Journal Homepage: -www.journalijar.com

INTERNATIONAL JOURNAL OF ADVANCED RESEARCH (IJAR)

Article DOI:10.21474/IJAR01/12035
DOI URL: http://dx.doi.org/10.21474/IJAR01/12035

ISSN NO. 2320-5407

RESEARCH ARTICLE

RECENT EVOLUTION OF WATER RESOURCES IN THE SASSANDRA CATCHMENT AREA (CÔTE D'IVOIRE) IN A CONTEXT OF CLIMATE VARIABILITY AND CHANGE

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Manuscript Info

Manuscript History
Received: 10 September 2020
Final Accepted: 15 October 2020
Published: November 2020

Key words: -
Climatic Variability, Drying Up, Volumes Mobilized, Catchment Area, Sassandra

Abstract

The objective of this study is to assess the impacts of climate change on the surface water resources of the Sassandra catchment area. This study conducted at the scale of the Sassandra sub-catchment areas took into account six (6) sub-catchment areas: Bafing in Badala, Boa in Vialadougou, Davo in Dakpadou, Lobo in Nibéhibé, N'zo in Kahin and Sassandra in Sémien. The methodological approach is based on the evaluation of the drying up coefficients, the duration of drying up and the volumes of water mobilized by the aquifers. All these parameters were estimated using Maillet's law. The analysis of the different dynamics was carried out using the cumulative sums test. The results showed that the breaks in rainfall and the drying up coefficient were between 1982 and 2000, 1985 and 2003 respectively. After these breaks, the drying up coefficients increased (Bafing in Badala, Boa in Vialadougou and Davo in Dakpadou) from 17 to 25.9% and decreased (Lobo in Nibéhibé and N'zo in Kahin) from 1.4 to 6.3%. A shortening of 3 to 5 days was observed on the Bafing in Badala, the Boa in Vialadougou and the Davo in Dakpadou. The volumes of water mobilized by the aquifers decreased on the Bafing in Badala, the Davo in Dakpadou and the Sassandra in Semien.While they increased on the Boa in Vialadougou, the Lobo in Nibéhibé and the N'zo in Kahin.

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Introduction:-

The West African region is one of the most vulnerable regions to the impacts of climate change on water resources. Thus, studies carried out in West Africa have shown a considerable drop in rainfall since the early 1970s (Yao et al., 2012; Kouamé et al. 2013; Kouassi et al., 2013; N'guessan et al., 2015; Kaboré et al., 2017; Kouassi et al., 2017; Koffi et al. 2020), which has resulted in a reduction in river flows. In parallel with the vagaries of climate, the demand for water is steadily increasing in countries, particularly in developing countries. Like other regions of the country, the Sassandra catchment area is experiencing climatic disturbances caused by deteriorating climatic parameters, making water resource management in river systems difficult. These sub-catchments are characterized by very important runoff phenomena and feed a very active network of tributaries. As a result, they are constantly subject to strong anthropogenic pressures due to agricultural activities, hydroelectric dams and drinking water supply facilities. Given the strategic position of the catchment area (agricultural and hydrodynamic), the need for a

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better assessment of the impacts of climatic factors influencing water resources is essential.The objective of this study is to assess the impacts of climate change on the surface water resources of the Sassandra catchment area

Materials and Methods:-

Search area:

The study area is the Sassandra watershed in Côte d'Ivoire. It is located between 5°75' and 8°16' West longitude and between 5° and 9°75' North latitude (Figure 1). The sub-basins have been extracted taking into account the different climatic zones. They are the Boa in Vialadougou (5800 Km^2), the Bafing in Badala (6300 Km^2), the Sassandra in Semien (21830 Km^2), the N'zo in Kahin (4498 Km^2), the Lobo in Nibéhibé (6955 Km^2) and the Davo in Dakpadou (7032 Km^2). In Côte d'Ivoire, these sub-catchments drain the North-West, West and South-West regions. Indeed, the Sassandra watershed covers the four types of climate encountered in Côte d'Ivoire. In the North, on the Boa River in Vialadougou, the dry sub-tropical climate reigns (Sudano-Guinean climate) with annual rainfall varying from 1000 to 1700 mm. The equatorial climate is characteristic of the central part of the basin (Bafing in Badala, Sassandra in Semien and Lobo in Nibéhibé) with annual rains between 1300 mm and 1750 mm. To the west, on the N'zo at Kahin, represents the mountain climate with rainfall between 1600 and 2000 mm. The south of the basin, on the Davo river at Dakpadou, is characterised by a humid equatorial climate. The annual rainfall varies from 1000 to 1700 mm.

The sub-basin of the Boa at Vialadougou is generally covered by savannah vegetation. The other sub-basins are characterised by forest or transitional vegetation. The topography is not very uneven except in the western zone (N'zo to Kahin). It 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 main soil types are acrisols (ferric and orthic), cambisols (eutric and humic) and ferrasols (humic and xanthic). The hydrographic network is relatively very dense.

The main geological formations are granites, granodiorites, migmatites, charnockites, mylonites and gneisses. The existence of aquifers in the Sassandra basin is conditioned by the presence of fractures and altered levels. There are two types of aquifers, similar to the basement areas, namely alteration and cracked aquifers. These layers are essentially recharged by meteoric precipitation. The dynamics of underground flows are conditioned by the existence and organisation of cracks and fractures.

The population of the large cities is very high in the basin with a density of 103 inhabitants per square kilometer. Economic activity revolves around agricultural activities of perennial types (coffee, cocoa, oil palm, cotton and cashew nuts), fishing and agro-pastoral activities.

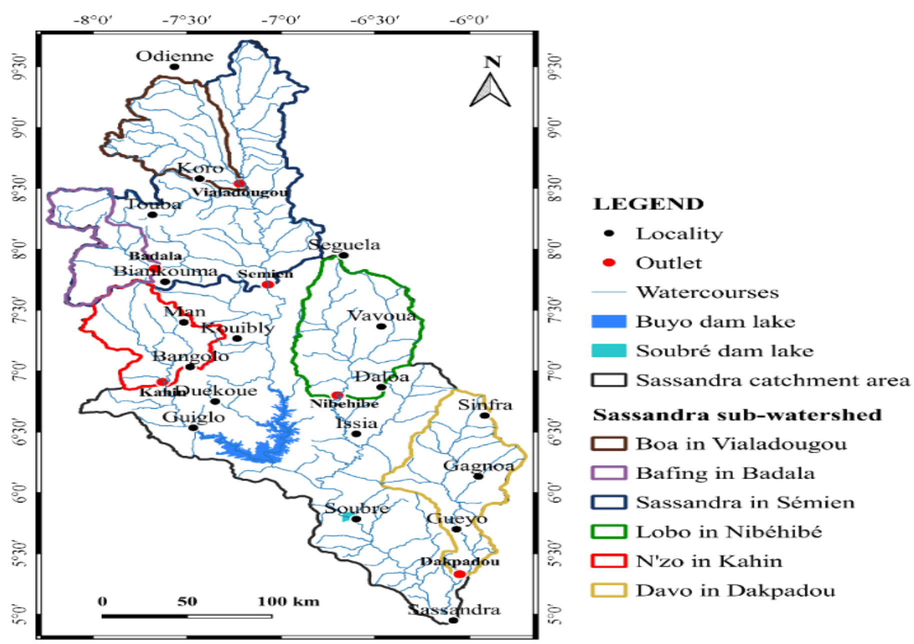


Figure 1:- Geographical location of the Sassandra sub-basins.

Data:

The rainfall and daily flow data used in this study cover the period 1970-2015. The rainfall data come from the airport operating and development company (SODEXAM). Fourteen (12) stations were selected, including 5 synoptic stations: Daloa, Gagnoa, Man, Odienné and Sassandra (Figure 2). The flow data come from the Directorate of Standards, Regulations and Quality (DNRQ), a structure under the supervision of the General Directorate of Human Hydraulic Infrastructures (DGIHH). Six stations have been selected. The selection of the stations was made taking into account the gaps (less than 10%) and the geographical position of the station in relation to the hydroelectric dams.

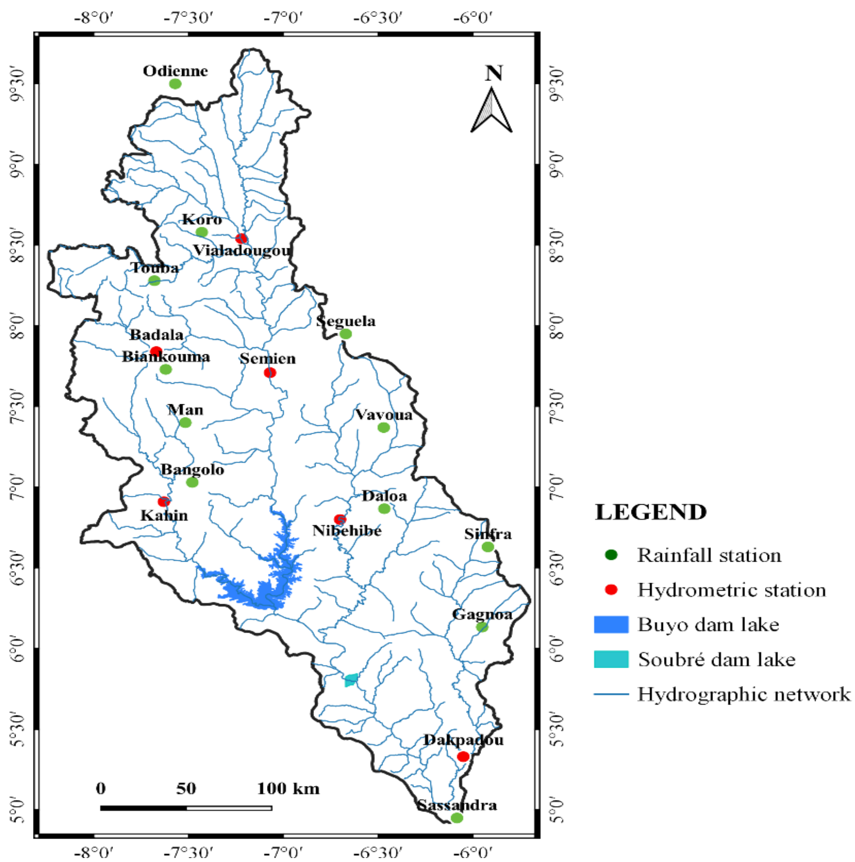


Figure 2:- Geographical location of the hydro-meteorological stations in the Sassandra catchment area.

Methods for processing the results:

Cumulate sum test:

The test based on the distribution of cumulative sums is a parametric test. This test allows the detection of possible abrupt changes in the hydroclimatic value series. It is based on the assumption that the number of values in the series below the median and the number of values above the median are the same (Chiew and McMahon, 1993). Several authors (Rome et al., 2015; Fellah et al., 2017; Qadem et al., 2019) have used this test to detect breaks in hydroclimatic series. The test statistic is defined as follows:

$$|KS| = \frac{1}{n}\max\left|\sum_{i=1}^{k} a_i - M\right| \quad \text{(eq. 1)}$$

Where KS: test statistic, Ai: value of the study variable, M: median or mean of the series of variables

Evaluation of the drying up coefficients and drying up times of the sub-catchment:

In order to evaluate the drying up coefficients on the sub-watersheds, the application of Maillet's law of exponential decrease is required. This law has already been used by other authors (Kouassi et al., 2013; Sorokoby et al., 2013, Yao, 2015; N'gnessan, 2017). The equation in exponential form is as follows:

$$Q_t = Q_0 e^{-kt}$$ (eq. 2)

With Q_t = flow rate at the given time t; Q_0 = initial flow rate (flow rate at the start of tapping); k = Maillet tapping coefficient.

The method for extracting the drying phases consists in selecting decreasing flow rates during phases not influenced by rainfall. The sequential curve approach has been adopted (Figure 3). This choice is based on the fact that this approach is rigorous, as underlined (Descroix et al., 2015).
The expression of the drying time T (in days) can be formulated by the equation:

$$T = \frac{1}{k}$$ (eq. 3)

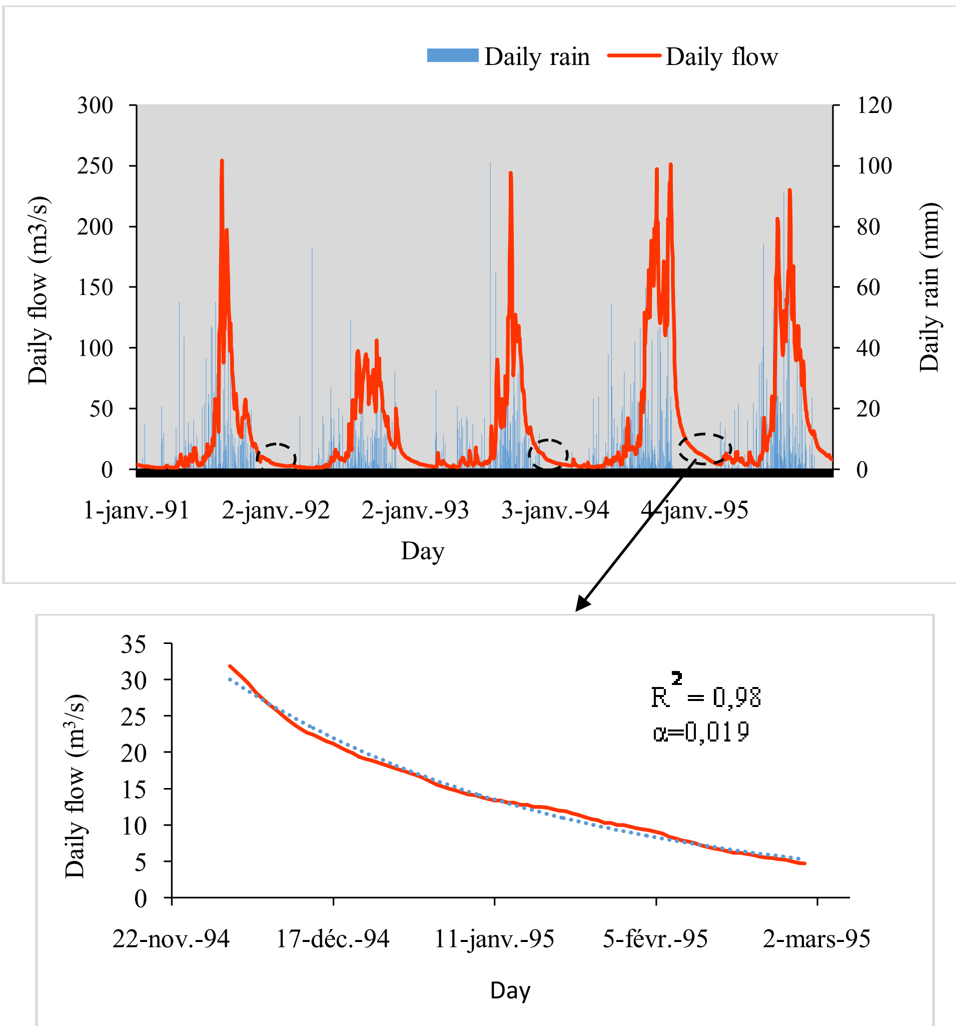


Figure 3:- Example of a drying sequence curve (Flow: Boa river at Vialadougou; rain: Odienné).

Assessment of the volumes of water mobilized by the aquifers of the sub-catchment:
In an uninfluenced regime, it is estimated that the annual depletion curve expresses the successive emptying of the underground tank(s). The quantity of water recovered at the gauging station corresponds to the dynamic volumes mobilized by all the aquifers in the catchment area. It has been used to estimate the volumes of water mobilized by the aquifers in Côte d'Ivoire (Kouassi et al., 2013;Sorokoby et al., 2013, Yao, 2015; N'gnessan, 2017). The volume of water mobilized is given by the equation:

$$Vmobilized = \int_0^\infty Q_0 e^{-kt}\, dt = \frac{86400 \times Q_0}{k}$$ (eq. 4)

Results: -

Analysis of annual rainfall before and after the breaks:

The analysis of the results in Table 1 shows that the breaks are between 1982 and 2000. The average annual rainfall varies between 1087.7 and 1620.8 mm before the breaks. After the breaks, they vary between 980.2 and 1689.4 mm. These results show a decrease in rainfall in Odienné, Touba, Séguéla, Man and Sassandra. On the other hand, an increase in rainfall was observed after the breaks in Vavoua, Daloa, Guiglo, Gagnoa and Soubré. The downward variation rates vary between 4.6 and 16.3%. While upward variation rates vary between 1.1 and 16.2%.

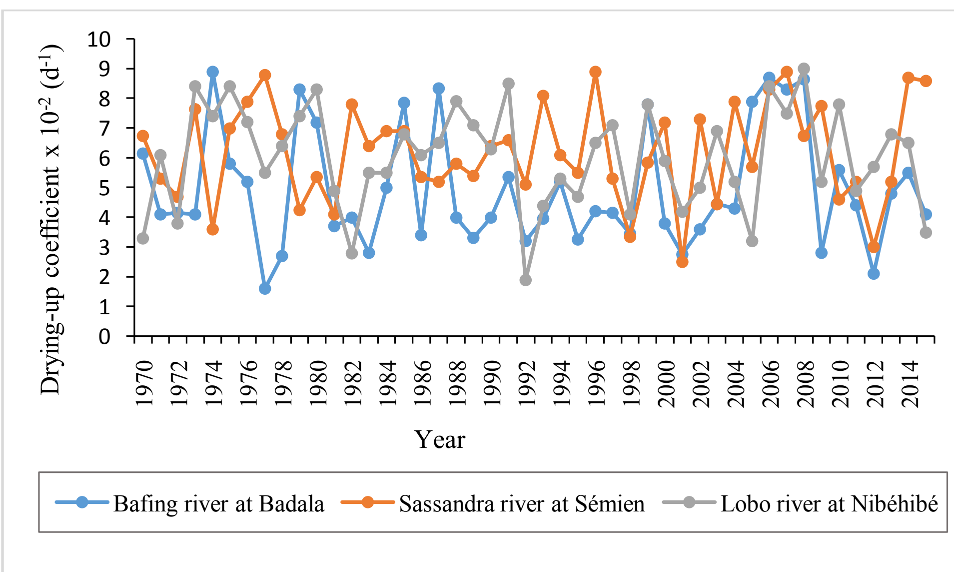
Table 1:- Variation of annual rainfall before and after breaks.

Station	year of the break-up.	Annual rainfall (mm)		
		Average before breaking.	Average after breaking.	Rate of variation. (%)
Odienné	1982	1540.13	1346.92	-12.5
Touba	1992	1132.03	1080	-4.6
Séguéla	1993	1087.7	980.15	-9.9
Man	2000	1603.94	1418.66	-11.6
Vavoua	1984	1103.91	1115.56	+1.1
Daloa	1994	1206.08	1283.08	+6.4
Guiglo	1985	1620.77	1689.44	+4.2
Gagnoa	2000	1321.82	1535.32	+16.2
Soubré	1986	1289.43	1444.24	+12.0
Sassandra	1982	1540.13	1288.79	-16.3

Analysis of the drying up coefficient of the sub-watersheds:

Interannual variation of the drying up coefficient:

The interannual evolution of the drying up coefficients of the sub-catchment areas is presented in figure 4. In the dry sub-tropical climate, on the Boa river at Vialadougou, these drying up coefficients vary between 1.1 10^{-2} and 8.9 10^{-2} d^{-1}. In the equatorial climate, the drying coefficients vary between 1.6 10^{-2} and 8.9 10^{-2} d^{-1} on the Bafing river at Badala. On the other hand, on the Sassandra river at Semien and the Lobo river at Nibéhibé, they vary respectively from 2.5 10^{-2} to 8.9 10^{-2} d^{-1} and from 1.9 10^{-2} to 9 10^{-2} d^{-1}. In mountainous areas, these drying coefficients fluctuate between 4 10^{-2} and 9.6 10^{-2} d^{-1} on the N'zo river at Kahin. In the humid equatorial climate, they fluctuate between 3.3 10^{-2} and 9.3 10^{-2} d^{-1} on the Davo river at Dakpadou.



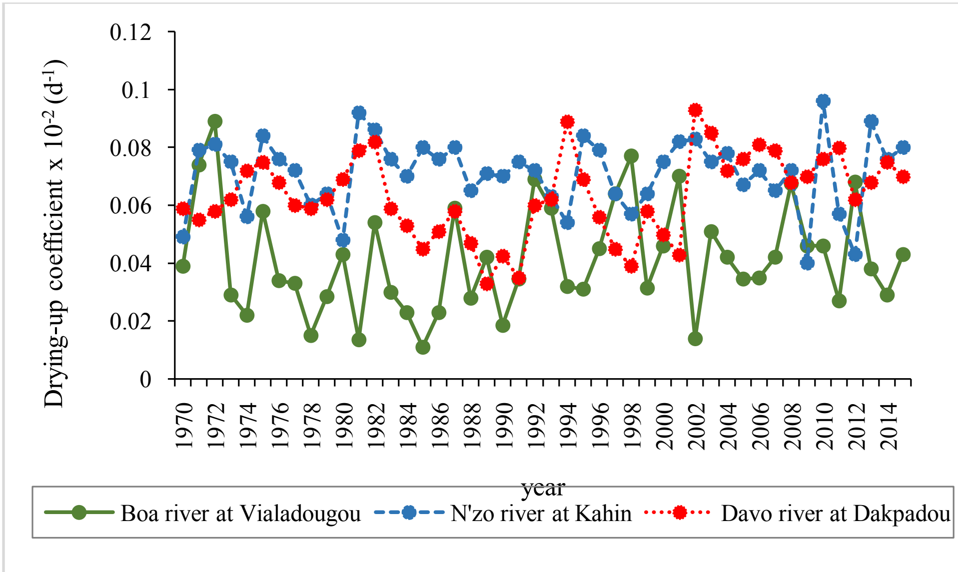


Figure 4:- Interannual variation in the drying up coefficients of the Sassandra sub-basins.

Variation in the drying up coefficients before and after breaks:

The results in Table 2 show the variation in average drying coefficients before and after the break years. These results show that the average drying coefficients vary between $3.7.10^{-2}$ d^{-1} and $6.3.10^{-2}$ d^{-1} before the break years. After the years of breakage, the drying coefficients vary between $3.2.10^{-2}$ d^{-1} and $6.2.10^{-2}$ d^{-1}. An increase in the drying coefficient was observed on the Bafing river at Badala, the Boa river at Vialadougou and the Davo river at Dakpadou. The rate of increase in the average drying coefficient varies between 17% and +25.9%. On the other hand, a decrease was observed on the Lobo river at Nibéhibé (1.6%) and the N'zo river at Kahin (2.8%). The variation before and after the breaks on the Sassandra river at Semien is constant at 6.2 10^{-2} d^{-1}.

Table 2:- Variation of the drying coefficient before and after breakage.

Rivers	**Station**	**year of the break-up**	**Average drying coefficient x 10^{-2} (d^{-1}).**		**Rate of variation (%)**
			Average before breaking	**Average after breaking**	
Bafing	Badala	2003	4.7	5.5	+17.0
Boa	Vialadougou	1991	3.7	4.6	+24.3
Davo	Dakpadou	2001	5.8	7.3	+25.9
Lobo	Nibéhibé	1991	6.3	5.9	-6.3
N'zo	Kahin	1987	4.1	3.2	-22.4
Sassandra	Sémien	1985	6.2	6.2	0.0

Analysis of the drying up times of the sub-watersheds:

Interannual variation in drying up times:

Figure 5 shows the year-to-year variation in the average drying time. In the equatorial climate, these average durations vary from 11 to 63 days on the Bafing river at Badala. On the other hand, they vary between 11 and 40 days on the Sassandra river at Semien and 11 and 53 days on the Lobo river at Nibéhibé. In the dry sub-tropical climate, average durations vary between 11 and 91 days on the Boa river at Vialadougou. In a mountainous climate, the average duration varies between 10 and 25 days on the N'zo river at Kahin. In humid equatorial climate, they vary between 11 and 30 days on the Davo river at Dakpadou.

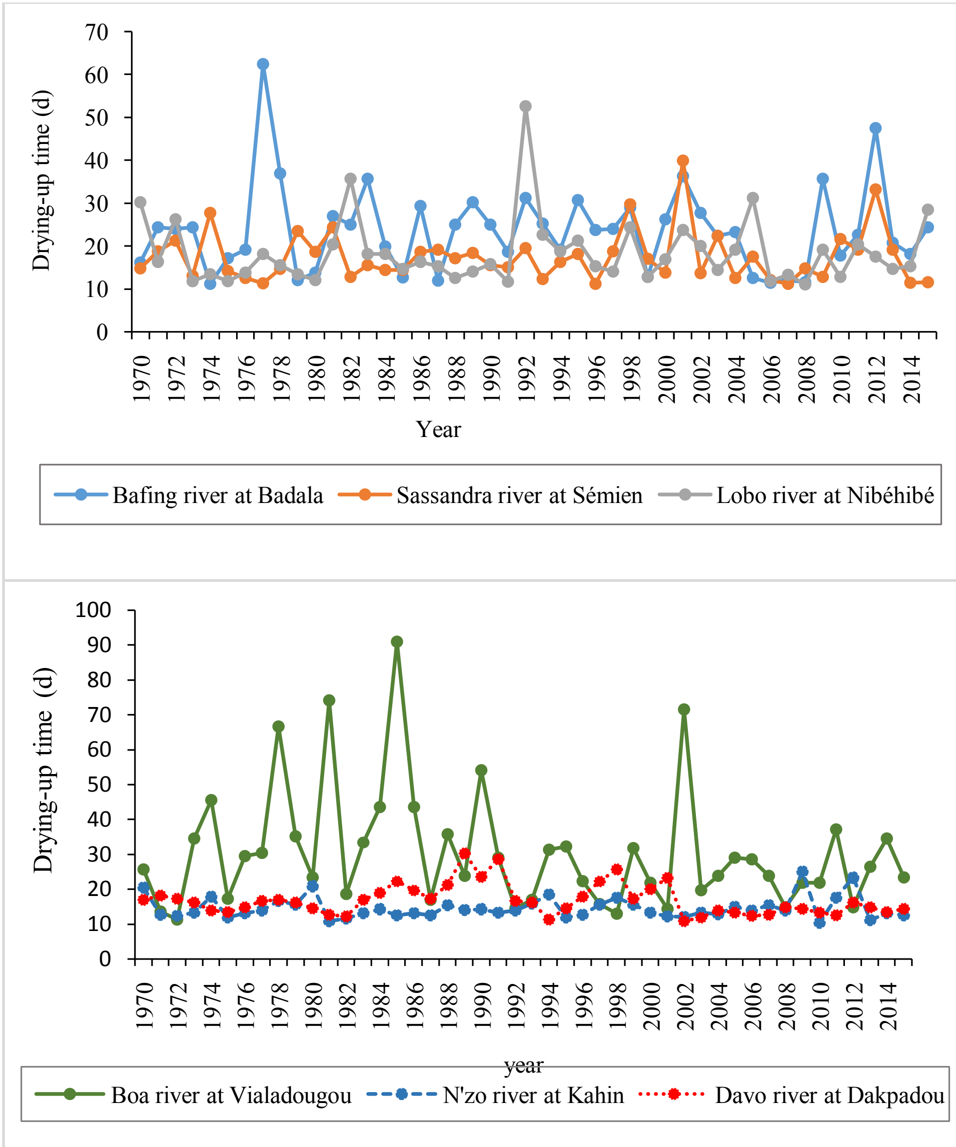


Figure 5:- Interannual variation in the drying up time of the Sassandra sub-basins.

Variation in the drying up time before and after breaks:

Table 3 shows the average drying times before and after the break-up years. The values of the drying times fluctuate between 14 and 27 days before the break years. They vary between 14 and 22 days after the break years. These results show a decrease in the average duration on the Bafing river at Badala, the Boa river at Vialadougou and the Davo river at Dakpadou. The rate of reduction varies between 14.3 and 18.5% (3 to 5 days). On the other hand, constant values of the drying up time were recorded after the break years on the Lobo river at Nibéhibé, the N'zo river at Kahin and the Sassandra river at Sémien.

Table 3:- Variation of drying time before and after break.

Rivers	Station	Year of the break-up	Average drying time (day).		Rate of variation (%)
			Average before breaking	Average after breaking	
Bafing	Badala	2003	21	18	-14.3
Boa	Vialadougou	1991	27	22	-18.5
Davo	Dakpadou	2001	17	14	-17.6
Lobo	Nibéhibé	1991	16	16	00

N’zo	Kahin	1987	14	14	00
Sassandra	Sémien	1985	16	16	00

Analysis of the volumes of water mobilized by aquifers of the sub-watersheds:

Interannual variation in the volumes of water mobilized by aquifers:

The interannual evolution of the volumes of water mobilised by aquifers is shown in Figure 6.At the level of the equatorial climate, the volumes of water mobilised vary between 0.064 and 0.002 km^3 on the Bafing in Badala with an average of 0.022 km^3. On the other hand, on the Sassandra in Sémien and the Lobo in Nibéhibé, they vary respectively from 0.1 to 0.09 Km^3 and from 0.004 to 3.10-5 Km^3. The average volume of water mobilised is 0.045 Km^3 on the Sassandra at Semien and 0.001 Km^3 on the Lobo at Nibéhibé. As regards the dry sub-tropical climate, on the Boa in Vialadougou, they vary between 0.031 and 0.001 Km^3 with an average of 0.01 Km^3. In mountainous areas, the volumes of water mobilised fluctuate between 0.033 and 0.001 km^3 with an average of 0.01 km^3 on the N'zo at Kahin. At the level of the humid equatorial climate, they fluctuate between 0.028 and 0.001 Km^3 on the Davo at Dakpadou with an average of 0.009 Km^3.

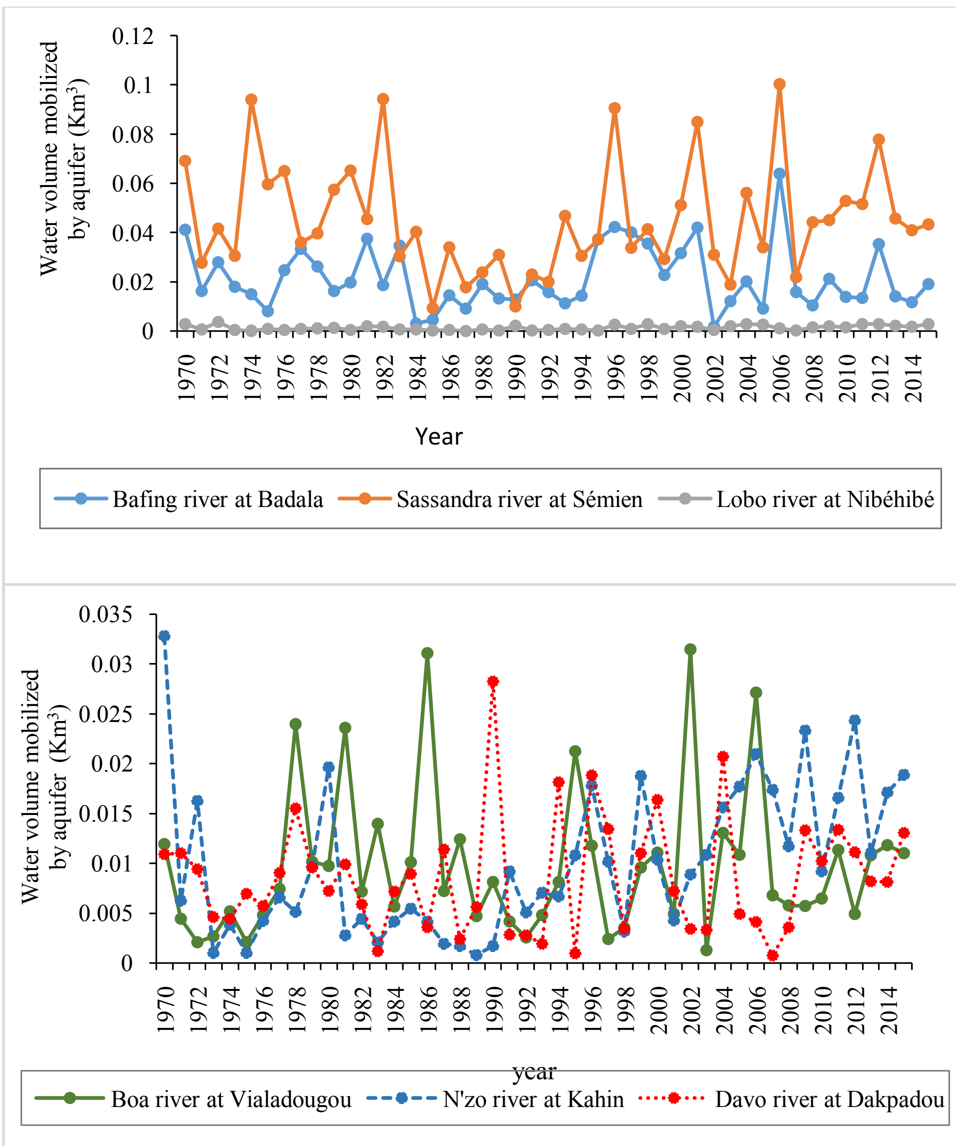


Figure 6:- Interannual variation in the volume of water mobilized by the aquifers of the Sassandra sub-basins.

Interannual variation in the volumes of water mobilized by aquifers before and after break:
The results in Table 4 show the variation in the volumes of water mobilised by aquifers before and after the break. These volumes of water mobilised by aquifers vary between 0.003 km^3 and 0.180 km^3 before the break years. They fluctuate between 0.005 km^3 and 0.150 km^3 after the years of break. An increase in the volumes of water mobilised was observed on the Boa in Vialadougou (11%), the Lobo in Nibéhibé (29.2%) and the N'zo in Kahin (54%). On the other hand, a drop was recorded after the breaks on the Bafing in Badala (-50.7%), the Davo in Dakpadou (-21.1%) and the Sassandra in Semien (-16.7%).

Table 4:- Changes in the volume of water mobilized by aquifers before and after breakage.

Rivers	**Station**	**Year of the break-up.**	**Volume of water mobilized by aquifers (km^3).**		**Rate of variation (%)**
			Average before breaking	**Average after breaking**	
Bafing	Badala	2003	0.050	0.025	-50.7
Boa	Vialadougou	1991	0.038	0.042	+11
Davo	Dakpadou	2001	0.029	0.023	-21.1
Lobo	Nibéhibé	1991	0.004	0.005	+29.2
N’zo	Kahin	1987	0.003	0.005	+54
Sassandra	Sémien	1985	0.180	0.150	-16.7

Discussion:-

The cumulative sums test allowed the detection of breaks in the annual rainfall. These breaks, which occurred between 1982 and 2000, differ from one station to another. This difference in the other stations could be due to the fact that they do not belong to the same climatic zone. The effect of continentality and morphology could also be mentioned to explain this variability in the years of rupture. The interannual variability of rainfall in the Sassandra catchment area indicates a slight decrease in rainfall heights in Odienné, Touba, Séguéla, Man and Sassandra after the break years. An increase in rainfall was observed in Vavoua, Daloa, Guiglo, Gagnoa and Soubré. This decrease would be due to the fact that the Sassandra basin is in an area impacted by climate change, as it is located at the level of West Africa after these years of ruptures. The increase in rainfall could be linked to the resumption of the long wet season. Many authors (Descroix et al., 2015; Panthou et al., 2014) have observed a resumption of rainfall in West Africa after the 1990s. These authors had shown that the decade from 2000 to 2010 had seen an increase in high rainfall events, which would be at the origin of the increase in rainfall over the post-1990s period.

The variation in the average drying up coefficients evaluated before and after the break years show an increase at Bafing in Badala (4.7 to 5.5. 10-2 d-1), Davo in Dakpadou (5.8 to 7.3. 10^{-2} d^{-1}) and Boa in Vialadougou (3.7 to 4.6. 10^{-2} d^{-1}). The relatively high values of the drying up coefficients indicate that these rivers are more sensitive to the surrounding climatic conditions and respond better to the drying up phenomenon. This increase would be due to a slight decrease in rainfall observed at Man, Odienné, Séguéla. These results are in agreement with those of N’gnessan et al., (2017) on the Lobo. N’gnessan et al., (2017) showed that a rainfall deficit observed since 1970 has resulted in an increase in the drying up coefficients and a decrease in the volumes mobilized by the aquifers. On the other hand, a decrease in drying up coefficients was observed on the rivers of the Lobo at Nibéhibé (6.3 to 5.9. 10^{-2} d^{-1}) and N'zo at Kahin (4.1 to 3.2. 10^{-2} d^{-1}) despite the decrease in rainfall at Man and Daloa. The fluctuation of these rivers does not depend essentially on the rainfall in Man and Daloa. The average drying up period varies from one river to another. During the dry period, it is high on the Boa in Vialadougou (30 days), Sassandra in Sémien (18 days), Lobo in Nibéhibé (18 days) and Davo in Dakpadou (17 days). It is low on the N'zo in Kahin (15 days). A long drying time indicates slow drying, while a short drying time indicates rapid drying. Thus, rivers such as the Boa in Vialadougou, the Sassandra in Sémien, the Lobo in Nibéhibé and the Davo in Dakpadou have experienced slow drying up and the N'zo in Kahin, rapid drying up. Slow depletion reflects the low permeability of the aquifers. High permeability would result in rapid discharge and thus rapid drying up (Goula et al. 2006). These results are in line with the studies carried out by Saley (2003), Sorokoby et al. (2013) on the rivers of the Sassandra catchment area. Saley (2003) showed a rapid drying up on the Ko and N'zo rivers and a slow drying up on the Bafing and Sassandra rivers in Semien. As for Sorokoby et al. (2013), they showed a slow drying up on the catchment areas of Débo and Bô in Soubré. The average duration of the drying up varies upwards or downwards after the years of breakages. This variation in the duration of drying up could be explained by the distribution of rainfall in the basin. It could also be linked to the importance of the rains that arrive in the dry season and which support the low water level (Goula et al.

2006). In fact, low water flows depend on the filling of the water table at the end of the rainy season and the law of the river's drying up.
The volumes of water mobilised by the aquifers have regularly decreased on the Sassandra (Sorotona and Semien), the Bafing in Badala, the Gagnoa and Davo (Gagnoa-Issia and Dakpadou) after the years of break. These years of ruptures were identified in 1985, 1987, 1991, 2001 and 2003. This reduction in water volumes is characterized by a slight drop in rainfall observed at Touba, Séguéla and Man after 1992, 1993 and 2000 respectively. The low rainfall has contributed to the reduction of water reserves and the volumes of water mobilized by the aquifers of the different catchment areas of the region.

Conclusion:-

This study assessed the impacts of climate change on surface water resources. The results show that the years of rainfall failure (1982-2000) differ from one climatic zone to another. The rainfall variability made it possible to observe an average decrease in rainfall heights in Odienné, Man and Sassandra after the breaks. On the other hand, an increase in average rainfall was observed in Daloa and Gagnoa. The variability of the drying up coefficients made it possible to show an average increase in the drying up coefficients on the Bafing in Badala, the Boa in Vialadougou and the Davo in Dakpadou after the breaks (1985-2000). These rivers are therefore subject to a much more rapid emptying of the aquifers supplying the base flow. On the other hand, a slower emptying has been observed on the Lobo at Nibéhibé and the N'zo at Kahin with an average decrease in drying up coefficients. A shortening from 3 (Bafing in Badala and Davo in Dakpadou) to 5 days (Boa in Vialadougou) of the drying time was observed. The variability in the volumes of water mobilized by the aquifers made it possible to show an upward trend on the Boa in Vialadougou, the Lobo in Nibéhibé and the N'zo in Kahin. On the other hand, a reduction in the volumes of water mobilized was observed on the Bafing in Badala, the Davo in Dakpadou and the Sassandra in Sémien after the ruptures.

Acknowledgment:-

The authors thank the Department of Hydraulic Infrastructure division, Government of Côte d’Ivoire for data acquisition

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