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## Comparative Analysis of Meteorological Drought based on the SPI and SPEI Indices

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### Abstract

The management of water resources in our states has become increasingly difficult in recent times due to the frequency and intensity of droughts. In the context of climate change, extreme weather and climate phenomena such as floods and droughts that are increasingly occurring have adverse consequences on the socio-economic development of the Senegalese territory. Droughts that affect water availability, agricultural production, and livestock operations are generally identified and characterized using drought indices. The objective of this paper is to analyze the hydrological drought trend in two Senegalese regions, the Senegal River valley and the Casamance basin, with different climatic characteristics (Sahelian continental climate and South Sudanian tropical climate, respectively) during the period 1981-2017. For this purpose, daily data from uniformly installed 8 meteorological stations in the two areas were examined, and trends in the standardized precipitation index (SPI) and standardized precipitation-evapotranspiration index (SPEI) were also assessed. The similarities and differences between the indices of the two regions were then examined. In most stations in both areas, there is a statistically significant trend of increasing SPI and SPEI (75% of the stations for SPI and 87.5% for SPEI), despite some negative trends (e.g., SPI in Bakel, SPE and SPEI in Matam, SPEI in Saint Louis). Moreover, the trend of the indices averaged over the stations of the two indices, although generally positive in the two climatic zones considered (with the exception of the SPI in the valley where it is negative), is only significant in the Casamance basin zone.

*Keywords:* Climate Change; Standardised Index; SPI; SPEI; Trend; Hydrological Drought; Environmental Issues.

### 1. Introduction

Drought is a natural hazard caused by a reduction in precipitation below the average. When the phenomenon occurs over a season or for long periods, it creates conditions that are insufficient to meet human and environmental demands [1]. Unlike aridity, which is defined as a permanent state, drought is a temporary climatic phenomenon that usually begins with a dry spell or a period of abnormally dry weather. A drought can also be broadly defined as a temporary and recurrent reduction in rainfall in an area, and is considered one of the most important impacts of climate change on natural and socio-economic systems [2]. Few extreme events are as economically and ecologically disruptive as drought, which affects millions of people around the world each year [3]. Its effects occur after long periods without rainfall, so it is difficult to objectively quantify its characteristics in terms of intensity, magnitude, duration and spatial extent [4-6]. In recent years, drought has become more intense and frequent, negatively impacting many sectors of the economy such as water resources, agriculture and natural ecosystems [7, 8].

Various definitions of drought have been suggested in the literature, all related to specific impacts of drought on economic activities, ecosystems and society, as well as on water management issues. The studies of Wilhite and Glantz

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[9], and Dracup et al. [10] referred to drought as a condition of insufficient moisture caused by a deficit of precipitation over a certain period. According to Pereira et al. [11], drought can be defined as a temporal imbalance in water availability consisting of persistent below-average precipitation of unpredictable frequency, duration and severity. According to Vicente-Serrano et al. [7], drought is described as a natural phenomenon that occurs when water availability is significantly below normal for a long period of time and cannot meet demand.

As reported in Halwatura et al. [12], drought periods can be characterized from a few hours (short-term) to millennia (long-term). The time lag between the onset of a water scarcity period and its impact on the environment and/or socio-economic activities is called the time scale of a drought [7]. Accordingly, drought indices generally consider short-term droughts (three months or less), medium-term droughts (4-9 months) and long-term droughts (12 months or more). Short-term droughts have an impact on water availability in Casamance and the valley and are therefore mainly meteorological and agricultural droughts. On the other hand, long-term droughts also affect surface and groundwater resources and thus hydrological drought [8].

The effects of drought result from a deficiency of surface or ground water in the hydrological system. The first component of the hydrological system affected is usually soil moisture. As the event continues, other components will be affected. This means that the effects of drought have gradually spread from the agricultural sector to other sectors and eventually a shortage of stored water resources becomes detectable. In this respect, drought manifests itself in two aspects: (a) a lack of soil moisture; and (b) shortages of stored water in other reservoirs. Both manifestations generally result from a deficit of precipitation on different time scales. As noted in the study by Wilhite [13], for example, identifying the onset, termination, extent and severity of drought is very difficult because the causal factors of drought are often closely linked and become apparent after a long period of rainfall deficit.

Droughts are effectively monitored using a drought index. A drought index is a quantitative measure that characterises drought levels by assimilating data from one or more variables (indicators) such as rainfall and evapotranspiration into a single numerical value [14]. In Senegal, several drought indices have been described and used. This study examines the sensitivity of the Falémé River, in the Senegal River basin, to droughts due to rainfall deficits. A decrease in water resources has been observed in many African countries in recent years. Water resources in Senegal are characterized by high temporal and spatial variability. Many areas of the country have experienced water scarcity. The valley is the most vulnerable area as it is located in the northern part and is characterized by a low annual rainfall of 200-300 mm [15-17].

These drought indices are often chosen according to the nature of the indicator, local conditions, data availability and validity. The Standardised Precipitation Index (SPI) is the most widely used meteorological drought index. It is calculated from long precipitation data records (period of more than 20 years). In the calculation of the SPI, it is often assumed that precipitation and other meteorological factors are stationary without temporal trends. The standardised precipitation-evapotranspiration index (SPEI), reported for example in the study by Vicente-Serrano et al. [5], is a modification of the SPI that takes into account the effects of evapotranspiration. According to Vicente-Serrano et al. [5], the SPEI is calculated at different time scales based on the probability of non-surpassing precipitation and differences in potential evapotranspiration. The index has the ability to describe the multi-temporal nature of drought. SPI and SPEI can be calculated on different time scales, with time scales of 1, 3, 6, 12 and 24 months commonly used [18, 19]. Drought at time scales of 1, 3 and 6 months are relevant for impacts on agriculture, while 12 and 24 month scales are relevant for hydrological and socio-economic impacts, respectively [20].

Over the past decades, Senegal has experienced an increasing trend of drought and large areas have suffered prolonged and severe droughts at different time scales [15-17, 21, 22]. The situation has continued to deteriorate despite a return to wet years in the period 2000 [16]. Nationwide droughts occur almost every year, leading to losses in agricultural production and shortages of water resources. Particularly in northern Senegal, where monthly, annual and interannual variations in rainfall and temperature are significant, drought has become one of the main natural disasters. Droughts of different duration and severity frequently strike the Senegalese territory each year and result in a significant reduction in the supply of drinking water to the inhabitants and have destructive effects on agricultural production, resulting in considerable ecological losses and adverse socio-economic impacts.

In Senegal, the effects of drought are also exacerbated by poor management of water resources and agriculture [23]. The agricultural sector, which is highly dependent on water sources, is severely affected by drought. However, the effects of drought are not limited to the agricultural sector, they also spread to other sectors. For example, the forestry and environmental sectors are suffering from the drought. The social sector is also affected in terms of changes in agricultural commodity prices, production structure, livestock production capacity, rural-urban migration flows and other welfare measures. Given the frequency of drought since the 1970s, its impact on the country's economy through its effects on agricultural production and natural resources and the possible increase in its impacts in the coming years, mitigation or adaptation measures are essential. The present study was therefore undertaken to make a comparative analysis of hydrological drought in Senegal in the tropical South Sudanese continental environment (Casamance) and the Sahelian environment (river valley) during the period 1981-2017.

## 2. Study Area

The Casamance basin is located in latitude between 12°20' and 13°21' North and in longitude between 14°17' and 16°47' West. The basin covers an area of approximately 20150 km<sup>2</sup> and stretches 270 km from west to east and 100 km from north to south [24]. The climate of the Casamance is Atlantic Sudanian and South Sudanian [25]. The Casamance basin can be subdivided into three parts: the upper basin (Upper Casamance), the middle basin (Middle Casamance) and the lower basin (Lower Casamance) [26]. The Casamance River, which drains the basin, is formed between Fafakourou and Vélingara by the meeting of several small marigots that are often dry in the dry season, and receives a series of tributaries such as the Tiango1 Dianguina (815 km<sup>2</sup> to Saré-Sara), the Dioulacoulon (200 km<sup>2</sup> to Sara Kéita), and the Soungrougrou, (the most important tributary)

The climate of the region is Sudano-Guinean, with rainfall from June to October, with maximum intensity in August and September, and a dry season from November to May. Average rainfall varies from 700 to 1300 mm. The lowest average monthly temperatures are recorded between December and January and vary between 25 and 30°C, the highest are noted between March and September with variations of 30 to 40°C [21].

The Senegal River is the second largest river in West Africa. It is 1800 km long and its basin covers an area of 300,000 km<sup>2</sup>. The Senegal River basin is occupied by a large plain that extends from the foot of the Fouta Djallon Mountains to the north of Senegal (Saint Louis region). The Senegal River is formed by the meeting of the Bafing and the Bakoye at Bafoulabé in Mali. The *Bafing*, which is its main component, is 800 km long and has its source in the central plateau of the Fouta Djallon massif, near the town of Mamou (Guinea). On its Guinean course, it receives contributions from the Téné and about sixty other small tributaries. The Senegal River basin is generally divided into three entities [17, 27] (Figure 1): the upper basin, the valley and the valley.

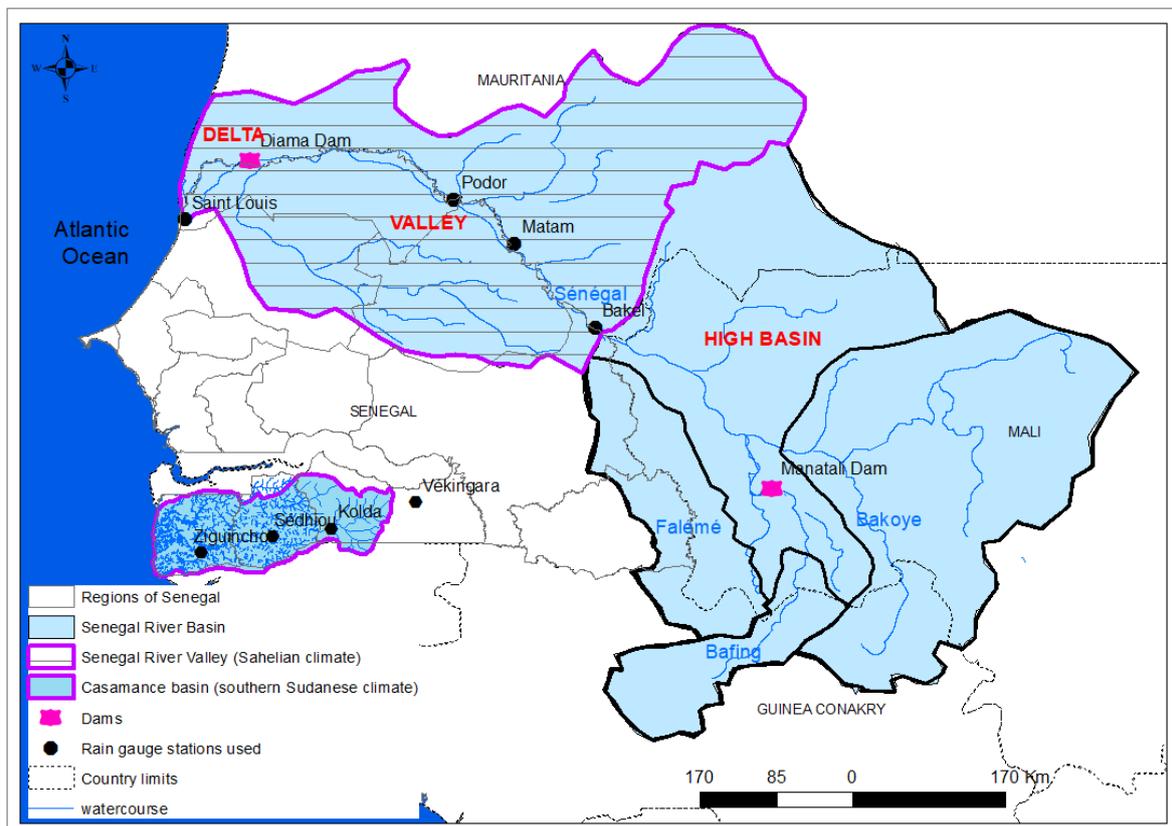


Figure 1. Presentation of the valley in the Senegal River basin, the Casamance basin and the selected stations

The valley, which is the part selected in the Sahelian climate for this study, runs from the Senegal-Falémé river confluence to the traditional limit of the salt tongue rise (Rosso Mauritania); the valley itself is sometimes divided into three parts: the upper valley (between the Senegal-Falémé confluence and the Senegal-Oued Gharfa confluence, at Maghama in Mauritania), the middle valley (from the Senegal-Oued Gharfa confluence to the western limit of the Ile à Morphil in Podor) and the lower valley (from Podor to Rosso Mauritania). Data for these stations were obtained for the years 1980-2017. The study area and the location of the meteorological stations are shown in the valley located in the middle and lower Senegal River basin. Its climate is tropical, but weather conditions are extremely unpredictable. Rainfall varies greatly from one situation to another. The average annual rainfall in the valley is 300 mm [28].

### 3. Data and Methods

#### 3.1. Data

The basic data consists of monthly temperature and rainfall records from 4 weather stations in the Sahelian domain (Bakel, Matam, Podor and Saint Louis) and 4 other stations in the southern Sudanian domain (Ziguinchor, Sédhiou, Kolda and Vélingara). The data were made available to us by the Agence Nationale de l'Aviation Civile et de la Météorologie (ANACIM). The data were used to calculate the average monthly and annual temperature of the entire Senegal River valley (Sahelian domain) and Casamance (South Sudanese domain) over a 38-year period (1980-2017). The average rainfall for each area was calculated using the arithmetic mean, and this was used to calculate indices.

#### 3.2. Methods

In order to characterise the hydrological drought in the two regions, we used two derived indices: the Standardised Precipitation Index - SPI [29] and the Standardised Precipitation-Evapotranspiration Index - SPEI [5]. Both drought indices were calculated for each meteorological station and subsequently represented as a single average value for each region [1].

The calculation of the PESI requires a time series of data on total monthly rainfall (P) as well as monthly potential evapotranspiration (PET). The monthly PET values were calculated by the Thornthwaite method [30, 31], a temperature-based method that uses only the mean monthly temperature and site latitude to estimate potential evapotranspiration. The monthly mean temperature and cumulative rainfall values were used to calculate the SPEI. The formula for determining PET according to Thornthwaite is as follows:

$$PET (mm mois) = 16 \left(\frac{10t}{I}\right)^a \times F(\gamma) \tag{1}$$

where  $t$  is the average monthly temperature in °C, and  $I$  is the annual thermal index. It is the sum of the twelve monthly thermal indices  $i (m)$  and is given by the Equation 2:

$$I = \sum_{m=1}^{12} i (m) \tag{2}$$

With  $i (m)$ , the monthly thermal index which is presented as follows:

$$i(m) = \left(\frac{t}{5}\right)^{1.514} \tag{3}$$

The variable  $a$  is a complex function of the thermal index  $I$  with:

$$a = 0,49239 + 1,79 \cdot 10^{-2} I - 7,71 \cdot 10^{-5} I^2 + 6,75 \cdot 10^{-7} I^3 \tag{4}$$

$F(\gamma)$ The correction factor is a function of the latitude of the location and the month. Its values are tabulated.

The calculation of the SPEI in this study follows the method mentioned in the study of Vicente-Serrano et al. [5]. The SPEI is based on a climatic water balance which is determined by the difference between Precipitation (P) and Potential Evapotranspiration (PET) for month  $i$ :

$$D_i = P_i - ETP_i \tag{5}$$

$D_i$  provides a simple measure of water surplus or deficit for the month under analysis. The TEP is calculated according to the Thornthwaite equation [32].

The calculated values  $D_i$  are aggregated at different time scales, following the same procedure as for the SPI. The difference,  $D_{i,j}^k$  in a given month  $j$  and year  $i$  depends on the chosen time scale,  $k$ . For example, the accumulated difference in one month of a given year, with a time scale of 12 months, is calculated according to the Equation 6;

$$X_{i,j}^k = \sum_{l=13-k+j}^{12} D_{i-l,j} + \sum_{l=1}^j D_{i,l,j}, \quad si j < k, et \tag{6}$$

$$X_{i,j}^k = \sum_{l=j-k+j}^j D_{i,l,j}, \quad si j \geq k \tag{7}$$

where  $D_{i,j}$  is the difference in P-PET of the  $l$ st month of year  $i$ , in mm.

And then the log-logistic distribution is selected to normalise the D-series to obtain the SPEI. The probability density function of the log-logistic distributed variable is expressed as follows:

$$f(x) = \frac{\beta}{\alpha} \left(\frac{x-\gamma}{\alpha}\right)^{\beta-1} \left[1 + \left(\frac{x-\gamma}{\alpha}\right)^\beta\right]^{-2} \tag{8}$$

where  $\alpha$ ,  $\beta$  and  $\gamma$  are respectively the scale, shape and origin parameters for D values within the range ( $\gamma > D < \infty$ ).

Thus, the probability distribution function of the series D is given by:

$$F(x) = \left[1 + \left(\frac{\alpha}{x-\gamma}\right)^\beta\right]^{-1} \tag{9}$$

With  $F(x)$ , the SPEI can easily be obtained as normalized values of  $F(x)$ . For example, following the classical approximation of Abramowitz and Stegun [33]:

$$SPEI = W - \frac{C_0 + C_1W + C_2W^2}{1 + d_1W + d_2W^2 + d_3W^3} = \tag{10}$$

where:  $W = \sqrt{-2 \ln(p)}$  for  $p \leq 0.5$  and  $p$  is the probability of exceeding a given D value,  $p = 1 - F(x)$ . If  $p > 0.5$ ,  $p$  is replaced by  $1 - p$  and the sign of the resulting SPEI is reversed. The constants are:  $C_0 = 2.515517$ ,  $C_1 = 0.802853$ ,  $C_2 = 0.010328$ ,  $d_1 = 1.432788$ ,  $d_2 = 0.189269$  and  $d_3 = 0.001308$ . Positive SPEI values indicate above-average moisture conditions, while negative values indicate drought conditions. A drought event is defined when the SPEI value is less than or equal to -1 during a certain period.

For the calculation of SPI, McKee et al. [29] developed this index which quantifies long-term precipitation anomalies over several time steps. The standardised precipitation is calculated by dividing the difference in precipitation from the long-term mean by the standard deviation, where the mean and standard deviation are determined from past long-term records. This standardised precipitation was then normalised to reflect the variable nature of precipitation and SPI values were obtained. SPI values are expressed in units of standard deviation from the long-term medians and offer the corresponding probabilities of occurrence of each drought category with respect to the normal probability density function [34]. The standardized precipitation index (PSI) was calculated for each time interval by the Equation 11:

$$SPI = \frac{(P_i - P_m)}{\sigma} \tag{11}$$

With  $P_i$ : the rainfall of month or year  $i$ ;  $P_m$ : the average rainfall of the series over the time scale considered;  $\sigma$ : the standard deviation of the series over the time scale considered.

McKee et al. [29] used the classification system according to PSI values and defined the criteria for a "drought event" for all time scales. A drought event occurs whenever the PSI is continuously negative and its value reaches an intensity of -1 or less and ends when the PSI becomes positive. The intensity of the drought is defined by the SPI value. In general, SPI values above zero represent above normal precipitation, while SPI values below zero represent negative values indicating below normal precipitation. Due to the similarities in the principles of calculating SPEI and SPI, the same classification is maintained for SPEI (Table 1).

**Table 1. Classification of drought sequences according to SPI values**

PSI values	Drought sequences	PSI values	Wet sequences
0.00 < SPI < -0.99	Slightly dry	0.00 < SPI < 0.99	Slightly damp
-1.00 < SPI < -1.49	Moderately dry	1.00 < SPI < 1.49	Moderately humid
-1.50 < SPI < -1.99	Severely dry	1.50 < SPI < 1.99	Severely damp
SPI < -2.00	Extremely dry	2.00 < SPI	Extremely wet

On the basis of long-term historical time series data, the analyst can tell the impact of these anomalies on the above mentioned areas. The duration of the drought/period can be obtained by counting the months from the beginning to the end of the negative SPI (SPEI) values and their magnitude by positively summing the SPI values of all months of the period/drought. The SPI and SPEI for the study area were calculated at time scales of 12 and 24 months that reflect long-term precipitation patterns.

#### 4. Results

Table 2 gives the trends of SPI and SPEI on the annual scale (12 months) that were calculated, and the results of which are compared with the trend of the annual rainfall total. The trend was calculated by linear least square and statistical significance was calculated at 95% confidence level using the non-parametric Mann-Kendall test [35], for both indices, in each station (Table 2) of both regions (Figures 2 and 3). A negative trend value means an increase in dry spells, and the statistical significance of the trend was checked using a 5% risk of error ( $p$ -value < 0.05). In addition, SPI and SPEI trends were calculated for the meteorological data of Ziguinchor (Casamance) and Matam (Senegal River valley) on a time scale of 12 and 24 months, over the period 1980 to 2017.

In the Sahelian-climate Senegal River valley, the standardised precipitation index (SPI) at the 4 stations showed no consistent trend (Table 2). The Podor and Saint Louis station series showed an increasing trend (a trend that is only statistically significant in Matam) as did the precipitation indices even though the trends for these two stations are not significant. The trend was downward for the Bakel and Matam site (and statistically significant in Matam) where the precipitation indices show upward trends and are statistically significant at these two stations. While in this area all rainfall trends are increasing, they are insignificant for stations with positive SPI trends and statistically significant for stations with negative SPI trends. Furthermore, for the trends in precipitation indices, the coefficients do not identify

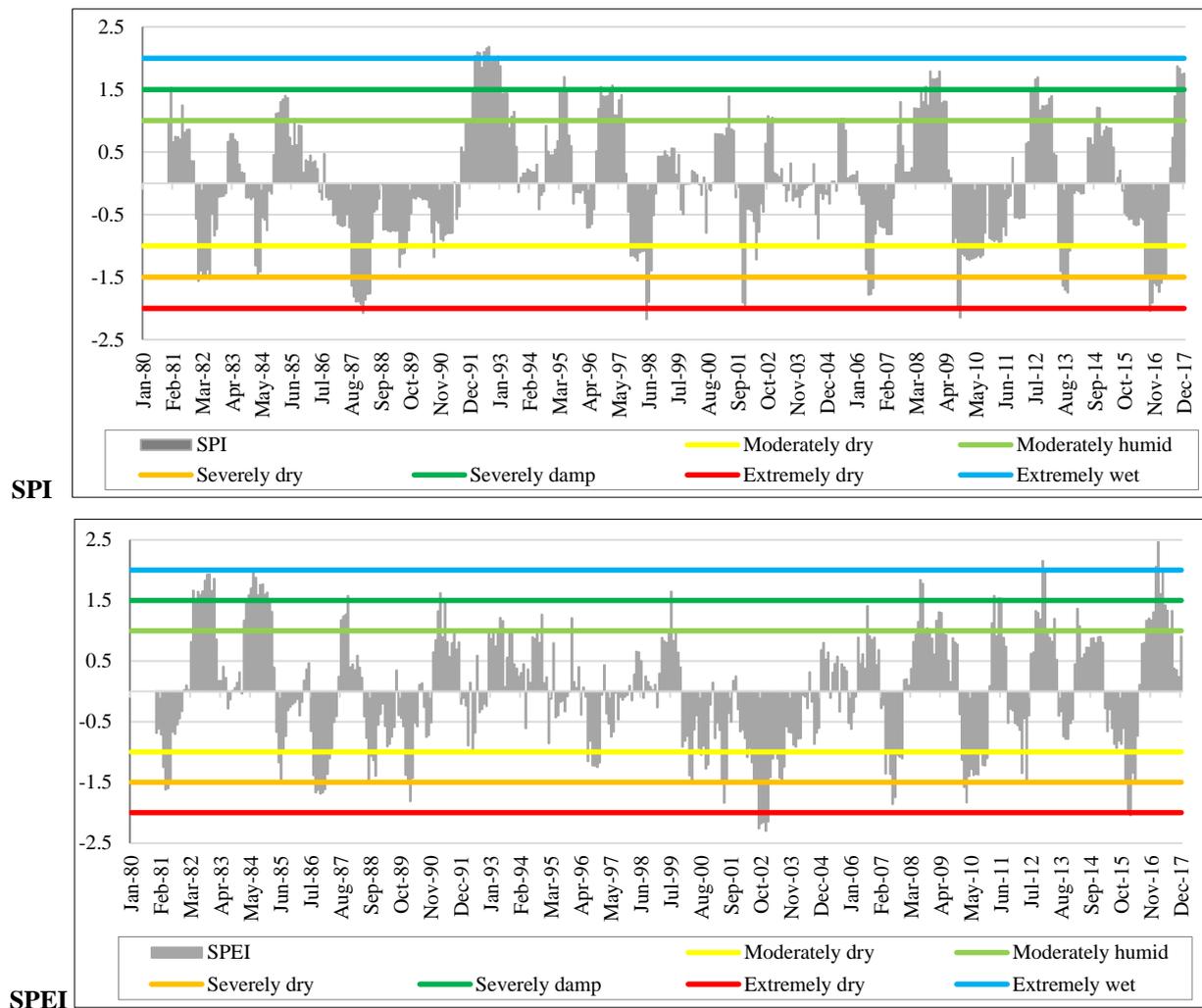
significant variations. Kendall's *tau* varies between 0.1594 mm per year (in Saint Louis) and 0.3371 mm per year (in Bakel) (Table 2). The period with the highest number of consecutive wet months (SPI>0) (Figure 2) ranged from June 2007 to June 2009 (a total of 25 months), while the period with the highest number of consecutive dry months (SPI <0) ranged from June 1986 to April 1991 (a total of 59 months). On average, wet periods alternated with dry periods in this region.

**Table 2. Characteristics of the climatic stations selected in the study areas**

Zones	Stations	Latitude	Longitude	Altitude in m	SPI	SPEI	Annual Rainfall	T°C
Senegal River Valley	Bakel	14°54'	12°28'	25	-0.0009	<b>0.0767</b>	<b>0.3371</b>	
	Matam	15°39'	13°15'	15	<b>-0.1675</b>	0.0393	<b>0.2517</b>	
	Podor	16°39'	14°58'	6	<b>0.1255</b>	0.0366	0.2192	<b>0.290</b>
	Saint-Louis	16°03'	16°27'	4	0.0475	-0.0272	0.1594	
River valley area					-0.0206	0.0193	<b>0.3257</b>	
Casamance Basin	Ziguinchor	12°23'	16°16'	26	<b>0.1967</b>	<b>0.2859</b>	<b>0.3541</b>	
	Sedhiou	12°47'	15°33'	10	<b>0.2253</b>	<b>0.1537</b>	0.1891	
	Kolda	12°53'	14°58'	35	<b>0.1540</b>	<b>0.2205</b>	<b>0.3229</b>	<b>0.633</b>
	Vélingara	13°09'	14°06'	38	<b>0.0694</b>	<b>0.1325</b>	0.1152	
Casamance basin area					<b>0.1117</b>	<b>0.2924</b>	<b>0.3684</b>	

Statistically significant trends with a p-value ≤ 0.05 are shown in bold.

The results of the analyses showed that the SPI indices are able to reproduce the drought episodes that occurred in the Senegal River valley during the last 4 decades. The SPI values at different time scales show that droughts in the valley were generally of mild (38% of the months in the series), moderate (8.1%) to severe (6.1%) intensity. The most extreme drought reached a value of -2.17 in May 1998 (Figure 2).



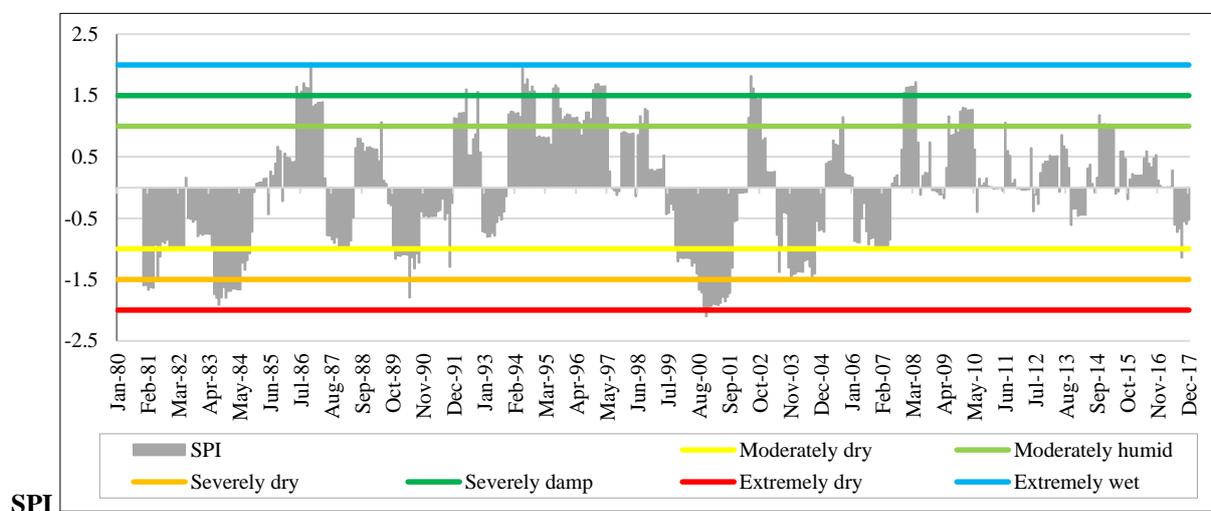
**Figure 2. Average SPI (left) and SPEI (right) values for stations in the Senegal River Valley area (coloured lines indicate critical index values under dry and wet conditions)**

Like the SPI, the trend in the SPEI is down in Saint Louis and is statistically insignificant (Table 2). The largest decrease (-0.1675) is noted at the Matam station, followed by Saint Louis (-0.0272). At Bakel (with a *tau* of 0.0767 mm per year), Matan (0.0393) and Podor (0.0366), the SPEI shows an increasing trend, which is statistically significant at Bakel. The behaviour of the total annual rainfall index, which has a positive trend at all four stations, is only well correlated with the behaviour of the SPEI at the stations in Bakel and Podor (in contrast to the stations in Matam and Saint Louis, which have negative trends). In contrast to the mean SPI, the mean SPEI shows a slightly increasing trend (0.0193 mm per year), but not statistically significant. The longest observed wet period was from December 2007 to November 2009 (a total of 24 months), while the longest dry period was from December 2001 to November 2004 (a total of 36 months) (Figure 2). Similar to the SPI, the SPEI values at different time scales show that the droughts in the valley were generally of mild intensity (33.7% of the months in the series), moderate to (11.7%). The most extreme drought reached a value of -2.3 in December 2003 (Figure 2).

For the Casamance basin area, the SPI (Table 2) showed an increasing trend at the four stations considered (Ziguinchor with a *tau* of 0.1967, Sédhiou with 0.2253, Kolda with 0.1540 and Vélingara with 0.0694), an increase that is statistically significant at three of the four stations (Sédhiou, Kolda and Vélingara). Only the Ziguinchor station showed a non-significant trend. As for the average SPI of the Casamance basin, the upward trend is also statistically significant over the period considered (the *tau* being 0.1117). These trends in SPI are consistent with those in rainfall, which are all positive although not statistically significant. This rainfall trend is only statistically significant for the average rainfall value in the Casamance basin (with a *tau* of 0.3684 mm per year). The longest phase during which the mean value of the SPI at the stations (Figure 3) remained constantly above 0 is from November 1993 to June 1997 (a total of 44 months). The longest phase during which the SPI values were below 0 was from June 1999 to April 2002 for a total of 34 months.

According to the classification of McKee et al. [29], which assesses the severity of drought, one month (or 0.22% of the series) was considered 'extremely dry', 32 months (or 7.19%) 'severely dry', 43 months (or 9.66%) 'moderately dry' and 139 months (or 31.24%) 'slightly dry' over the period 1981-2017. While the wettest SPI is recorded in February 1987 with a value of 2, the driest is recorded in December 2000 with a value of -2.11. As with the SPI, the trend in the SPEI (Table 2) is positive everywhere (on all four stations) and statistically significant in three of the four Casamance stations considered (only Ziguinchor recorded a non-significant trend). This positive trend is shown by a positive Kendall's ratio of 0.2859 in Ziguinchor, 0.1537 in Sédhiou, 0.2205 in Kolda and 0.1325 in Vélingara. These behaviours are well correlated with the behaviour of annual rainfall, whose trends, although not significant, are increasing, as shown by the positive *tau* everywhere (Table 2).

The average SPEI also shows a statistically significant increasing trend (0.2924). The trend analysis of the mean IPPS values (Figure 3) showed that the longest wet periods are from January 1986 to September 1988 (31 months in total), December 2003 to December 2007 (48 months) and January 2012 to June 2014 (30 months) and from October 2015 to December 2017 (27 months). The longest dry periods were from September 1982 to July 1984 (23 months in total), from October 1990 to November 1993 (38 months) and from January 1995 to October (1997) 34 months). In the Casamance Basin, the IPPS classification shows that 4 months (or 0.90% of the series) were considered 'extremely dry', 31 months (or 6.97%) 'severely dry', 47 months (or 10.56%) 'moderately dry' and 139 months (or 31.24%) 'slightly dry' over the period 1981-2010. While the wettest PESI is recorded in December 2012 with a value of 2.66, the driest is recorded in July 1991 with a value of -2.21.



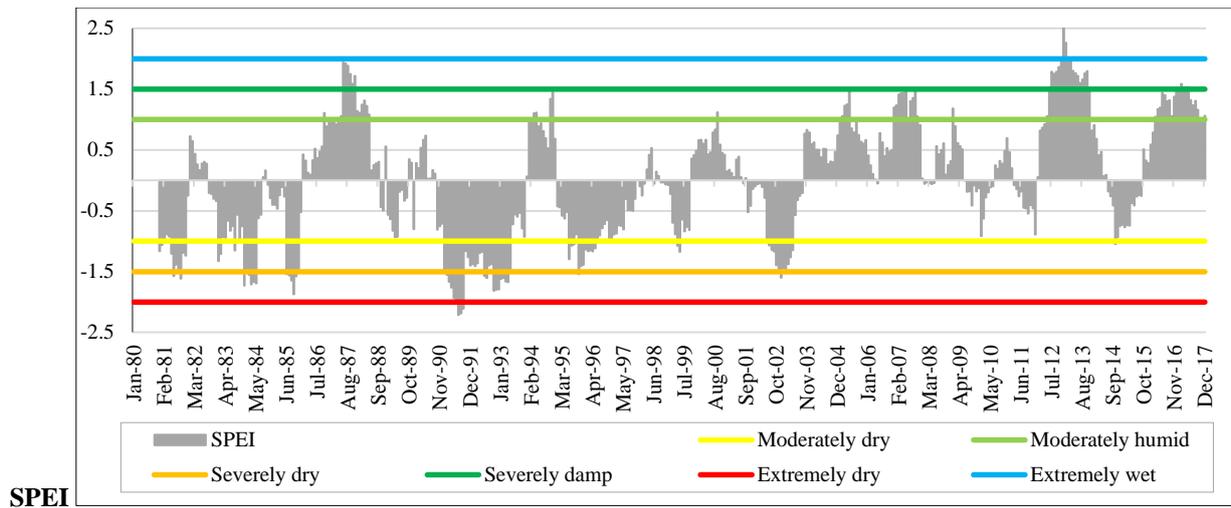


Figure 3. Average SPI (left) and SPEI (right) values for stations in the Casamance basin area (coloured lines indicate critical index values under dry and wet conditions)

Figures 4 and 5 Table 3 show the trend and frequencies of dry and wet sequences of SPI and SPEI values calculated for meteorological data from Ziguinchor (in the Casamance basin) and Matam (in the Senegal River valley) stations on a time scale of 12 and 24 months, over the period 1980 to 2017.

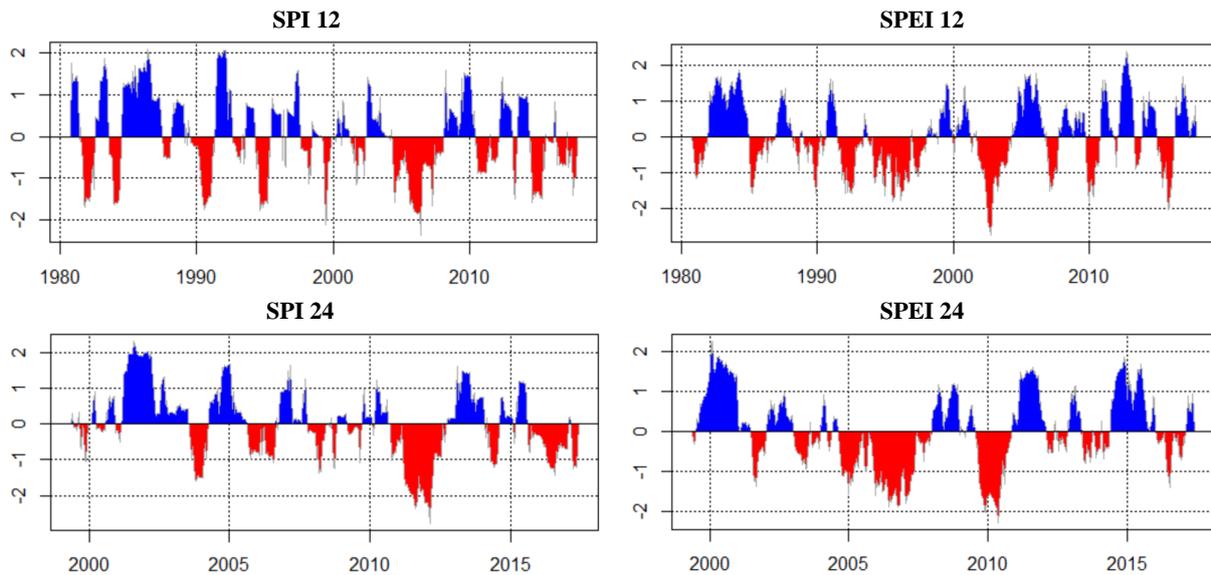


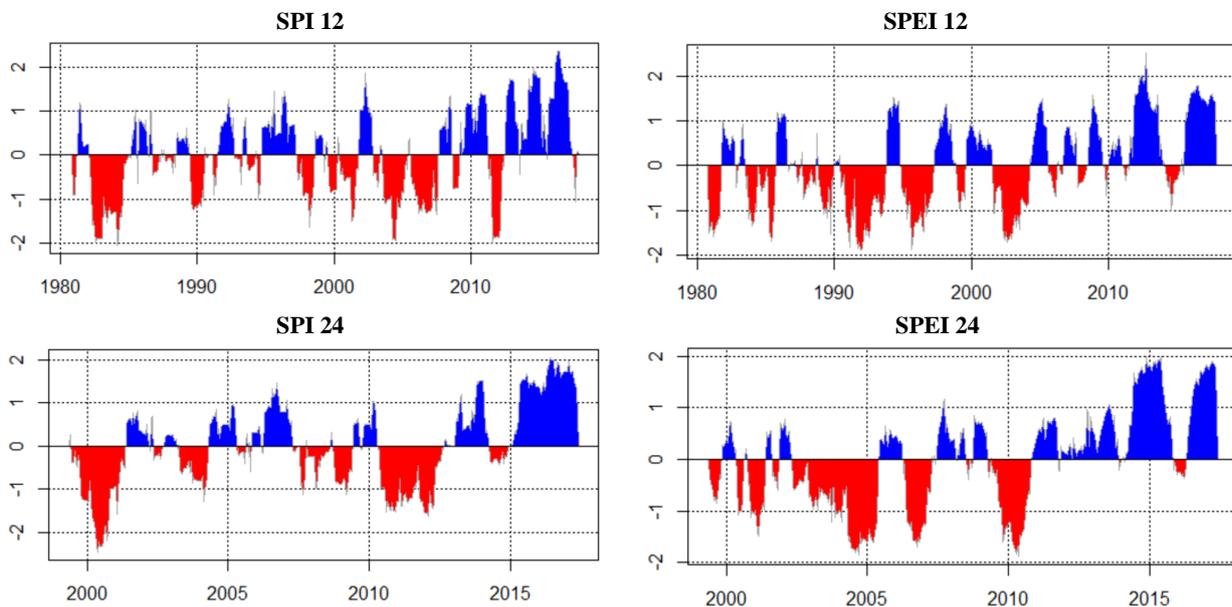
Figure 4. SPI (left) and SPEI (right) values for the selected Matam station in the Senegal River valley area, calculated over a 12 and 24 month period

Table 3. Characteristics of the stations in Matam (in the Senegal River valley) and Ziguinchor (in the Casamance basin) selected in the study areas

	Matam station				Ziguinchor station			
	SPI 12	SPEI 12	SPI 24	SPEI 24	SPI 12	SPEI 12	SPI 24	SPEI 24
Maximum value	2.09	2.37	2.31	2.26	2.36	2.54	2.06	2
Minimum value	-2.40	-2.73	-2.80	-2.30	-2.00	-1.90	-2.50	-1.90
<b>Percentage</b>	<b>SPI 12</b>	<b>SPEI 12</b>	<b>SPI 24</b>	<b>SPEI 24</b>	<b>SPI 12</b>	<b>SPEI 12</b>	<b>SPI 24</b>	<b>SPEI 24</b>
Extremely wet	1.12	0.45	1.85	0.46	1.35	0.45	0.92	0.23
Severely damp	6.52	6.74	5.54	7.39	4.94	6.97	7.39	8.55
Moderately humid	9.21	11.50	6.47	9.70	10.80	11.70	7.62	3.70
Slightly damp	31.70	31.20	38.60	31.90	33.00	30.10	32.30	41.10
<b>Total wet phase</b>	<b>48.50</b>	<b>49.90</b>	<b>52.40</b>	<b>49.40</b>	<b>50.10</b>	<b>49.20</b>	<b>48.30</b>	<b>53.60</b>

Slightly dry	35.50	32.80	32.80	34.20	31.70	32.60	35.80	27.90
Moderately dry	7.42	11.00	9.01	8.55	12.10	11.70	10.40	9.93
Severely dry	8.09	4.94	3.70	7.39	5.62	6.52	3.46	8.55
Extremely dry	0.45	1.35	2.08	0.46	0.45	0.00	2.08	0.00
<b>Total dry phase</b>	<b>51.50</b>	<b>50.10</b>	<b>47.60</b>	<b>50.60</b>	<b>49.90</b>	<b>50.80</b>	<b>51.70</b>	<b>46.40</b>
<b>Total series</b>	<b>100</b>							

At the Matam station in the Senegal River valley, during the study period, the trend of SPI-24 and SPEI-24, like that of SPI-12 and SPEI-12, is irregular with a clear alternation between dry and wet periods, as shown in the graphs (Figure 4). However, the graphs of SPEI-12 and SPEI-24 months show a clear predominance of wet periods, related to the increase in rainfall. In contrast, the period 1990-2000 is characterized by a dry phase. It should also be noted that the SPI-24 graph recorded the most extreme dry period with -2.8, followed by SPEI-12 with -2.73, SPI-12 with -2.4 and finally SPEI-24 with -2.3. For the wet phases, SPEI-12 has the most extreme wet value with 2.37, while SPI-12 has the lowest with 2.09. In total, SPI-12, SPEI-12 and SPEI-24 with frequencies of 51.5%, 50.1% and 50.6% respectively recorded slightly drier than wet episodes (only SPI-24 recorded less with 47.6%) (Table 3).



**Figure 5. SPI (left) and SPEI (right) 5values for the selected Ziguinchor station in the Casamance basin area, calculated over a 12 and 24 month period**

In contrast to the trend observed in Matam, at the Ziguinchor station in the Casamance basin, in recent years, SPI-24 and SPEI-24, both on a 12-month scale, show a slightly wetter trend with a remarkable increase in precipitation (Figure 5), which contrasts with the period 1980-2010 in the same region, where dry events were more remarkable. From 1993 to 1998, the second longest wet period was recorded, clearly shown in the 12-month graph (Figure 4). In general, the IPPS shows the difference between dry and wet months better than the SPI [1]. This is evident in the comparison between SPI-12 and SPEI-12. Wet episodes before 1990 are clearly indicated in the SPEI-12 but are absent from the SPI-12 (Figure 4). At the Ziguinchor station, the SPI-24 graph recorded the most extreme dry period with -2.5 (minus the one noted at Matam), followed by SPI-12 with -2, SPEI-12 and SPEI-24 with -1.9 (a severe, non-extreme drought by the way). As for the wet phases, as in Matam, SPEI-12 recorded the most extreme wet value with 2.54, while SPEI-24 recorded the lowest with 2. In Ziguinchor, SPEI-12 with 50.8% and SPEI-24 with 51.7% recorded slightly higher frequencies of dry episodes than wet ones, while SPI-12 with 50.1% and SPEI-24 with 53.6% recorded slightly higher frequencies of wet episodes than dry ones (Table 3).

### 5. Discussion

A drought index is a quantitative measure that characterises drought levels by assimilating data from one or more variables (indicators) such as rainfall and evapotranspiration into a single numerical value. In Senegal, several drought indices have been described and used [14-16] and two are used in this study: the SPI and SPEI. As described by Vicente-Serrano et al. [5], the influence of PET on drought conditions is difficult to estimate. In this analysis, it is possible to compare the extent of drought indicated by the SPI, which is a precipitation-based index in which PET is not included, and the PIEP, in which PET is included, for the same period. This comparison illustrates the different and sometimes

contrasting results regarding the assessment of drought when PET is included in the analysis [2]. For example, at the end of the time series of the Matam station, SPEI-12 and SPEI-24 indicate a wet period while SPI-12 and SPI-24 indicate a continuation of the drought (Figure 4).

The analysis of the SPI and SPEI results supports numerous studies in Senegal [16, 17, 19, 28, 36, 37] which concluded that there has been a rainfall deficit since the 1970s. Similar results were also obtained by Ali and Lebel (2009) [38] who showed the persistence of drought during the 1970s throughout West Africa, especially the Sahel. Over the most recent period, since 2000, only four years have been deficit years; this improvement in rainfall, which contrasts with previous years of drought, is in line with the view of some authors that the drought is over [39-41]. However, this return to normal is nuanced because rainfall variability, especially in the Senegal valley and basin, has continued even in recent years [42]. The same situation has been observed elsewhere in Africa [43] and in Asia, where it is also found in northern Ningxia and northern Shaanxi in China [44], which suggests that it is global in scale.

Despite the very frequent deficit, in all eight stations most years had rainfall below the local average. Wet years have been recorded, especially before the break-up and since the late 1990s. However, the irregular evolution of rainfall in recent years does not confirm the return to normalcy mentioned by some authors [16, 28] and the recent increase in rainfall in the Sahel [45]. Indeed, since the mid-1990s, 'a return to better rainfall conditions in the Sahel has been noted, but this has been accompanied by greater interannual variability in rainfall' [46]. In addition, rising temperatures are in line with climate change, which has become one of the most important environmental issues at global, regional and local levels.

At the annual level, no significant variation in the amount of precipitation is recorded in either region, as confirmed by Fratianni and Acquotta [47], and other studies have not shown significant changes in annual precipitation in the Mediterranean basin [48]. On the contrary, in recent years, the distribution of precipitation has changed due to the increase in extreme events. According to Vicente-Serrano et al. [5], both drought indices respond mainly to precipitation variability, which is the main explanatory variable of drought. Nevertheless, the trends of the drought indices in both regions are well correlated with the trends indicated by the total annual rainfall even though its trends do not show a significant change. However, there is a significant increase in temperatures classified as hot in both regions (with a Kendall's  $\tau$  of 0.29°C per year in the valley and 0.63°C per year in Casamance), a trend that affects the performance of the PESI, although increasing trends have been calculated in most cases over the last years.

The effects of drought in Senegal are also exacerbated by poor management of water resources and agriculture. The agricultural sector, which is highly dependent on water sources, is severely affected by drought. Indeed, the short duration of the rainy season, especially in the Senegal River valley, as revealed by the SPI and SPEI indices, impacts on both agricultural yields and vegetation cover. This meteorological drought is therefore symptomatic of an agricultural and edaphic drought [49] which explains, in part, the decline in rain-fed agriculture and the long displacements of herders (and even the death of livestock in the Senegal River valley, the salinisation of land in the Casamance estuary [50]). Beyond the agricultural sector, the effects of drought also spread to other sectors such as the forest and the environment, which suffer. The social sector is also affected in terms of changes in agricultural commodity prices, production structure, livestock production capacity, rural-urban migration flows and other measures of well-being [51]. Given the frequency of drought since the 1970s [15-17], its impact on the country's economy through its effects on agricultural production and natural resources and the possible increase in its impacts in the coming years, mitigation or adaptation measures are essential.

## 6. Conclusion

The analysis of hydrological drought trends in two different environments, the Sahelian continental climate and the South Sudanese tropical climate, was carried out using the thermoprecipitation series of four stations in the Senegal River Valley area and four stations in the Casamance Basin area, during the period 1980-2017. The standardised precipitation index, SPI, and the standardised precipitation-evapotranspiration index, SPEI, were calculated for each station, and average indices were also calculated for both regions. Similarities and differences were detected between the two environments. The index trends were more defined in the Casamance basin. In most stations of both areas, there is a statistically significant trend of increasing SPI and SPEI (75% of the stations for SPI and 87.5% for SPEI), despite some negative trends (like SPI in Bakel, SPI and SPEI in Matam, SPEI in Saint Louis). Moreover, the trend of the indices averaged over the stations of the two indices, although generally positive in the two climatic zones considered (with the exception of the SPI in the valley where it is negative), is only significant in the Casamance basin zone. At the same time, the indices in the Casamance basin showed a clear trend in all the stations considered, in contrast to the indices in the Senegal River valley where an alternation of dry and wet sequences is noted. As a result, the trends in the mean values of the indices are statistically significant in the Casamance basin and not significant in the Senegal River valley.

The average duration of the wet period was longer in the Casamance basin area, where a total of 44 consecutive months with SPI values above zero were calculated (November 1993 to June 1997), compared to 25 consecutive months in the Senegal River valley area (June 2007 to June 2009). On the other hand, the duration of dry spells was much higher

in the Senegal River Valley area with a total of 59 consecutive months with SPI values below zero (June 1986 to April 1991), compared to consecutive months 34 in the Casamance Basin area (June 1999 to April 2002).

However, the uncertainties in the drying trends of the PIEPS may be overestimated due to the use of the Thornthwaite PET estimate in this analysis. The use of this method is a limitation of the PIEPS, as the Thornthwaite PET is less physically realistic than other estimation techniques such as Hargreaves or the Penman-Monteith equation.

An increase in drought for most of the 21st century is predicted by future climate projections. Ecosystems and human activities could be profoundly affected by projected drying trends, while observed drying trends have an effect on socio-ecological systems, such as reduced agricultural yields and land salinisation. Concerted policy and practical action to conserve water is needed to minimise the impact of future drought, such as appropriate water management policies and climate-smart agricultural practices. As meteorological droughts are the first step in the progression of subsequent agricultural or hydrological droughts, this methodology could be used to activate a drought management response and to address the lack of information on the duration, extent or geographical intensity of droughts. The results of the study are also relevant for climate change studies to understand historical patterns and to develop future drought scenarios.

## 7. Declarations

### 7.1. Data Availability Statement

The data presented in this study are available in article.

### 7.2. Funding

The author received no financial support for the research, authorship, and/or publication of this article.

### 7.3. Declaration of Competing Interest

The author declare that there is no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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