimatic Variability

Climate Variability

These results presented in **table 4** show that the rainfall series analyzed show rupture in the majority of cases between 1966 (Gagnoa) and 1971 (Vavoua and Daloa). Ruptures were also identified in 1982 (Sassandra, Séguéla and Odienné). The null hypothesis of no rupture was rejected at the 99% and 95% confidence levels. The ruptures detected correspond to a significant downward trend in average rainfall during the 20th century in general and in particular since the end of the 1960s and the beginning of the 1970s. This decline was amplified during 1983. These breaks have made it possible to determine the different periods of rainfall fluctuations in the Sassandra catchment area. The magnitude of the rainfall decrease was quantified by calculating the deficits due to the breaks detected in the series. The different results obtained vary between 5.83% (Man) and 25.44% (Séguéla) with an average of 17.40%.

Table 4: Results of the cumulative sums test over the rainfall series for the period 1953-2015

		Befor rupture		**After rupture**		
Stations	*Rupture Year*	*Average (mm)*	*Standard deviation*	*Average (mm)*	*Standard deviation*	*Deficit (%)*
Sassandra	1982	1601.8	193.3	1288.8	302.7	19.54
Gagnoa	1966	1637.2	238.7	1386	196.7	15.34
Soubré	1970	1630.4	267.7	1388.3	249.8	14.85
Guiglo	1966	1733.1	387.5	1627.3	293.5	6.1
Vavoua	1971	1305.6	240.2	1101.0	251.1	15.67
Man	1968	1694.4	234.1	1595.6	227.3	5.83
Daloa	1971	1460	327.6	1233.5	178.9	15.51
Séguéla	1980	1344.4	485.8	1002.4	180.1	25.44
Touba	1981	1310.8	199.0	1047.8	206.1	20.52
Odienné	1982	1601.8	193.3	1355.3	210.6	15.39

Hydrometric Variability

The results of the break detection test distribution of cumulative sums applied to the annual hydro-metric series for the period 1970-2015 are recorded in **Table 5**.

These results show that the hydro-metric series analyzed show breaks between 1993 and 2001. The null hypothesis of no break was rejected at the 99% and 95% confidence levels. The breaks detected correspond to a significant upward trend in the mean flow rates. The magnitude of this increase in flow was quantified by calculating the deficits caused after the breaks detected in the series. The different results obtained fluctuate between 30.03% (Kahin) and 71.91% (Vialadougou) with an average of 50.88%. The Sémien, Nibehibé and Dapkadou stations recorded an increase in average flow rates of 54.89%, 43.65% and 53.91% respectively.

Table 5: Résultats du test des sommes cumulées sur les séries hydrométriques de la période 1970-2015

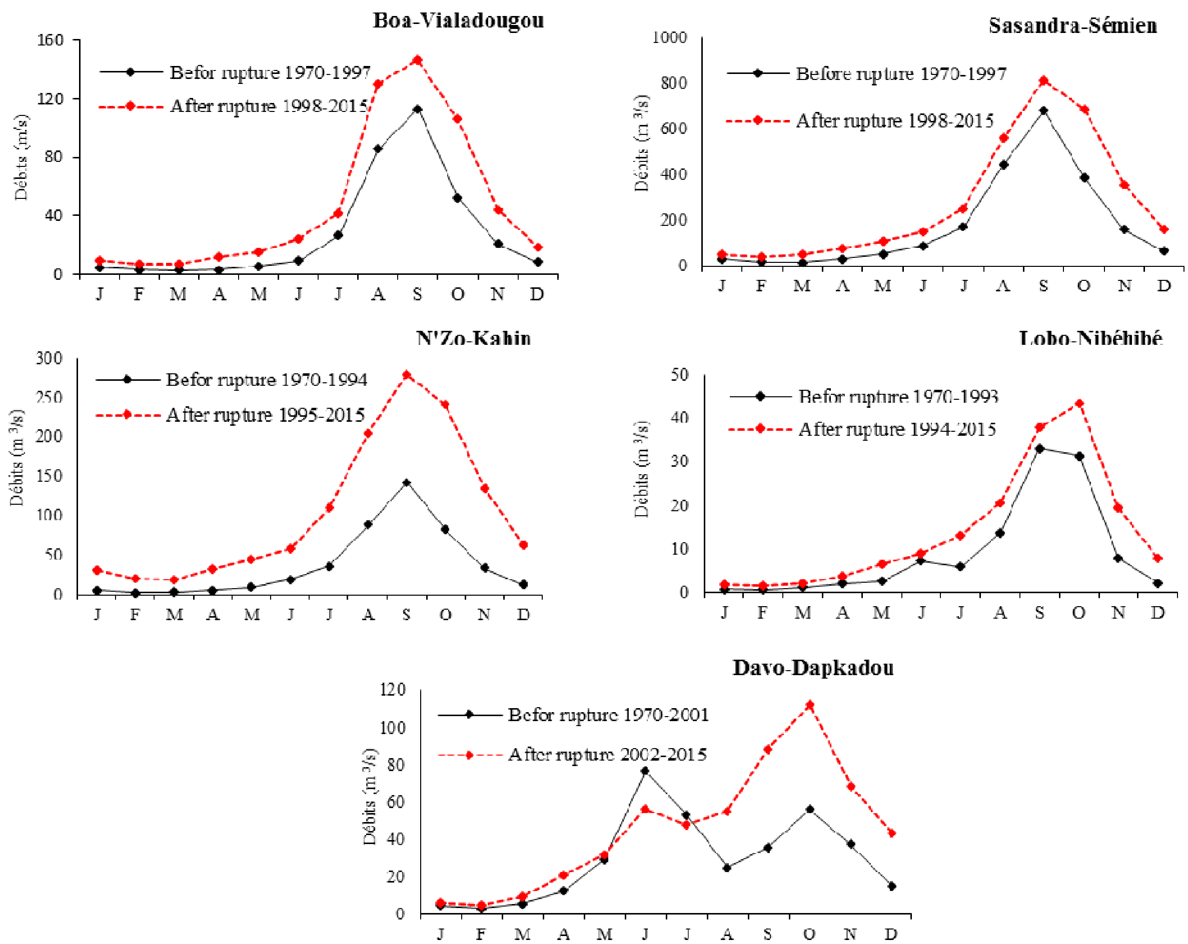
		Befor rupture		**After rupture**		
Stations	*Rupture Years*	*Average (m^3/s)*	*Standard deviation*	*Average (m^3/s)*	*Standard deviation*	*Excess (%)*
Vialadougou	1997	27.91	7.97	46.8	15.3	**71.91**
Sémien	1997	177.1	43.26	274.3	94.7	**54.89**
Kahin	1994	79.3	51.1	103.1	42.4	**30.03**
Nibehibé	1993	8.98	5.30	13.9	5.7	**43.65**
Dapkadou	2001	29.51	8.99	45.42	16.71	**53.91**

Monthly Variation in Flows by Period

The comparative evolution of the average monthly flows before and after the breaks are shown in **Figure 2**. Overall, the graphs show that the flows recorded after the breaks are higher than the flows before the breaks, except at the Dapkadou station, which records an opposite situation in the months of June and July. Indeed, at the Dapkadou station, during the months of June and July, the flow rates, which were respectively 76.61 m^3/s and 53.21 m^3/s before the 2001 break, dropped to 56.35 m^3/s in June and 48.16 m^3/s in July. Flood flows after the breaks are of the order of 146.42 m^3/s at Vialadougou (1997), 816.91 m^3/s at Sémien (1997), 278.98 m^3/s at Kahin (1994), 43.65 m^3/s at Nibehibé (1993) and 112.33 m^3/s at Dapkadou (2001). On the other hand, the hydro-graphs before the ruptures are characterized by low flows. Flood flows for this period are 112.91 m^3/s at Vialadougou, 682.08 m^3/s at Sémien, 142.46 m3/s at Kahin, 33.09 m3/s at Nibehibé and 76.62 m^3/s at Dapkadou.

The differences between the extreme values of the flows of the two periods (before and after rupture) are of the order of 33.51 m^3/s, 134.83 m3/s, 136.52 m^3/s, 10.56 m^3/s and 35.71 m^3/s respectively at the stations of Vialadougou, Sémien, Kahin, Nibehibé and Dapkadou.

Figure 2: Monthly mean hydrographs before and after rupture of the hydrometric stations at Vialadougou, Sémien and Kahin, Nibehibé and Dapkadou



4.1.2. Analysis of Hydrological Drought Sequences

The analysis of Hydrological droughts by the Normalized Hydrological Index (IHN) shows an alternation of dry and wet sequences from 1970 to 2015 with a greater number of dry sequences before the different break years **(Figure 3)**. Thus:

At the Vialadougou and Sémien stations, the ruptures took place in 1997. From 1970 to 1997, the IHN recorded 23 dry years at Vialadougou and 25 dry years at Sémien. Among these dry years, the index shows four sequences of successive dry years at Vialadougou: 1970-1978 (9 years), 1982-1983 (2 years), 1986-1993 (8 years), and 1996-1997 (2 years) at Vialadougou; and three successive sequences at Sémien: 1970-1978 (9 years), 1980-1993 (13 years), and 1995-1996 (2 years);

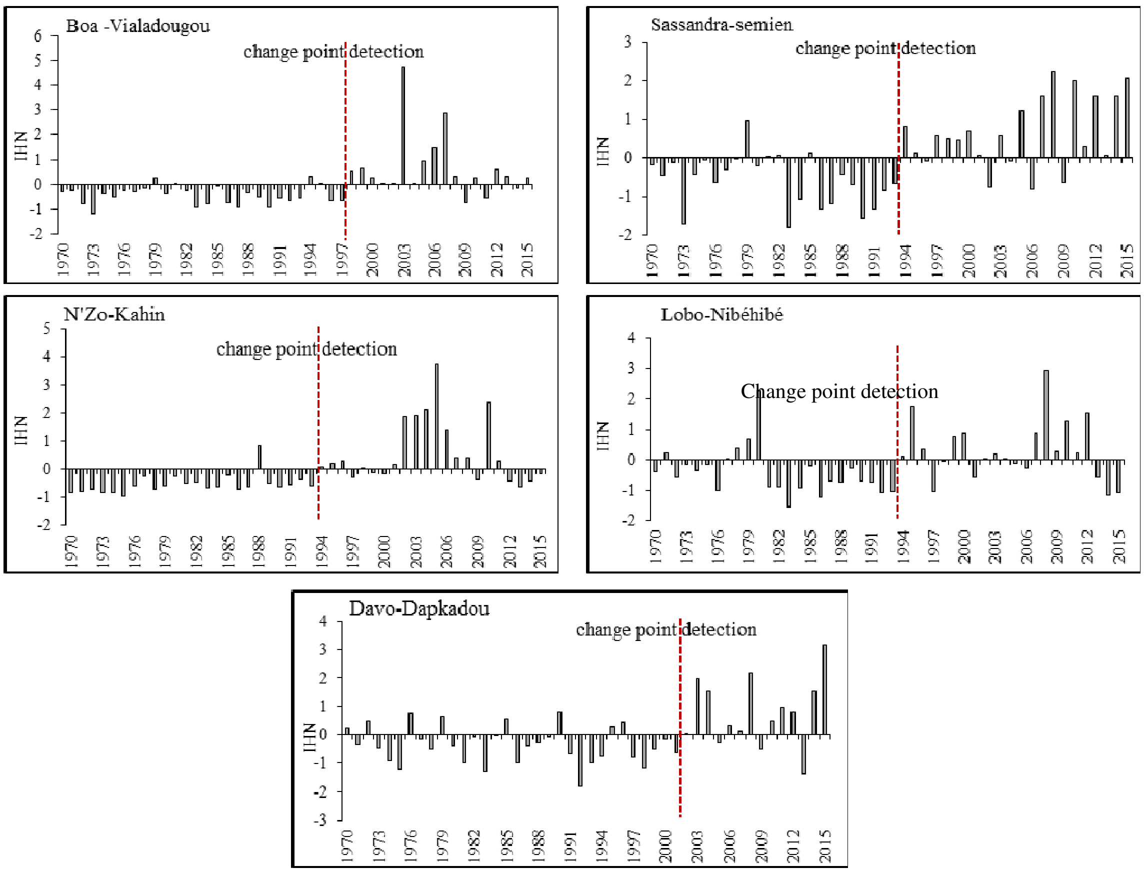
The IHN recorded 24 dry sequences at the Dapkadou station over the period 1970-2001. The successive dry-year sequences are: 1973-1975 (3 years), 1980-1984 (5 years), 1986-1989 (4 years), 1991-1994 (4 years) and 1997-2001 (5 years). From 2002 to 2015, which is characterized by mostly wet years, the index records 3 dry sequences (2005, 2009 and 2013) ;

The Kahin station records its break in 1994. From 1970 to 1994, there are 21 dry sequences with 3 sequences of consecutive dry years: 1970-1979 (10 years), 1981-1993 (13 years) and 1999-2000

(2 years). For the period 1995-2015, the IHN indicates 5 dry sequences (1997, 1999, 2000, 2009 and 2013). The successive dry sequence extends from 1999-2000;

At Nibehibé, 16 dry sequences mark the period before the break in 1993. Over the period 1970-1993. Among these dry years, some are consecutive: 1972-1977 (6 years), 1981-1984 (4 years) and 1990-1993(4 years). After the rupture year, this station records 6 dry sequences (1997, 2001, 2004, 2005, 2006 and 2013) dry sequences.

Figure 3: Evolution des indices IHN sur la période 1970-2015



4.1.2.1. Analysis of Intensity, Duration and Frequency Parameters

On an annual scale over the period 1970-2015 (45 years), the most remarkable droughts in terms of intensity were those of 1973, 1983 and 1992 **(table 6)**. These dry episodes were qualified as severely dry in terms of intensity. The highest intensities were recorded at the hydro-metric stations of Dapkadou (-1.79), Nibehibé (-1.70) and Vialadougou (-1.56) in 1992, 1983 and 1973 respectively. The analysis of the duration of drought episodes shows that it varies from 6 to 13 consecutive years over the whole basin. The calculated HLI shows the longest drought period with 14 (1980-1993) years of consecutive dry sequences at the Sémien station.

Table 6: Intensité et durée des séquences de sécheresses hydrologiques durant la période 1970-2015

Stations	Intensity (IHN)	Type	Maximum duration	Date of occurrence
Vialadougou	**-1.56**	Severely dry	9	**1973**
Dapkadou	**-1.79**	Severely dry	5	**1992**
Nibehibé	**-1.70**	Severely dry	6	**1983**
Sémien	-1.44	Moderately dry	**14**	1983
Kahin	-1.37	Moderately dry	13	1975

4.1.3. Analysis of the Hydrological Droughts Occurrence

4.1.3.1. Transition States Probability of Markov Chains 1

Over the period 1970-2015, the probability of two successive years of hydrological drought (DD) is high over the watershed as a whole (greater than 50%) and varies from 60% (Lobo to Nibehibe) to 79% (N'Zo to Kahin). The maximum is reached at the Kahin (79%) and Vialadougou (74%) stations **(table 7)**. When a wet year is followed by a dry year (WD), the probability is low at all hydrometric stations in the basin except at Dapkadou where the probability is medium (55%). For two successive wet years (WW), the probability is very high at Vialadougou (65%) and Kahin (67%), the probability is medium at Nibehibé and Sémien and low at Dapkadou. When a state is dry, the probability of having the following year wet (DW) is low in the basin (probability ranging from 21% to 40%).

Table 7: Occurrence of hydrological droughts using Markov Chains 1 over the period 1970-2015

Running water	Station	Probability (%)			
		WW	*WD*	*DW*	*DD*
Boa	Vialadougou	**65**	35	31	69
Davo	Dapkadou	45	**55**	37	63
Lobo	Nibehibé	52	48	**40**	60
N'Zo	Kahin	**67**	33	**21**	**79**
Sassandra	Sémien	50	45	26	**74**

* D: dry year; W: wet year

4.1.3.2. Transition States Probability of Markov Chains 2

The Markov chains of order 2 applied to hydrological data over the period 1970-2015 **(table 8)** show the probabilities of obtaining a dry year after two successive dry years (DDD), which are high over the entire basin (probability ranging from 60% to 86%) with peaks reached at the stations of Kahin (86%), Sémien (83%) and Vialadougou (78%). When three states are successively wet (WWW), the stations of the basin have high probabilities (>50%) with the stations Vialadougou (75%) and Kahin (67%) recording the highest probabilities; The probabilities of obtaining a wet year after a doublet of successive dry years (DDW) and a dry state after two successive wet states (WWD) are relatively low throughout the basin; The occurrence of a dry year between two wet years (WDW) reaches its maximum at the stations of Vialadougou and Sémien. On the other hand, the probability of having a wet year between two dry years (DWD) is low over the whole basin except for the regions of Vialadougou (62%) and Sémien (63%).

Table 8: Probabilities of hydrological drought occurrences according to Markov 2 over the period (1970-2015)

Running water	Station	Probability (%)							
		WWW	***WWD***	***WDD***	***WDW***	***DWW***	***DWD***	***DDW***	***DDD***
Boa	Vialadougou	**75**	25	43	**57**	38	**62**	22	**78**
Davo	Dapkadou	50	50	60	40	50	50	35	65
Lobo	Nibehibé	64	36	60	40	50	50	40	60
N'Zo	Kahin	**67**	33	50	50	**67**	33	14	**86**
Sassandra	Sémien	57	43	43	**57**	38	**63**	17	**83**

* D: dry year; W: wet year

4.2. Discussion

The results of the rupture tests indicate a decrease in rainfall, which was manifested by ruptures identified mainly between 1966 (Gagnoa) and 1971 (Vavoua and Daloa). Late changes point detection were also identified in 1980 (Séguéla) and 1982 (Sassandra and Odienné). These rupture dates fit well with the results of numerous studies in the sub-Saharan zone **(Noufé *et al.*, 2011; Ahoussi *et al.*, 2013; Gaye, 2016)** and in the Sassandra watershed **(Yao *et al.,* 2012; Kouamé, 2017; Santé *et al.,* 2019; Djoro *et al.,* 2020)**. Rainfall deficits range from 14.85% to 25.44% with an average of 17.40% over the entire basin. This decrease in rainfall could be linked to deregulation in the seasonal migration of the Intertropical Front (FIT) to the North **(Ahoussi *et al.,* 2013)**. Indeed, the movement of the FIT is dependent on the thermal contrast between the continent and the oceans. The regression of continental contributions to water recycling in the atmosphere could also explain this rainfall decrease in the Sassandra watershed. In addition, there is the regression of forest areas in the profile of the creation of plantations which causes a modification in the recycling of water in its atmospheric phase **(Brou *et al.,* 1998).**

During the period 1970-2015, the flow series show breaks that occurred between 1993 (Lobo in Nibehibé) and 2001 (Davo in Dapkadou). An upward trend in flows of 30.03% to 71.91% was observed after the changes in the basin. These ruptures occur following the rainfall ruptures observed in the Sassandra basin. The increase in flows after the breaks could be the consequence of the strong degradation of surface conditions in favour of agricultural activities and the announced rainfall recovery **(Brou *et al.,* 2005)**. This increasing flow trend has also been observed by several authors in the Sudano-Sahelian environment **(Albergel, 1987; Cappelaere *et al.,* 2009)**. As for the annual decline in flows before the break years, it is the result of the rainfall deficit observed after 1970. Indeed, rainfall deficits have an immediate hydro-logical impact on the basin.

The analysis of the values of the Normalized Hydro-logical Index (IHN) calculated over the period 1970-2015 revealed that the Sassandra basin experienced important hydro-logical droughts before the ruptures of 1993 (Nibehibé), 1994 (Kahin), 1997 (Vialadougou and Sémien) and 2001 (Dapkadou). Peaks characterized by "severely dry" droughts were reached in 1973, 1983 and 1992. Cette observation est conforme à la dynamique pluviométrique sur la période 1970-2015

The IHN similar to the standardized rainfall index that has been used by many authors in various regions of the world **(Sharma and Panu, 2012)** is relevant for the characterization of hydro-logical drought in the basin. Moreover, the changes in IHN values at the different stations indicate that in terms of intensity, the stations of Dapkadou (-1.79), Nibehibé (-1.54) and Vialadougou (-1.56) have been the most affected by droughts. In terms of duration, the indices indicate an increase in successively dry years before the breaks, which occurred around 2000. Thus, the Kahin Station recorded the longest period of hydrological deficit (15 successive years). These results confirm the numerous studies carried out in West Africa **(Servat *et al.,* 1998; Paturel *et al.,* 1998; L'Hôte *et al.,* 2002)** and in the Sassandra watershed **(Yao *et al.*, 2012; N'Go, 2015; N'Go *et al.,* 2017).** These authors showed that the decades 1970-1979, 1980-1989 and 1990-1999 were dry periods. According to them, the 1982-1984 drought is the most intense drought of the century in West Africa. The hydrological deficit is also the most important there. The hydrological decline intensified during the 1980s and 1990s before experiencing a slight increase around the 2000s which can be explained by the effect of the long period of rainfall deficits (1970-2000). It had a pronounced effect on runoff, particularly during the periods 1970-1974 and 1981-1993.

The application of the Markov chains to the hydrological data indicates that over the period 1970-2015, the probabilities of obtaining two to three successive dry years in the basin reach 69% and 74.4% on average. The highest probabilities are in the North (Boa in Vialadougou) and West (N'Zo in Kahin and Sassandra in Sémien) of the basin. The values obtained are respectively 69%, 79% and 74% for the first-order Markov chains and 78% (Boa at Vialadougou), 86% (N'Zo at Kahin) and 71% (at Sémien) for the second-order Markov. These results highlight the accentuation of the hydro-logical drought caused by a decrease in runoff following the drop in rainfall observed in the basin after 1970 and anthropic activities (micro dams, hydroelectric dams, agro-pastoral dams etc...). These results are in line with the work of **Kouamé (2017)** on the Davo watershed and **Yao *et al.* (2012)** on the Lobo watershed. The authors showed that the hydrological regime of these basins remains sensitive to rainfall variations.

5. Conclusion

The Normalized Hydrological Index (IHN) was used to characterize hydro-logical drought events in the Sassandra basin. The driest sequences in terms of intensity and duration occurred before the ruptures that occurred between 1993 (Lobo in Nibehibé) and 2001 (Davo in Dapkadou). These "extremely severe" events peaked in 1973, 1992 and 1983 with respective intensities of -1.56 in Vialadougou, -1.70 in Nibehibé and -1.79 in Dapkadou. In terms of duration, the indices indicate that the Kahin Station records the longest period of hydro-logical deficit (15 successive years). The Markov chains 1 and 2, allowed to evaluate the probabilities of occurrence of hydro-logical droughts. The results show that the succession of dry events increased before the break years. Thus, the highest probabilities of obtaining two or three successive dry years are recorded in the North (Boa at Vialadougou) and West (N'Zo at Kahin and Sassandra at Sémien) of the basin. The values obtained are respectively 69%, 79% and 74% for first-order Markov chains and 78% (Boa to Vialadougou), 86% (N'Zo to Kahin) and 71% (to Sémien) for second-order Markov.

The Markovian method applied to the flow data is proving to be a good indicator of hydro-logical drought at the regional scale. Thus, in the Sassandra watershed, the probability of a dry year will depend on the state of the previous year and even more on the state of the day before yesterday. This study will enable the populations and decision-makers to develop new strategies for a better management of water resources in a context of climate change.

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