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Hydrological drought characterization within the Comoé river catchment using SDI-Index.

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Abstract— Knowledge of the past manifestations of drought is of capital interest, because it allows firstly to make a quantified assessment of socio-economic losses and secondly to set up models for the management of future droughts based on past events. The main goal of the study is to understand the evolution of the Comoé River flow deficit. For that, monthly flows (at least 40-year record) are used to generate hydrological drought called Streamflow Drought Index (SDI). Change point and Trend statistical tests applied to SDI.3 (3-month scale) series showed that change years are between 1970 and 1976. A trend towards hydrological dryness is observed through negative Sen slopes. the Comoé at Aniassué has experienced more dry episodes than the other gauges (about 50% of the record). In addi-tion, the M'Basso station recorded the most extreme dry events (5% of the study period). This analysis shows that the stations further downstream of the Comoé are vulnerable to long-lasting droughts, unlike those located in the upper and middle Comoé (Kafolo, Sérébou and Akakomoékro). The SDI used in this study really addresses the issue of the flow deficit and deserves to be much more widely used in studies in sub-Saharan Africa.Further studies could, also, be carried out for a rational management of the river water to mitigate the human influence on drought.

Index Terms— Climate Variability, Hydrological Drought, SDI-index, Sen's slope, Comoe river, West Africa.

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1 Introduction

DROUGHT is a natural hazard that results from insufficient precipitation (runoff, soil moisture) compared to the long-term average (over at least 30 years), which is called a normal value [1]. One of the main consequences of multi-annual droughts is severe famine, such as that associated with the Sahel drought of the 1980s, which resulted in many casualties and significant socio-economic losses [2]. African populations living in drought-prone areas are vulnerable to the direct impacts of droughts (e.g., famine, livestock deaths, soil salinisation), as well as indirect impacts (e.g., diseases such as cholera and malaria) [3]. Hydrological drought refers to a decrease in surface or groundwater resources, usually river flows, reservoir storages and aquifers [4].

Hydrological droughts can have impacts by reducing water supply, deteriorating water quality and limiting water for irrigation purposes and causing crop failure, reducing power generation, disturbing riparian habitat ecosystems, limiting recreational activities, and generally affecting economic and social activities. The consequences on the hydrological regimes of the large river basins of inter-tropical Africa are significant. In general, the water conditions of the rivers have decreased significantly. Average annual flows have fallen by more than 30% and sometimes by more than 50% [5]. In Côte d'Ivoire, studies carried out in the various basins (Comoé, Bandama, N'zi, N'zo) have also shown a decline in water resources, both surface and underground [6]. Almost all of these studies have not studied drought as such. The Comoé watershed, the subject of the study, is representative of the major hydro-bio-climatological complexes of Côte d'Ivoire. Due to its latitudinal spread, this watershed straddles the country's three climatic zones (tropical in the north, transitional equatorial in the centre and equatorial in the south) [6]. The insufficiency of gauges in the basin (with short duration series) is a reality in our study basin. The challenge is to understand the evolution of the drought at the outlet of some stations along the main river. This information will be of capital importance for the realization of hydro-agricultural infrastructures and drinking water supply. In addition, the analysis of hydrological droughts allows a direct quantification of deficits in usable water sources.

Although the origin of hydrological droughts is generally climatic, the quantification of hydrological droughts as independent phenomena has also received much attention from the scientific community. This is because there are usually no direct spatial or temporal relationships between the occurrence of climatic droughts and hydrological droughts [7],[8]. The characteristic hydrological drought index (flow deficit) used in this study is the Streamflow Drought Index (SDI) developed by [9]. The index has been used by several authors [10],[11],[12]. The objective of the study is to understand the evolution of the Comoé River flow deficit through the time series of the SDI. The knowledge of past manifestations of this phenomenon is of capital interest, as it would allow the setting up of future drought management models based on past events.

2 Material and Method

2.1 Study Area

The Comoé river basin is a transboundary basin shared by Côte d'Ivoire, Burkina Faso, Ghana and Mali (Fig. 1). It is located between latitudes 5 ° 02' and 11 ° 04' North and longitudes 2 ° 07' and 5 ° 81' West in the geographic coordinate system (WGS 84, zone 30 N). The Comoé River rises in the Banfora region of Burkina Faso. With a course of 1160 km, it is the longest river in Côte d'Ivoire. Its bed drains a catchment area of about 78 000 sq. km. It flows in a North-South direction and has no major tributaries. On the left bank are the Dioré, the Ba grossi of the Ifou, the Béki, and the Manzan, and on the right bank the Kossa. From the source to Sérébou, the bed of the Comoé is cut by a few rocky sills which give rise to minor rapids. Only one drop is of interest for a possible hydroelectric development: the rapids between Attakro and Aniassué, which give a few metres of fall. Apart from a steep gradient at the source, the average gradient is fairly low: 250 m of gradient for 1050 km, i.e., 0.25 m per km. The main tributaries of the Comoé River catchment make up about 24% of the hydrological network, while the secondary tributaries make up about 76% (Fig. 1).

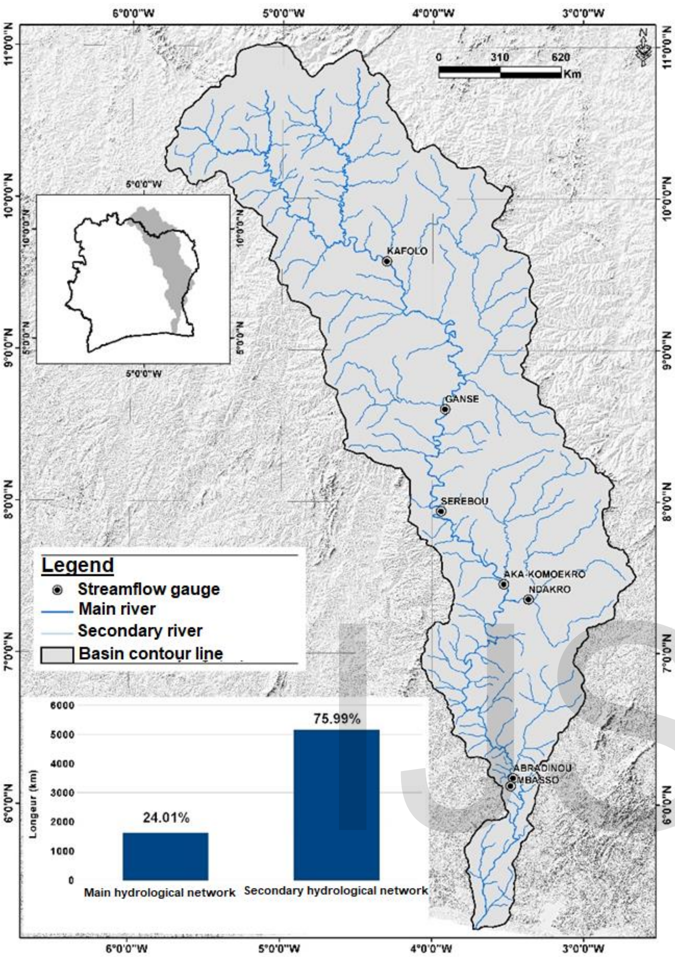

Fig. 1. Location of the Comoé watershed and streamflow gauges.

2.2 Data

The study data are only river flows on a monthly scale. And only the major gauges on the main course of the Comoé have regular data but with some gaps. This is due not only to the socio-political crisis (1999-2010) leading to an increasing impoverishment of the measurement network (many gauges are rendered useless due to poor calibration) but also to a lack of monitoring of the existing network. Many stations have gaps in their observations. The selected streamflow gauges and their records are the following. From north to south, the stations of Kafolo (1972-1995), Sérébou (1962-1997), Akakomoékro (1956-1997), Aniassué (1954-1999) and M'Basso (1956-1995) downstream (Figure 1). The data used have at least a 40-year record, with the exception of the Kafolo station. The monthly flows of these different stations were used to generate the hydrological drought indices according to the following methodology.

2.3 Method

2.3.1 Formulation of the Streamflow Index (SDI)

Hydrological drought is defined as a significant decrease in the availability of the water resource in all its forms that occurs in the terrestrial phase of the hydrological cycle [10]. It is assumed that a monthly series of measurements of a flow volume in a basin over a given period $Q_{i,j}$ with i indicating the hydrological year and j the rank of the month in which the survey was carried out in that year (j=1 for October if the hydrological year started in October and j=12 for the month of September). Based on this series, we obtain (1):

$$V_{i,k} = \sum_{j=1}^{3k} Q_{i,j} \qquad i = 1,2,\ldots \quad j = 1,2,\ldots,12 \quad k = 1,2,3,4 \qquad (1)$$

Where $V_{i,k}$ is the cumulative runoff volume of the ith hydrological year (of the time series) of the kth reference period, k=1 of the period from October to December, k=2 for October-March, k=3 for October-June, and k=4 for October-September.

Based on the cumulative runoff volume $V_{i,k}$, the hydrological drought index SDI is defined for each reference period k of the ith hydrological year of the following series by the following formula (2):

$$SDI_{i,k} = \frac{V_{i,k} - \bar{V}_k}{s_k} \qquad i = 1,2,\ldots, \quad k = 1,2,3,4 \qquad (2)$$

Where $\bar{V_k}$ and S_k are respectively the mean and the standard deviation of the cumulative volume elapsed during the reference period k as well as these have been estimated over a long period. In this definition, the truncation level is set by $\bar{V_k}$ although other values could be used. This type of index had already been used, but the question of non-stationarity of the series was not addressed as the author had worked at the annual scale. Generally, for small basins, the flow has an asymmetric probability distribution which can be fitted by the Gamma family of functions. The distribution is then transformed into a normal distribution. The easy-to-use two-parameter lognormal distribution is used for fitting monthly flow series [11]. Thus, the SDI taking into account non-stationarity is defined as follows (3 and 4):

$$SDI_{i,k} = \frac{y_{i,k} - \bar{y}}{S_{y,k}} \qquad i = 1,2,\ldots, \quad k = 1,2,3,4 \quad (3)$$

$$\text{where } y_{i,k} = \ln(V_{i,k}), \quad i = 1,2,\ldots, \quad k = 1,2,3,4 \qquad (4)$$

are the logarithms of the cumulative flows with the mean and standard deviation estimated over a long record. The classification of hydrological drought states is identical to that of the SPI (Standardized Precipitation Index). Five states are considered from 0 (no drought) to 4 (extreme drought) and are defined in Table 1. The SDI for 3-month scale (SDI.3) was preferred in the study. The computer tool used to calculate the SDI is the DrinC software developed by [13].

TABLE 1

DEFINITION OF THE STREAMFLOW DROUGHT INDEX STATES [10]

State	Description	Criterion	Probability (%)
0	No Drought	SDI ≥ 0.0	50
1	Mitigated drought	-1.0 ≤ SDI < 0.0	34.1
2	Moderate drought	-1.5 ≤ SDI <- 1.0	9.2
3	Severe drought	-2.0 ≤ SDI < -1.5	4.4
4	Extreme drought	SDI < -2.0	2.3

2.3.2 Autocorrelation test of monthly flow series

Autocorrelations or lagged correlations are used to assess whether a time series is dependent on its past. For a time series x of length n we consider the $n-1$ pairs of observations one time unit apart. The first such pair is (x[2], x[1]), and the next is (x[3], x[2]). Each such pair is of the form (x[t], x[t-1]) where t is the observation index, which we vary from 2 to n in this case. The lag-1 autocorrelation of x can be estimated as the sample correlation of these (x[t], x[t-1]) pairs.
The acf() command du logiciel R provides a shortcut. This command was used to test this hypothesis.

2.3.3 Stationarity and change point tests in the calculated SDI.3 series

The methods selected among many others for the determination of breaks and trends in a series are based on the synthesis work of [14]. Hydrological series are rarely symmetrical and the normality condition is not always verified. In order to overcome the assumptions for the application of parametric tests, i.e., normality and independence, so-called "resampling" methods are used to obtain an estimate of the distribution of the test statistic under the null hypothesis and thus to determine the critical values. Resampling techniques are a particularly flexible approach as they can be used even when the data are auto-correlated or cyclical, using block-bootstrap techniques [15],[16]. The different tests used in this study are listed in Table 2, and the related statistics are in [17].

TABLE 2
DIFFERENTS STATISTICAL TESTS USED IN THE STUDY

Test	Change detection	Trend detection
Non-parametric	Free CUSUM distribution	Mann-Kendall
Parametric	t-Student	Linear regression

2.3.4 Linear trend slope estimation

In the present study, the linear trend is analyzed and the magnitude of the trend is estimated through Sen's slope method used by [18]. Sen's median slopes method gives a robust estimate of the tendency. It calculates the slope (5) as a change in the value of the distribution in a given time interval.

$$Q' = \frac{x_{t'} - x_t}{t' - t} \quad (5)$$

Q': Slope between data points $x_{t'}$ and x_t
$x_{t'}$: Value of x at t'
x_t: Value of x at t

Sen's slope estimator is expressed as the median of the slopes (6 et 7).

$$\begin{cases} Q = Q'_{\left(\frac{N+1}{2}\right)} \quad if\ N\ is\ even & (6) \\ Q = \dfrac{Q'_{\left(\frac{N}{2}\right)} + Q'_{\left(\frac{N}{2}\right)/2}}{2} \quad if\ N\ is\ uneven & (7) \end{cases}$$

Where, N is the number of slopes calculated.
Finally, the slope is examined by bilateral test with a standard deviation of 100(1-α) %, and the true slope is obtained by a non-parametric test.

3 RESULTS

3.1 Assessment of autocorrelation and skewness of monthly flow series

Table 3 provides information on the flow characteristics, from upstream to downstream, at the different stations on the main course of the Comoé. The annual modulus increases from upstream to downstream. The Kafolo station with a value of 57.3 m^3/s has the lowest average. The further downstream the modulus increases, with values of 136.49, 158.65 and 188.62 m3/s respectively for the stations of Sérébou, Akakomoékro and Aniassué. The M'Basso station, further downstream, has an average flow of 165.62 m3/s, unlike Aniassué. The high standard deviations indicate a high variability of flow in the basin. The monthly flow series are highly asymmetrical (Table 3), hence the use of the Log-Normal law for the adjustment of the monthly flow totals in the calculation of the flow deficit index.

TABLE 3
CHARACTERISTICS OF THE MONTHLY FLOW SERIES

Station	Kafolo	Sérébou	Akakomoékro	Aniassué	M'Basso
Month	284	414	462	552	439
Mean	57.03	136.49	158.65	188.62	165.62
Median	11.00	27.00	23.20	38.00	42.00
SD	105.69	249.36	304.65	315.84	276.29
Skewness	2.82	2.74	2.91	2.44	2.57

In Fig.2, the horizontal dotted lines represent the confidence intervals of the correlation coefficient equal to 0. The vertical lines represent the correlation coefficients between month i and subsequent months. As an example, the lag-plot indicates that there is significant autocorrelation for lags 1, 11, and 12 for the Kafolo station, as the vertical line is above the horizontal line of the confidence interval of the correlation coefficient equal to 0 (Figure 2a). In our study, lag-1 is sufficient to judge the presence of autocorrelation in the data. This is the case for all hydrometric stations, where autocorrelation is observed (Fig. 2a, 2b, 2c, 2d and 2e).

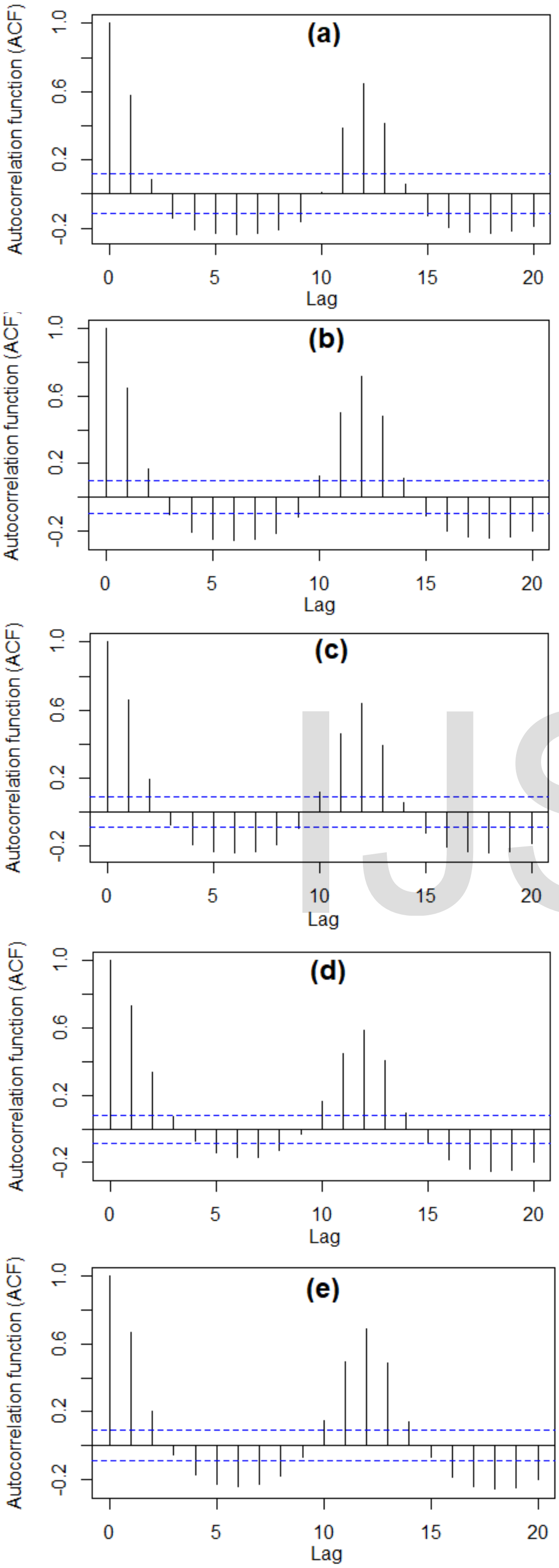

Fig. 2. Autocorrelation function plot (ACF) of streamflow time series: a-Kafolo; b-Sérébou; c-Akakomoékro; d-Aniassué et e-M'Basso.

3.2 Interannual analysis of SDI.3 series

Fig. 3 illustrates the evolution of the SDI.3 over the whole record of the different stations studied. The Kafolo series begins with a major wet trend from 1972 to 1982 (Fig. 3a). However, this period is punctuated by incursions of a few months with low water levels.

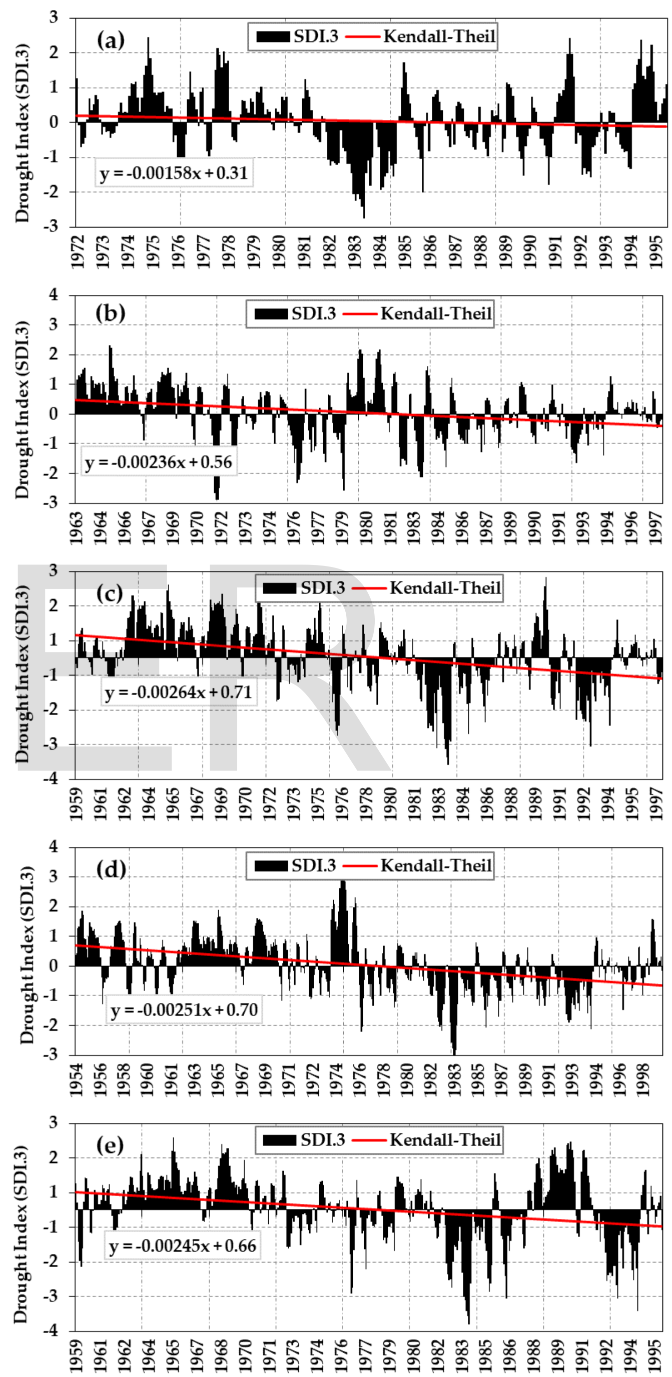

Fig. 3. Interannual analysis of SDI.3 series: a-Kafolo; b-Sérébou; c-Akakomoékro; d-Aniassué et e-M'Basso.

From 1982 to 1985, a period of strong hydrological deficiency sets in with SDI.3 values between -1 and -3, synonymous with severe to extreme droughts. Immediately after this period, there was an alternation of dry and wet months. A resumption of runoff is observed from 1994 onwards. At the Sérébou station, a period of above-normal flow is observed from 1963 to 1970. This was followed by a dry period until the end of 1978 (Fig. 3b). The following three years remained wet. The period after 1982 is characterised by mostly dry months. In Akakomoékro, the break in runoff was observed around 1975, giving way to a period of hydrological indigence where runoff was lower than normal. As at Akakomoékro, the turning point is found around 1976 at the Aniassué station (Figure 3c). In contrast to the other stations, the long dry period just after the break is only slightly interspersed with incursions of wet months (Fig. 3d). At the M'Basso station, the year 1972 marked the beginning of a decline in runoff. This state of affairs became more pronounced between 1982 and 1987. Immediately afterwards, a slight recovery is observed from 1987 to 1991, which also soon gives way to a flow deficit until the end of the record (Fig. 3e).

3.3 Change point and trend in the SDI.3 series

The results of the application of the break and trend tests to the SDI.3 series are reported in Table 4. The tests show some complementarity. The year when stationarity was broken for all flow gauges is around 1970. More precisely, the Sérébou station was established in October 1970, the Akakomoékro station in September 1975, the Aniassué station in April 1976 and the M'basso station in July 1972. The breaks are confirmed by the CUSUM and t-Student test at α = 0.01. Unlike the other stations, the Kafolo series has a short record (less than 30 years) which does not guarantee the reliability of the test results. The trends observed in the series are downward. These hypotheses were tested using the non-parametric Mann-Kendall test and the parametric linear regression test. The results are highly significant for all stations with a risk of error of α = 0.01.

The rates of change observed show a decrease in water conditions over time, resulting in negative rates of change (Table 5). The stations of Sérébou and Akakomoékro suffer less from the drought with respective rates, in absolute value, of 4.29% and 3.78%. The stations of Aniassué and M'Basso, further downstream of the basin, the rate of change is practically double that of the stations further upstream with respective values of 8.91% and 9.58%. The very high value of the rate for the Kafolo station indicates a high level of indigence for this upstream part of the basin, which is subject to lower rainfall.

TABLE 4
STATISTICAL TESTS FOR CHANGE POINT AND TREND APPLIED TO SDI.3 SERIES

Station	Test de rupture				Test de tendance			
	CUSUM		*t-Student*		*Mann-Kendall*		*Linear Regression*	
	MD	Stat $_{\alpha=0,01}$	t	Stat $_{\alpha=0,01}$	Z_{score}	Stat $_{\alpha=0,01}$	Z_{score}	Stat $_{\alpha=0,01}$
Kafolo	136 **(April-1994)**	38	12.15	2.43	-10.16	2.67	-10.37	2.34
Sérébou	70 **(October-1970)**	35	7.86	2.30	-6.70	2.58	-5.77	2.62
Akakomoékro	99 **(September-1975)**	35	9.81	2.35	-8.72	2.57	-9.01	2.63
Aniassué	136 **(April-1976)**	36	12.15	2.43	-10.16	2.43	-10.36	2.41
M'basso	96 **(Jun-1972)**	35	7.93	2.48	-6.65	2.59	-6.32	2.62

TABLE 5
SEN'S SLOPE AND CHANGE RATE OF HYDROLOGICAL DROUGHT

Station	Mean	Sen's slope (.10-3)	Change percent (%)
Kafolo	0.03	-1.58	-23.83
Sérébou	0.05	-2,36	-4.29
Akakomoékro	0.04	-2.65	-3.78
Aniassué	0.02	-2.51	-8.91
M'Basso	0.02	-2.45	-9.58

3.4 Occurrences of observed drought intensities

On the basis of Table 1, characterising the hydrological drought status, the frequency of the different drought classes in terms of intensity was calculated. The frequency of the drought classes is shown in Figure 4. Slightly less than half of the study period remains in deficit for the stations of Kafolo (48%), Sérébou (48%), Akakomoékro (46%) and M'Basso

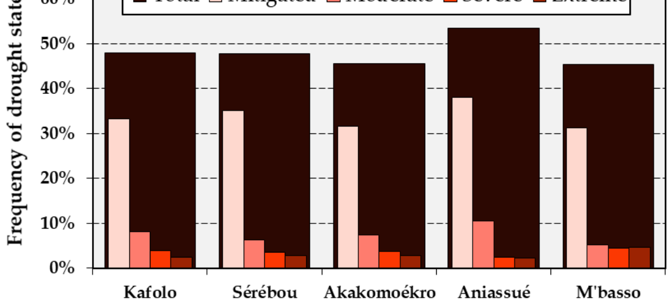

Fig. 4. Frequency of different droughts states along the main course of the Comoé River.

(45%). At the Aniassué station, runoff remained below average for just over half the months of the study period. Mild drought is the most observed in the basin, followed by moderate drought (between 11% and 5% of the record). Severe to extreme droughts were rare. M'Basso had the highest number of extreme drought situations with 5% of the entire record, i.e., about 10% of the dry months.

4 Discussion

The year of change observed in the SDI.3 series is around 1970 for all hydrometric stations. Indeed, West Africa experienced a widespread drought from 1970 to 1990, a drought without equivalent in the world, which continued in the Sahel until 2002 [19], [20]. Indeed, according to the work of [6] on the Comoé basin, watercourses could fall by more than 50% towards the end of the 21st century. These different series are punctuated by severe to intense episodes, especially in the downstream part of the basin (Aniassué and M'Basso). Moreover, a period of strong hydrological deficit was observed from 1982 to 1985 over the whole catchment area with very low SDI.3 (≤ -2) synonymous with severe to extreme drought. During this period, the whole world experienced a significant decrease in precipitation. The literature reshowed the occurrence of four extreme drought events in Africa during the last 50 years. Of these events, three were severe. These are the episodes of 1972-1973, 1983-1984 and 1991-1992. Especially the episode from 1982 to 1983 that was affected much of the earth [21]. Indeed, the 1970-1990 rainfall deficit led to a twofold deficit in flows in West Africa [5],[19]. The consequences on the hydrological regimes of the large river basins of intertropical Africa are significant. In general, the water conditions of the rivers have decreased significantly. Average annual flows have fallen by more than 30% and sometimes by more than 50% [5]. The rivers in the wetter regions, which were relatively unaffected until 1980, have also experienced significant decreases in flow.

The rate of progress of the drought from one month to the next is higher for the stations further downstream along the main course of the Comoé. This rate is almost double that of the stations further upstream. This could be due to the high pressure of demand or the very marked low-flow conditions in this part of the basin. Indeed, the pressure on the resource through human activities that consume water (domestic use, irrigated agriculture, traditional mining activities, etc.) can have an impact on the hydraulic capacity of the river. In this respect, the work of [22] is very edifying. its results showed that that with human water consumption drought intensities increased substantially by 50%–500% over the western, central, and eastern US, southern Canada, and central Mexico, where human water consumption appears to be the main driver causing the drought event for both years. Over Europe, the intensification of drought conditions is milder than that over the US due to lower human water consumption, but it is still substantial over central and southern parts of the region under major drought events such as those of 1976, and 2003. Over these regions, the drought conditions are driven primarily by human water consumption. We find that the intensification of droughts is driven by industrial and households' water consumption (≈70–90% of total water consumption) over west-central Europe, including the UK, Germany, France and The Netherlands, while it is caused primarily by irrigation water consumption (>70% of total consumption) over southern Europe, including Spain, Italy, and Greece. The magnitude of the intensification is 10%–200% for the year 1976, but it rises to 40%–300% due to increased human water consumption for the year 2003. Over Asia, during the major drought of 2001, the intensification of droughts was most severe over India, Pakistan, Afghanistan, Uzbekistan, Turkmenistan, and north-eastern China, where irrigation water consumption exceeds 90% of total water used (Wada et al 2012). For these regions, drought intensities increased by 200%–500% as a result of substantially reduced local and downstream flow [22].

5 Conclusion

In order to understand the impact of drought on the different parameters of the water cycle, hydrological drought was addressed through the Streamflow Drought Index (SDI). On the basis of this index, past manifestations of this phenomenon were investigated. Thus, the Comoé at Aniassué has experienced more dry episodes than the other stations (about 50% of the record). In addition, the M'Basso station recorded the most extreme dry events (5% of the study period). This analysis shows that the stations further downstream of the Comoé are vulnerable to long-lasting droughts, unlike those located in the upper and middle Comoé (Kafolo, Sérébou and Akakomoékro). The study shows that hydrological drought is the order of the day in the catchment area, with a downward trend in the SDI.3 series significant at a risk of $\alpha = 1\%$. The change years are between 1970 and 1976. A significant flow deficit is observed after the break dates in the SDI.3 series. As the Comoé catchment is drought prone, an approach is taken to understanding the flow regime (in low-flow) and the natural resilience of the catchment to these flow deficit events. Further studies could be carried out for a rational management of the river water to mitigate the human influence on this disastrous phenomenon.

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