Climate Variability and Its Impact on Groundwater Resources: A Case Study of Sakassou Department, Central Côte d'Ivoire

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Abstract: ***This study examines climate variability and its effects on groundwater resources in the Sakassou Department of central Côte d'Ivoire, a region dominated by agriculture. Consequently, monitoring the evolution remains a critical concern. Using hydroclimatic data from 1981 to 2017, many statistical methods (e.g., Nicholson Rainfall Index, Pettitt Test, Hubert Segmentation) and the Thornthwaite water balance approach are applied. Results reveal a significant climatic shift in 1991, marked by alternating wet and dry phases and a 13.26% rainfall decline, reducing effective infiltration by 72.01%. These findings highlight the vulnerability of groundwater recharge to climatic changes, offering insights for improved water resource management in similar tropical settings.***

Keywords: Climate Variability, Rupture, Water Resources, Sakassou, Côte d'Ivoire

1. Introduction

Water is precious. It is enough that we lack it, even a little, to discover its importance. This lack of water is very often the product of climate variability. Indeed, climate variability can manifest itself in long periods of drought with negative effects on the hydrological cycle, the environment and socio-economic activities. In Côte d'Ivoire, global and local studies have highlighted the impacts of climate variability on water and the environment. Thus, a deficit of 21% was observed in the Ivorian rains [1]. These different observations can also be observed in the department of Sakassou with an essentially rural and agricultural population. Given the variability of the climate and the sometimes dramatic consequences that this can entail, the evolution of water resources is a worrying issue, both for economic development (agriculture, hydroelectric energy) and for the future of populations (health, drinking water supply, food security). This study thus aims to provide a hydrological contribution to the international scientific community's reflections on climate variability and instability. This study aims to characterize climate variability in central Côte d'Ivoire and its impact on these groundwater resources.

2. Data And Methods

2.1 Presentation of the study area

The study area is located in central Côte d'Ivoire, between longitudes 5°00'–5°40' W and latitudes 7°10'–7°40' N. It covers an area of 1688.4664 km² and includes four (4) sub-prefectures and includes more than 15 villages (Figure 1). The climate is Baouléan with 4 seasons including 2 dry seasons (December to March and mid-July to the end of August) and 2 rainy seasons (April to mid-July and September to November). The average temperature in this department is between 24.3 and 27.1°C. Geomorphologically, it is a low-lying area. There is a variety of relief, including very steep high plateaus (254 to 316 m above sea level), plateaus with a steep slope (224 to 254 m above sea level), plateaus (201 to 224 m above sea level), plains (186 to 201 m above sea level) and shallows (178 and 201 m above sea level).

Geologically, the study area is made up of 3 mains areas:

- Eburnean granitoids: in homogeneous biotite granite units, biotite granites, two-mica granites, intrusive granites. To the north and east of the study area;
- Birrimians: This set is largely made up of undifferentiated meta-sediments and a small part of meta-sediments plus meta-vulcanites. The volcano sedimentary rocks are characterized by conglomerates, sandstones and shales visible around Lake Kossou [2]. To the south and west of the study area;
- Antebirrimian: This group is essentially made up of ancient migmatites, mainly to the north of the study area.

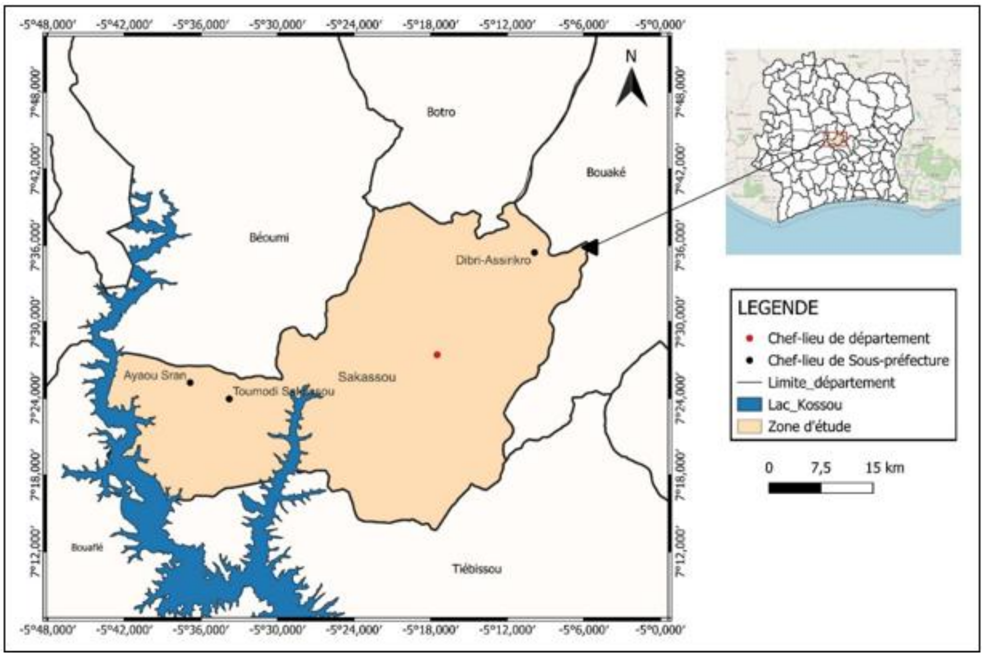

Figure 1 : location of the department of Sakassou

2.1 Data

This study required the use of annual and monthly rainfall, temperatures and relative humidity covering the period 1981-2017 of the Langui-Bonoua and Sakassou stations. These climate data come from the Airport and Meteorological Development Corporation (SODEXAM). Khronostat 1.01 and XLSTAT were used for this study.

2.2 Methods

The methodological approach is divided into two stages. A statistical study, based on the use of statistical tests and an evaluation of the characteristic variables of groundwater. The study takes into account the closest station to the study area, Sakassou.

2.2.1 Studying climate variability

a) Nicholson Rainfall Index

This index measures the deviation from a long-term average using station data. The annual rainfall index is defined as a reduced centred variable. It is obtained by calculation using equation 1**[3]**:

$$IP = (Xi - Xm) / \sigma \qquad (1)$$

With:
Xi: Rainfall for year i;
Xm: Average interannual rainfall over the reference period;
σ: Standard deviation of interannual rainfall over the reference period;
Ip: Rainfall index.

The rainfall index thus reflects a rainfall surplus or deficit for the year in question compared to the reference period

b) Hanning 2-order low-pass filter (weighted moving averages)

It is a method of eliminating seasonal variations in a given time series. The calculation of weighted rainfall totals is carried out by means of a succession of equations**[4]**. These equations make it possible to estimate each term in the series :

$$X(t) = 0{,}06x(t-2) + 0{,}25x(t-1) + 0{,}38x(t) + 0{,}25x(t+1) + 0{,}06x(t+2) \qquad (2)$$

For $3 \leq t \leq (n-2)$

Where X (t) is the weighted total rainfall of the term t; X (t-2) and X (t-1) are the main observed rainfall totals of the two terms immediately preceding the term t. $X_{(t+2)}$ and $X_{(t+1)}$ are the observed rainfall totals of the two terms immediately following the term t. is the weighted total rainfall of the term t; X (t-2) and X (t-1) are the main observed rainfall totals of the two terms immediately preceding the term t. X (t+2) and X (t+1) are the observed rainfall totals of the two terms immediately following the term t. (n being the size of the series) :

$$X(1) = 0{,}54X(1) + 0{,}46X(2) \quad (3)$$
$$X(2) = 0{,}25X(1) + 0{,}5X(2) + 0{,}25X(3) \quad (4)$$
$$X(n-1) = 0{,}25X(n-2) + 0{,}5X(n-1) + 0{,}25X(n) \quad (5)$$
$$X(n) = 0{,}54X(n) + 0{,}46X(n-1) \quad (6)$$

To better visualize periods of rainfall deficit and surplus, the moving averages were centered and reduced using the following formula:

$$Y't = (X(t) - m) / \sigma \quad (7)$$

Where m is the mean of the weighted average series and σ is the standard deviation of the weighted moving average series. This method seems more effective because it allows the series to be cut in a perceptible way.

2.1.2 Determination of fractures within a hydroclimatic series:

a) Pettitt rupture Test

This test assumes in principle that any series of time series is made up of a sequence of independent random variables X1, X2,..., XN. This sequence is assumed to have a break at a date τ if the Xt (t=1,…,-1) have a common distribution denoted F1(X), different from the common distribution F2(X) of the

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Xt(t= τ+1,…, N). F1(X) and F2(X) are two subdivisions of the main series. In this context, the H0 : τ=N of non-rupture with respect to the alternative hypothesis H1 : 1≤τ<N is carried out by means of a non-parametric statistical test. No assumption is then made about the nature of the probability distribution of the variable defining the series of observations**[5]** . The continuity condition is the only one required for the functional forms of F1(X) and F2(X). The statistical variable Ut,N of this test is defined by the formula of equation 14 denoted:

$$\boldsymbol{U_{t,N} = \sum_{i=1}^{t} \sum_{j=t+1}^{N} D_y} \ (14)$$

This formulation makes it possible to test the belonging of the two samples (X1,...,Xt) and (Xt+1,..., XN) to the same population. Ut, N is considered for the values of t between 1 and N. The H0 non-failure hypothesis against the H1 failure hypothesis is tested by the KN variable in equation 15 denoted:

$$\boldsymbol{K_N = max|U_{t,N}|} \ (15)$$

The probability of not exceeding an approximate value k, with regard to rank theory, is given by the formula in equation 16 denoted:

$$\mathbf{Prob}(\boldsymbol{K_N > k}) - \boldsymbol{2expo}(-\boldsymbol{6^2/(N^3 - N^2)}) \ (16)$$

Hypothesis H0 is rejected if for a risk α of the first kind, the probability given is less than α. The series will present a break with the date t=τ defining KN. This test, sensitive to a change in the average of the series studied, is a test on the rank

b) Hubert's segmentation procedure

This approach, defined by **[6]** suitable for finding one or more breaks in a time series. In practice, the initial series is divided into m segments or subseries using the least squares technique (m>1) in such a way that the mean calculated on any segment is significantly different from the mean of the neighboring segment(s). The partition of this series into m segments is a segmentation of order m. The segmentation operation is as follows:

Either **ik**, k = 1, 2,…, m, the initial series rank of the terminal end of the k^{th} segment ;

X k the average of the k^{th} segment ; Dm, the squared deviation between the series and the segmentation under consideration is obtained by the formula of equation 17 denoted:

$\boldsymbol{D_m = \sum_{k=1}^{k=m} d_k}$ (17)

With $\boldsymbol{D_m = \sum_{i=i_{k-1}-1}^{i=k} (X_i - \overline{X}_k)^2}$ so that dk is the minimum possible.

The segmentation retained at the end of the operation is such that for a given order m of segmentation, the square deviation Dm is minimum and the means of the two contiguous segments are significantly different.

This constraint is satisfied by the Scheffé test, which is based on the concept of contrast. Hubert's segmentation procedure can be considered as a stationarity test.

If the procedure does not produce an acceptable segmentation of order greater than or equal to 2, the assumption of stationarity of the series is accepted.

c) Statistical trend tests

Les tests de tendances sont des tests qui permettent de dégager ou d'estimer par le biais de certaines méthodes l'existence ou non d'une tendance dans une série chronologique avec un niveau de signification donné.

d) Mann-Kendall test

The non-parametric Mann-Kendall test (**[7] [8]**) allows you to study the presence or absence of a trend in a given time series. Let the series

Xt = (x1, x2,... xn), this method defines the standard multivariable normal UMK as:

$U_{\mathrm{MK}} = \frac{S}{\sqrt{Var(s)}}$ (9)

Où :

$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(x_j - x_i)$ (10)

sng (x) = $\left\{ \begin{matrix} 1, x>0 \\ 0, x = 0 \\ -1, x<0 \end{matrix} \right\}$ (11)

$S = \frac{n(n-1)(2n+5) - \sum_{i=1}^{n} t_i \, i(i-1)(2i+5)}{18}$ (12)

Where S is the relationship between the number of observation pairs, and n is the total number of samples. A time series has a clear trend, defined at the 5% significance level. In this test, the null hypothesis H0 "absence of trend" is accepted if the Pvalue is greater than 5%. In this case, the time series studied does not show a trend. If the Pvalue is less than 5%, then the variable under study shows a trend. The direction of the trend is defined by the statistical Mann-Kendall coefficient "U.MK". If U is positive, the trend is upward, but if U is negative, then the trend is downward.

e) Sen's Estimator

The SEN'S method **[9]** is used to estimate the slope of a time series of regularly spaced data. It consists of calculating the slopes of all the data in the series according to the following equation:

Pij = (Xj – Xi) / (j-1) (13)

with Pij : the slope calculated between the data points i and j, Xj: the measurement data on the date j and Xi the one on the date i, (i= 1, 2, 3, 4,………n et j =i+1……n)

The Sen's slope estimator is given by the median slope PM, according to the following equation:

PM = $\left\{ \begin{matrix} \frac{1}{2}\left(P_{\frac{N}{2}} + P_{\frac{N+2}{2}}\right) \text{ si N est pair} \\ P_{\frac{N+2}{2}} \text{ si N est impair} \end{matrix} \right\}$ (14)

with N : Number of slopes calculated

A confidence interval of either Lower Slope (Pinf) and Upper Slope (Psup) is calculated to define the true confidence interval for the median slope PM.

Pinf=M1 and Psup= M2. + 1.

$$\begin{cases} M1 = \frac{\frac{N-C}{2}}{N+C} \end{cases} \quad (15)$$

with N : Number of slopes calculated;
C : the range of ranks for the given confidence interval,
$C = Z_{1-\frac{\alpha}{2}} \sqrt{Var(S)}$ (16)
Where the centered variable reduces $Z_{1-\frac{\alpha}{2}}$ is read from the Gauss table and the Mann-Kendall variance Var(S) is determined by:
$Var(S) = \frac{1}{18}\left[r(n-1)(2n+5)\sum_p^q (t_p 1) t_p (2t_p 5)\right]$ (17)
with n : the number of observations, q: the number of identical values and TP: the number of repetitions for each identical value.

2.1.3 Calculation of average changes

For hydroclimatic variables with a break in the time series, it is interesting to calculate the average changes on either side of the break by applying the following formula **[10]**:

D = (Xj/Xi) -1 (18)

where Xj is the average over the period after the breakup and Xi is the average over the period before the breakup.

2.1.4 Water balance

For the determination of the water balance, the THORNTHWAITE method was chosen, taking into account the available data. The main parameters calculated are potential evapotranspiration (ETP), actual evapotranspiration (ETR) and excess or effective infiltration.

3. Results and Discussion

3.1 Fluctuating weather regime

The study of rainfall variability from the values of the Nicholson index and the Hanning low-pass filter made it possible to follow the major changes that have taken place in the region from 1981 to the year 2017. The rainfall indices of the Sakassou station were analyzed.

Interannual rainfall fluctuations in Sakassou (Figure 8) are characterized by wet periods from 1981–1988, 1997–1998, and 2008–2015. They are interspersed with two dry periods that range from 1989 to 1996 and from 1999 to 2007, and from 2016 to 2017. The low-pass filter makes it possible to clearly distinguish between the different periods.

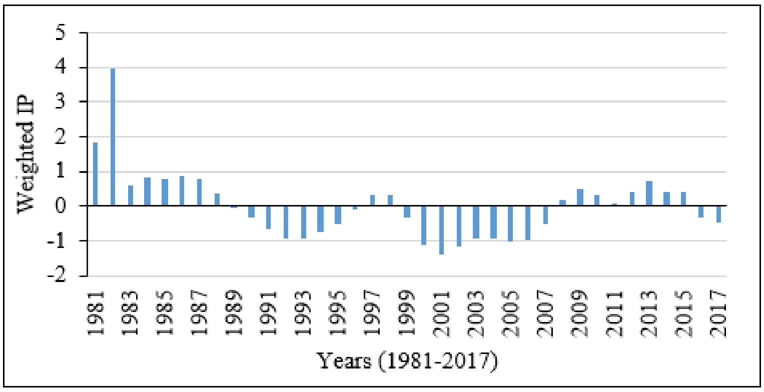

Figure 8: Nicholson's weighted rainfall index of the Sakassou station (1981-2017)

3.2 Frequency analysis of climate parameters

The frequency analysis of the climatic parameters has made it possible to highlight the very wet, wet, normal, dry and very dry years.

In Sakassou (1981-2017), we can see that very dry years occur in 1992, 1994, 2001, 2002, 2006 and 2007 respectively, as shown in Table I. While very wet years are found in 1981, 1982, 1985, 1987, 2010, and 2014 respectively.

Table 1: Répartition des périodes climatiques à la station de Sakassou (1981-2017)

		Sakassou Station
Periods Climate	Very dry	1992; 1994; 2001; 2002; 2006; 2007
	Dry	1983; 1996; 2003; 2004; 2005; 2008; 2017
	Normal	1986; 1990; 1993; 1995; 1998; 2000; 2011; 2012; 2013; 2015; 2016
	Wet	1984; 1988; 1989; 1991; 1997; 1999; 2009
	Very Wet	1981; 1982; 1985; 1987; 2010; 2014

3.3 Rainfall Statistical Tests

3.3.1 Homogeneity tests

The summary of the results of the homogeneity tests is summarized in Table 2. These tests made it possible to detect the presence or absence of rupture in the rainfall series studied (Figure 9).

Table 2: Results of the statistical tests of the rainfall series

STATIONS	Homogeneity tests: homogeneous series		Year of rupture
	Segmentation	Pettitt	
SAKASSOU	YES	YES	1991

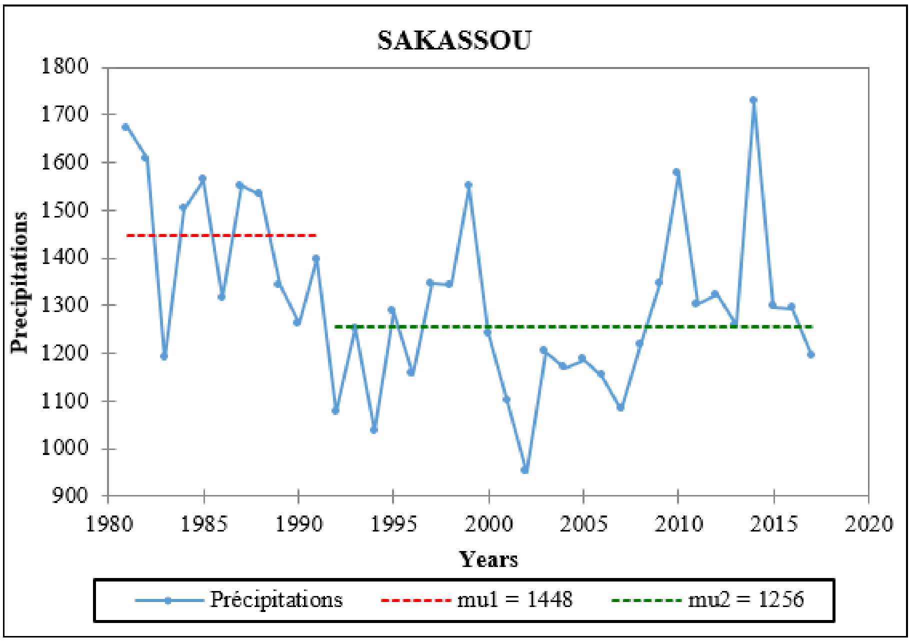

Figure 9: Segmentation test on the Sakassou station

3.3.2 Trend Testing

The results of the Sen's and non-seasonal Mann-Kendall trend tests are reported in Table 2. These results confirm those of the homogeneity tests. Rainfall in Sakassou shows a downward trend.

Table 3: Results of statistical tests of non-seasonal rainfall trend

Sen's Test				
Station	Pinf	Pmoy	Psup	H0: Trending No Significant
Sakassou	-7,026	-5,413	-3,426	no
Mann-Kendall Test				
Station	P value	H0: absence Trending	U.MK	Trend Sens
Sakassou	0,097	no	-0,192	drop

3.4 Detection of breaks in the precipitation regime

3.4.1 Hubert's segmentation

The results of Segmentation of the rainfall series of the Sakassou stations are reported in Table 3. The Sakassou series has been divided into four segments, indicating the existence of three ruptures within it. The break occurred between 1988 and 1989.

Hubert's segmentation procedure does not give a precise date of production of rupture. It places the break between two successive years.

Table 4: Segmentation de Hubert à la station pluviométrique de Sakassou

Beginning (Sakassou)	End	Average	Ecart-type
1981	1988	1491,250	159,649
1989	2017	1264,19	162,468

3.4.2 Pettitt Test

The fluctuations of the variable U of the Pettitt rupture test at the Sakassou station are illustrated in Figure 17. According to these fluctuations, the rainfall series at the Sakassou station experienced a significant climatic break in 1991. This break is characterized by a variable U equal to 176. It generated a rainfall deficit of around 13.26%

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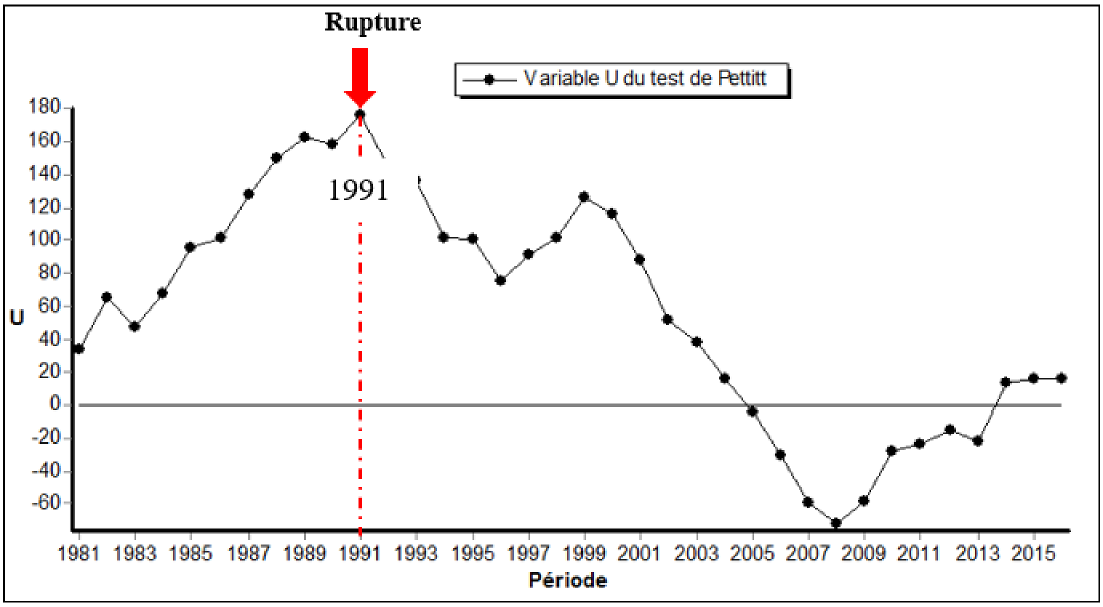

Figure 10: Pettitt test of the Sakassou rainfall series (1981-2017)

3.5 Assessing the Impact of Climate Variability on Groundwater: Using the Thornthwaite Method

To assess the impact of climate change on water resources in this tropical region, we calculated, using the Thornthwaite method, the parameters of the monthly and annual water balance before and after the 1991 breakup. The results are reported in Table 5. Analysis of the table shows that the average annual rainfall, which was estimated at 1448.2 mm before the rupture, increased to 1256.2 mm after the rupture, a decrease of 13.26%. The excess or effective rain, which was 389.8 mm before the break, is reduced to 151.7 mm after the break, a decrease of 61.09%. The average annual runoff, which was about 72.41 mm before the rupture, decreased to 62.81 mm after the rupture, a decrease of 13.26%. The estimated amount of water that infiltrates to recharge the aquifers with fissures in the region has decreased from 317.35 mm before the rupture to 88.84 mm after, a decrease of 72.01%. It can therefore be deduced from all these observations that the volume of water that infiltrates the aquifers, which was 0.54 km3 on average per year before the rupture, is currently reduced to 0.15 km3, a decrease of 72.01%.

Table 5: Récapitulatif des paramètres du bilan hydrologique avant et après la rupture de 1991.

Parameter (mm)	Before the Rupture	After the Rupture	Deficits (%)
Precipitation (mm)	1448,24	1256,18	13,26
ETP (mm)	1513,93	1629,71	-7,65
ETR (mm)	1058,47	1104,53	-4,35
Surplus (P-ETR) (mm)	389,77	151,65	61,09
Runoff (R) (mm)	72,41	62,81	13,26
Effective Infiltration (I.e.) (mm)	317,35	88,84	72,01
Volume of water infiltrated (km3)	0,54	0,15	72,01

Figure 11 shows the evolution of rainfall before and after the 1991 break. This Figure shows that the curve of the evolution of rainfall before rupture is mostly higher than that of rainfall after rupture.

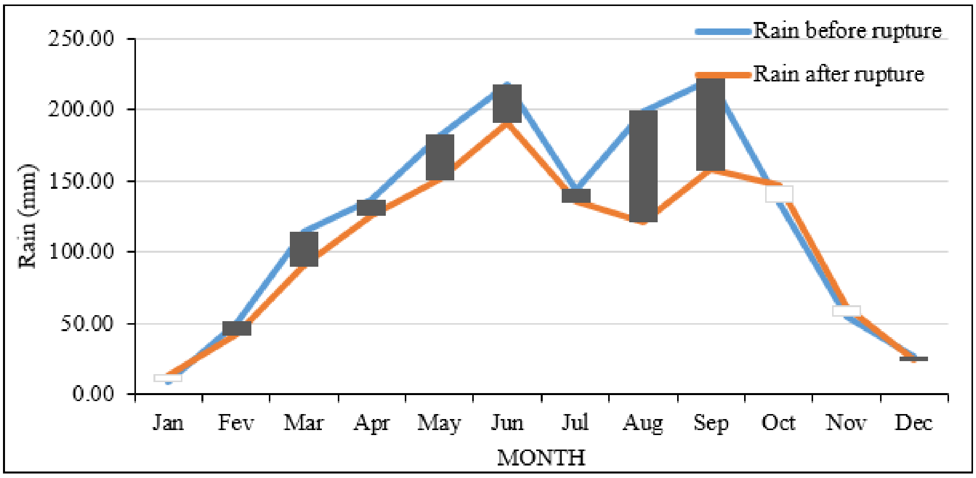

Figure 11: Monthly rainfall trends before and after the 1991 rainfall stationary break

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3.6 Discussion

The interannual variation in rainfall determined by rainfall indices coincides with statistical tests. Indeed, rainfall breaks in the study area are characterized by a decrease in rainfall.

3.6.1 Decrease in rainfall

Statistical methods (Nicholson's indices, Pettitt's test, Hubert's segmentation, etc.) agree on the reality of a significant decrease in rainfall in the department of Sakassou. This significant decrease in rainfall is evidenced by Nicholson's indices from 1988 (dry period 1988-2017) at the Sakassou rainfall station. The decline in rainfall has also been observed for more than thirty years in the Sahelian countries of West Africa and those of the Gulf of Guinea, which are subject to some form of drought **[11]**. This decline is reflected in significant rainfall deficits, as is the case in the department of Sakassou, and often with serious consequences.

This rainfall decrease, observed across West Africa since around 1970, became evident in Sakassou from 1991 onward. The downward trend in rainfall is confirmed by this study over the entire 36 years of observation.

This confirms the observations already made in West Africa by some authors such as **[10], [12]**,**[13]** , etc.... and in Côte d'Ivoire by **[14]** , **[15]**, **[16]**,**[17]**, **[18]**, etc... These observations reveal a trend towards aridification of the continent since 1970.

During the last century, the climate was relatively humid and it was during this period that the exceptionally wet years were recorded. Then, drought set in from 1983-1984. According to Fontaine and Janicot (1993), this deficit was generalized over the whole of West Africa and can be explained by a general decrease in convection despite a normal position of the intertropical convergence zone.

3.6.2 Climate rupture and rainfall deficit

The Pettitt test identified a significant break at these confidence levels (i.e., an error of 1 to 10%) in 1991 at Sakassou. The break thus took place in the direction of the decrease in rainfall during the observation chronicles, confirming this downward trend already announced by the analysis of Nicholson's indices.

The consequences of these ruptures are the significant rainfall decreases recorded respectively at the Sakassou station from 1988 onwards and already evidenced by the Nicholson indices. The rainfall deficit is 13.26% in the department of Sakassou. According to **[19]** this deficit varies from 10 to 31% in the Abidjan-Agboville region. It is of the same order as those obtained in the transboundary basin of the Comoé by **[20]** with rainfall deficits, ranging from 15% to more than 30%. According to the work of **[21]**, rainfall ruptures occurred from 1968 for Dimbokro and 1975 for Bocanda and M'Bahiakro, with rainfall deficits of 12.22 respectively ; 10.37% and 17.18%. Similarly, the work of **[22]** show a decrease in rainfall of 13 and 14% respectively in the N'zi and N'zo watersheds. Climatic disruptions described as late **[23]** were identified mainly in 1983 and 1996, in the Bonoua region, **[14]** and in 1992 in the Yamoussoukro region, **[24]**.

On the other hand, according to the work of **[15]**, some stations in the country did not experience a break in the rainfall series from 1950 to 1999. We can mention the resort of Tabou located on the coast in the South-West, as well as the majority of the stations in the east of the country such as Abengourou, Agnibilékro, Bondoukou and Aboisso.

3.6.3 Hydrological impacts

Climate variability is manifested by an increase in air temperatures, which affects the hydrological cycle in general and causes the formation of raincloud clouds in particular, hence the low annual rainfall levels **[24]**. The surplus obtained from the water balance gives an idea of the impact of rainfall changes on aquifer recharge. Excess water represents the flow out of the ground that can feed into groundwater or waterways. At the Sakassou station, the excess (or "effective infiltration"), which constitutes the share of precipitation likely to reach the groundwater, fell from 389.8 mm (before rupture) to 151.7 mm (after rupture), a decrease of 61.09%. This decline can have consequences on the environment such as : disruption of hydrological regimes, degradation of plant cover, decrease in the amount of water infiltrated, etc. Also the work of **[25]**, showed that groundwater recharge that was replenished by seasonal rainfall over three months in the study area is reduced to one or two months. Thus, the entire N'zi region, formerly called the "Cocoa Loop" in the 70s, has lost this qualifier, because of the decrease in rainfall in this region

3.6.4 Impact on aquifer recharge

The effective infiltration calculated by Thornthwaite's methods from 1991 onwards is 88.84 mm, or 7.07% of precipitation.

The cumulative deficit years after 1991 resulted in a very significant decrease in recharge, leading to a steady decline in the volumes of water in basement aquifers. Given their relatively low permeability and porosity, the storage capacity of water in the middle of the basement is modest and always dependent on seasonal fluctuations and the intensity of recharge **[26]**.

The recharge regime of the aquifers analysed through the infiltrated water sheet is marked by a deficit of around 72.01% by the Thornthwaite method. This deficit is in the same order as that obtained by **[18]**, in the Bagoé watershed (North-West Côte d'Ivoire) where it is estimated at 87.78%. Nevertheless, some groundwater tables in Niger's tertiary sedimentary basins have increased their recharge, despite the reduction in rainfall (**[27]; [28]**). This reduction is due to lower evapotranspiration, and especially to an increase in runoff due to deforestation. We have a stronger recharge, thanks to the surface water accumulated in the endorheic shallows, **[29]**.

4. Conclusion

Like most countries in the tropics, Côte d'Ivoire is prone to climate change. This study, conducted in the department of Sakassou, illustrates this phenomenon and gives an idea of its impact on water resources. Indeed, the Nicholson index and the Pettitt test indicate three breaks. These ruptures are characterized by an alternation of wet, normal and dry periods in the 1981-2017 climatological series. They highlight a significant break around 1991. The latter led to a period of deficit that began in 1992 and continues until today. The deficit period is characterized by a reduction in annual rainfall of about 13.26%. Water resources have suffered a significant decrease in their supply as a result of this climate change, as the water balance shows a decrease in surface runoff and a 72.01% decrease in effective infiltration after 1991. We have recorded a decrease in the volume of infiltrated water from 0.54 to 0.15 km3. However, seasonal bush fires, uncontrolled deforestation without sufficient reforestation, extensive slash-and-burn agriculture and the El Niño phenomenon are other factors in climate disruption.

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