Patterns of meteorological drought over Massili basin using standardized precipitation evapotranspiration index

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ABSTRACT

As a Semi-arid country, Burkina Faso is highly vulnerable to climate related disasters such as drought and flood. Analysing drought signature is therefore a key factor in advocating climate change adaptation at the local scales. In this study, Spatio temporal trend of drought were conducted for the period 1960–2021 within Massili basin using the standardized precipitation and evapotranspiration index (SPEI) package in R.The non-parametric method (Mann–Kendall) was then used to test for monotonic trend, whereas the magnitude was estimated using Sen's method. Accordingly, the result revealed that during the period 1960-1979, the mean value of SPEI varies from 0.06 to 0.71; over 1980 to 2009, the mean value of the SPEI varies from -0.08 to -0.88 and for the last decades (2010 to 2021), the mean value of the SPEI ranges from 0.05 to 0.75. Normal to middle wet conditions is thus observed over the periods 1960-1979 and 2010-2021 while the period (1980-2009) depicts a middle drought condition. The Mann Kendall test results show a decreasing trend of SPEI-3 and SPEI-24 with a Z value of - 0.784 and -0.530 respectively. A slight increasing trend is observed for SPEI-6 and SPEI-12 with Z ranging from 0.598 to 1.917 respectively. The magnitude of the decrease is indicated by the sens' slope value, which is -0.0014 for SPEI-3 and -0.00010 for SPEI-24 while the magnitude of the increase ranges from 0.00011 for SPEI-6 to 0.00037 for SPEI-12. This study highlights the importance of examining past drought features to obtain essential information to assist in designing and implementing efficient water resources management strategies over the Massili basin.

Keywords: Drought, Massili, Standardized Precipitation-Evapotranspiration Index, monitoring

1. INTRODUCTION

According to the Intergovernmental Panel on Climate Change sixth report [1] climate change is inflicting dangerous and widespread disruption in nature and affecting the lives of billions of people worldwide. In addition, the world faces unavoidable multiple climate hazards over the next two decades with global warming of 1.5°C. Extreme events such as droughts are more frequent and forecasted to frequently occurred in the future. Indeed, under global warming, dry areas in the world have increased by approximately 1.74% per decade during 1950–2008 [2]. Drought is defined as a period with an abnormal precipitation deficit, in relation to the long-term average conditions for a region continuous precipitation deficit lasting for a specific time period [3]. Wilhite [4] stated that drought is classified within four categories: meteorological, agricultural, hydrological, and socioeconomic droughts.

Meteorological drought results from a shortage of precipitation, while hydrological drought describes a deficiency in the volume of the water supply, which includes streamflow, reservoir storage, and/or groundwater heights. Agricultural drought refers to a shortage of available water for plant growth, and is assessed as insufficient soil moisture to replace losses due to evapotranspiration' losses [5]. Droughts are not localized in semi-arid areas but affect also many regions in the world. This creeping event is one of the main natural factors of agricultural, economic, and environmental damage. Accordingly, drought has a huge impact on countries' economic development owing to the fact that many economic activities are related to water availability. Narasimhan [6] reported that drought is one of the most important natural disasters leading to billions of dollars of loss every year in the field of agriculture. Droughts are the world's costliest natural disasters, causing an average $6–$8 billion in global damages annually and collectively affecting more people than any other form of natural disaster [7]. In Africa, particularly in Sub-Saharan countries, drought substantially impacts agriculture, human health, and the economy. At regional scale, the rainfall break recorded in 1970 over the Sahel has resulted in a damage of more than 98.9 million hectares of crops and the drinking water shortage for more than 4.9 million people [8]. In Burkina Faso, more than 1 million people have been internally displaced due to both ongoing violence and prevailing droughts [9]. Thus, this landlock country is extremely vulnerable to drought. Drought studies in Burkina Faso have addressed many issues such as the spatial variations, severity and duration, cost and adaptation. Carla [10] studied the costs and risks of coping with drought over the Central Plateau in Burkina Faso during the year that followed a severe drought in 1997 and the relationship between SPI and drought relief payments in the country and found the strongest relationships with a 9-month cumulative drought index. Lodoun [11] explored the evolution of the seasonal descriptors of precipitation in Burkina Faso between 1941 and 2000 by applying the standardized anomalies index, the spatial methods, and the aggregation methods. Sivakumar proposed methods to estimate drought spells and drought frequencies over Burkina Faso and west Africa countries. A drought index is defined as a number used to determine the magnitudes of drought events. A broad range of indices, such as the Palmer Drought Severity Index (PDSI), the Standardized Precipitation Index (SPI), and the Standardized Evapotranspiration Index (SPEI) are commonly applied to estimate drought severity, however, the SPEI which is a multiscalar index is more suitable and expressive than other indices in terms of drought characterization, climate variability. In this study the SPEI developed by Vicente [13] has been used to address the drought analysis. The SPEI is a variant of the Standardized Precipitation Index (SPI) and has significant potential as a meteorological drought index since it uses a more comprehensive measure of water availability, and climatic balance. In addition, as a multivariate drought index, the SPEI estimates the water balance, defined as the difference between precipitation and potential evapotranspiration. In the current study, SPEI was used to examine the possible trends in drought over the Massili basin in order to help in the design of context-based adaptation strategies to climate associated shocks

2. MATERIAL AND METHODS

2.1 STUDY AREA

The study was conducted within the Massili basin which is a subbasin of the Nakambe basin covering an area of 2612 km2 considering the outlet at Gonse Station. The relief of the area is mostly plain and the watershed has an altitude ranging from 376 to 3500. is located between the longitudes 1°15'West and 1°55' West and the latitudes 12°17'North and 12°50' North (figure 1). The region has a mean annual rainfall ranging from 700 to 900 mm/year with a dry season lasting from 6 to 7 months [14]. The annual maximum and minimum temperatures varied from 27.8 to 33.7 and 14.4-23.7°C, respectively. Agroecologically, the Massilli Basin is part of the North Sudanese zone Around 27% of the watershed is covered by tree and shrub savannas while 59% is occupied by farmland. The region experienced unimodal rainfall occurring from June to September

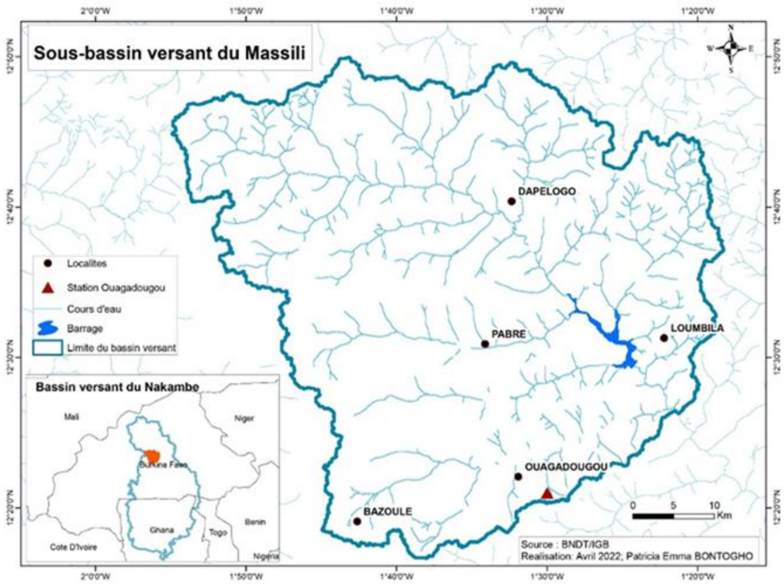


Figure 1: Map showing location of Massili river basin limited at Gonse station. Inset map on the left show at the bottom, the geographical location of the study area within Burkina Faso.

2.2. Climatic Datasets

Rainfall, minimum and maximum temperature records at monthly time steps over the period 1960 to 2021 of the referential station of Ouagadougou were collected from the National Meteorological Agency of Burkina Faso (ANAM-BF). This station was considered in this analysis based on its historical temporal coverage, homogeneity, and completeness of records. In addition, the dataset was explored in large number of meteorological oriented studies and has the potential to be used to monitor and assess droughts and their impacts. The gaps in the data series were completed using linear regression method in SPSS. The statistics of the observed records are presented in Table 1. Quality control was performed on the data to ensure the input dataset meet the standards for scientific investigations.

Table 1: Summary of basic statistics of monthly precipitation, minimum and maximum Temperature of the meteorological station of Ouagadougou

	Year	Month	Prcp	Tmax	Tmin
Min.	1990	1.00	0.00	29.50	14.30
1st Qu	1975	3.75	0.00	33.00	20.00
Median	1990	6.50	22.65	35.20	22.70
Mean	1990	6.50	65.32	35.27	22.32
3rd Qu	2006	9.25	110.40	37.23	24.60
Max.	2021	12.00	452.60	42.00	32.00

2.3 METHODOLOGY

There are various methods widely used to study temporal and spatial drought conditions. The Aridity Index (AI) method for instance is a climatic index useful for recording the development of the drought event. Potential evaporation data is required to calculate this index [15]. In addition, the Percent of Normal Index (PNI) is a drought assessment method characterized as the most straightforward drought index. Simsek [16] stated that this index is the ratio of the amount of rainfall at a given time interval and the average of precipitation. The Erinç Aridity Index (I-m) is also a drought index based on the average maximum temperature ratio, which is assumed to be caused by rainfall and evaporation deficit [17,18]. The Palmer Drought Severity Index (PDSI) was created by Palmer [19] to measure the cumulative dissipation of atmospheric moisture supply and demand in the surface. PDSI transforms past annual rainfall, humidity supply, and humidity demand into a hydrological calculation system [20]. Wells [21] emphasised that the PDSI is based on a primitive water balance rather than entirely rainfall-based.

The main objective of this study was to analyse meteorological drought over Massili watershed. For this purpose, the SPEI was selected due to its suitability for the meteorological drought analysis. As stated by Mishra [22], the SPEI is a multiscalar index, more suitable and expressive than other indices in terms of drought characterization, climate variability, and global warming. The choice of the SPEI indices has been also oriented by the limited availability of meteorological data on the study area.

The estimation of the standardized precipitation–evapotranspiration index (SPEI) combines precipitation and temperature data to measure precipitation anomalies at a given location following two steps:

- the estimation of the PET,
- the estimation of the climatic water balance which gives the SPEI.

2.3.1 Monthly Potential evapotranspiration estimate

Over the past decades, there has been a large body of literature on Potential evapotranspiration (PET). Therefore, wide ranges of methods are available for the estimation of this parameter going from physical mechanism, [23] to empirical relationship methods [24]. However, the main factor that determines the choice of the appropriate method remains the availability of the climatic dataset. Droogers [25] developed a modified Hargreaves model to assess the PET. This model is based on the Hargreaves model [26] which is a reference evapotranspiration equation commonly used to estimate crop irrigation requirements. Monthly Temperature and solar radiation are used to estimate the potential evapotranspiration. As stated by Hargreaves [27], the Hargreaves equation is more accurate for investigating PET in a dry area and with a long-time step comparatively to the Penman–Monteith equation. The Hargreaves method [28] requires monthly minimum and maximum temperature to derive solar radiation as another input in the Hargreaves equation [29].

$$PET_{HG} = 0.0023 * (T_{mean} + 17.8) * \left(\sqrt{T_{max} - T_{min}}\right) * R_a$$

PET_{HG} stands for the potential evapotranspiration of Hargreaves method, Ra is the extraterrestrial radiation, estimated as a function of latitude, Tmean is the average temperature (℃), Tmax and Tmin are the maximum and minimum temperatures (℃). The Climatic water balance (D_i) in a given period (mm), indicates the value of the water surplus or deficit for a given month. The estimation of this balance is based on the difference between the Precipitation P_i (mm) and the potential evapotranspiration of Hargreaves method PET_i (mm)

$$D_i = P_i + PET_i$$

2.3.2 SPEI estimation

The SPEI is a function of precipitation and potential evapotranspiration (PET) and has the ability to detect the main impact of increased temperatures on water demand. SPEI calculation depends on the accumulating deficit or surplus (Di) of water balance at different timescales. In order to estimate the SPEI, the water deficit has been normalized into a probability distribution by applying the generalized extreme value (GEV) distribution.

The GEV probability density function is given as:

$$f(x) = \begin{cases} \left(\frac{1}{\sigma}\right)\left[\left(1 + \xi z(x)\right)^{-1/\xi}\right]^{\xi+1} e^{-\left[\left(1+\xi z(x)\right)^{-1/}\xi\right]}, \xi \neq 0, 1 + \xi z(x) > 0 \\ \left(\frac{1}{\sigma}\right) e^{-z(x)-e^{---z(x)}}, \\ \xi \neq 0, -\infty < x < +\infty \end{cases}$$

Where:

$$Z(x) = \frac{x - \mu}{\sigma}$$

Where x, μ, σ, is the shape, scale and location parameters respectively. The cumulative distribution function F(x) of the GEV is then calculated as:

$$F(x) = e^{-(t(x))}$$

Where:

$$\mathbf{t}(x) = \begin{cases} \left(\mathbf{1} + \xi\left(\frac{x - \mu}{\sigma}\right)\right)^{\frac{-1}{\xi}}, & \text{if } \xi \neq 0 \\ e^{-(x-\mu)/\sigma}, & \text{if } \xi = 0 \end{cases}$$

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

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

According to the classical approximation of Abramowitz [30], F(x) is the SPEI which can easily be obtained as the standardized values of F(x).

$$\mathbf{SPEI} = \mathbf{W} - \frac{\mathbf{C_0} + \mathbf{C_1W} + \mathbf{C_2W^2}}{\mathbf{1} - \mathbf{d_1W} + \mathbf{d_2\,W^2} + \mathbf{d_2\,W^3}}$$

$W = \sqrt{-2\ \ln(p)}$ For $p \le 0.5$

with p the probability of exceeding a determined D value, p= 1-F (x).

If p > 0.5, then p is replaced by 1-p and the sign of the resultant SPEI is reversed;

C_0 =2.515517, C_1= 0.8022853, C_2 = 0.010328, d_1 =1.432788, d_2 =0.189269, and d_3 =0.001308 (constants)

SPEI at different time scale were computed in this study. Table 2 shows different ranges of SPEI and drought grade classification criteria for any given region. According to Wang [31], increasingly severe rainfall deficits are indicated as SPEI decreases below –1.0, while increasingly excess rainfall are indicated as SPEI increases above 1.0.

Table 2: Categorization of drought and wet grade according to the SPEI

Categorization	SPEI values	Categorization	SPEI values
Extremely wet	SPEI ≥ 2	Normal	−0.5 ≤ SPEI ≤ 0.5
Severely wet	1.5 ≤ SPEI < 2	Mild drought	−1 < SPEI < −0.5
Moderately wet	1 ≤ SPEI < 1.5	Moderate drought	−1.5 < SPEI ≤ −1
Mildly wet	0.5 < SPEI < 1	Severe drought	−2 < SPEI ≤ −1.5
		Extreme drought	SPEI ≤ −2

2.3.3 Mann-Kendall Test.

Trends of drought characteristics were tested using Mann-Kendall test package in R. Mann-Kendall is a nonparametric statistical test method and is suitable for detecting nonlinear tendencies of nonnormal distribution variables. Indeed, this widespread statistical method is used for the analysis of the trend in both climatology and hydrology time series normality [32, 33,34,35]. Among the advantages of the MK test, it can be noticed that the data are not need to be normally distributed. In addition, this trend test has weak sensitivity to outliers and skewed distributions.

The Mann Kendall z value (Zs) is estimated to measure the trend significance. This value is calculated as followed:

$$\mathbf{Zs} = \begin{cases} \dfrac{\boldsymbol{S-1}}{\sqrt{\boldsymbol{Var(S)}}}, & \boldsymbol{S} > 0 \\ \mathbf{0}, & \mathbf{S = 0} \\ \dfrac{\boldsymbol{S+1}}{\sqrt{\boldsymbol{Var(S)}}}, & \boldsymbol{S} < 0 \end{cases}$$

A positive Zs value indicates an increasing trend while a negative Zs shows a decreasing

trend.

2.3.4 Sen's Slope Estimator.

Sen's estimator is a non-parametric method which has been widely used to detect the trend and estimate the time series' magnitude [36] The change is estimated per unit time. the slopes Ti of all data pairs are calculated as follows:

The slope of "n" pairs of data based on Sen'slope test is estimated following the equations:

$$\boldsymbol{\beta i} = \mathbf{Median} \left[\frac{x_j - x_k}{j - k}\right] \quad \forall\ (k < j)$$

Where:

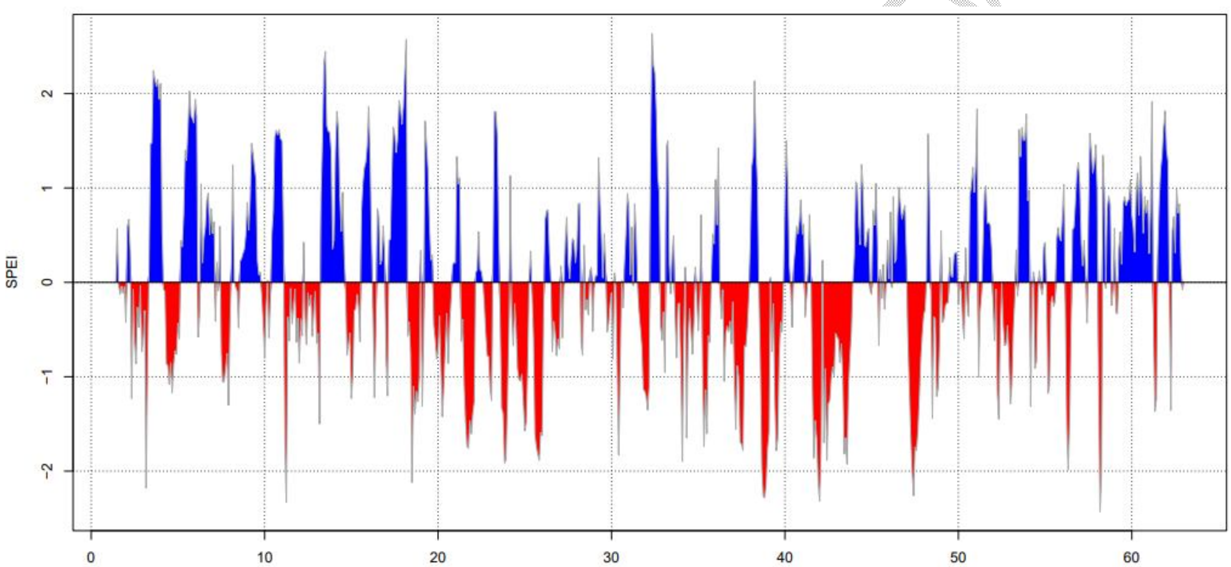
X_j and X_k represent values data at time j and k, respectively, and time j is after time k ($k \leq j$).

The median of "n" values of βi is the Sen's slope estimator test.

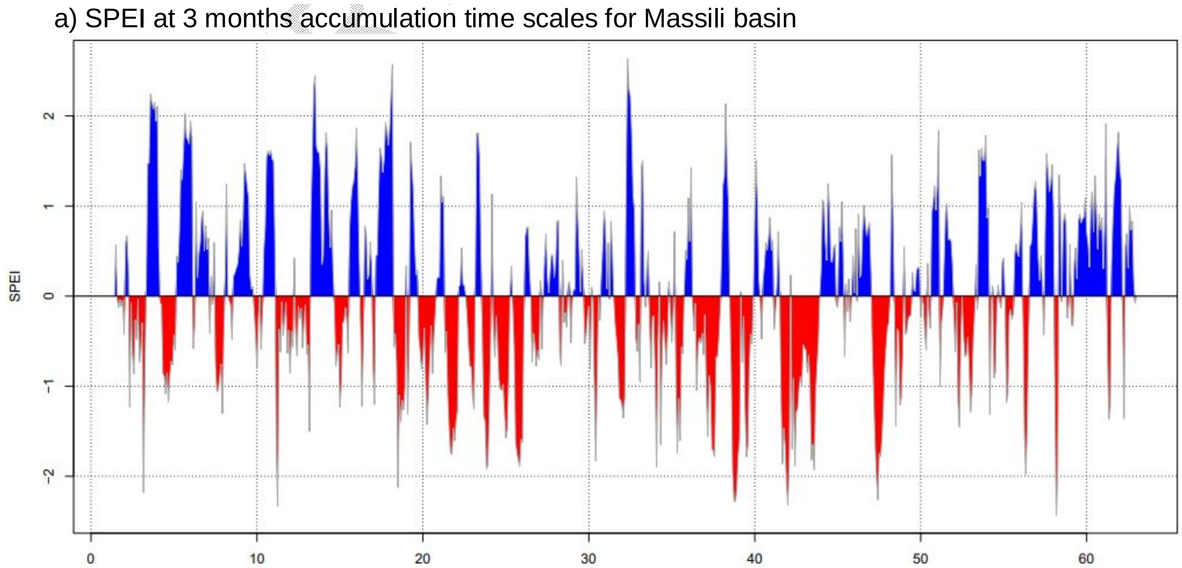
Negative βi value depicts a downwarding trend; Positive βi value indicates an upwarding trend.

3. RESULTS AND DISCUSSION

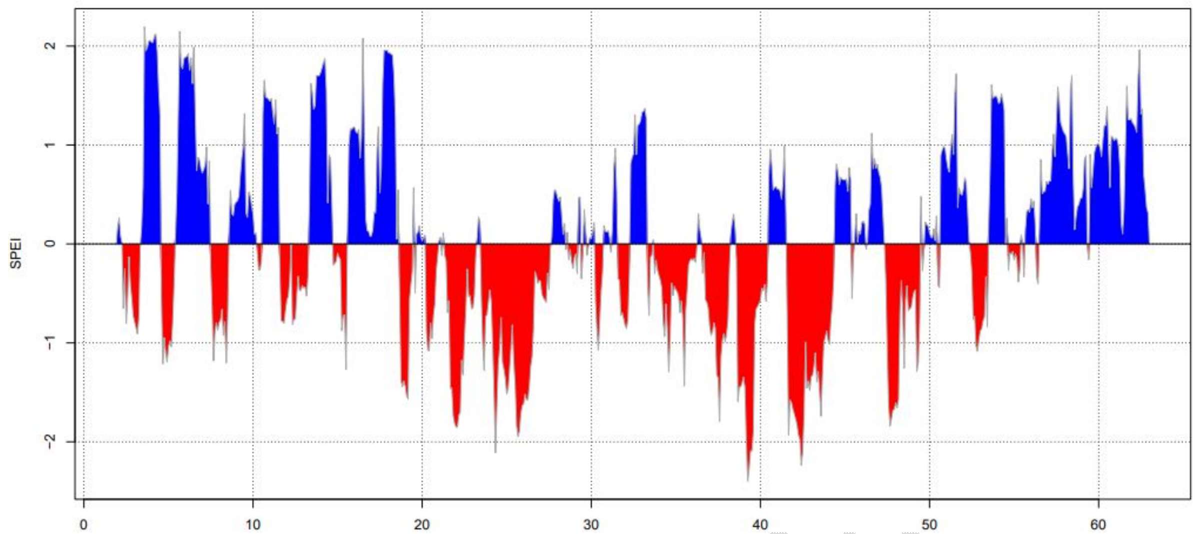
Figure 2 illustrates the historical patterns of drought conditions at SPEI-03 (a), SPEI-06 (b), SPEI- 12 (c) and SPEI-24 (d) in Massili watershed for 1960 to 2021. Dry and wet events were identified as moderate, severe, and extreme based on the classification standard provided in Table 2. The two first sub figures show a quasi-continuous drought condition between 1960 and 2021, with some minor humid periods. When considering SPEI-12 and SPEI 24, four significant episodes of drought frequency can be identified for Massili basin over 1980–1990, 1990–2000, 2000-2010 (occurrence of extreme drought) and 2010-2020. The most severe droughts situation occurred during the 1970s and during the decades 2000- 2010.



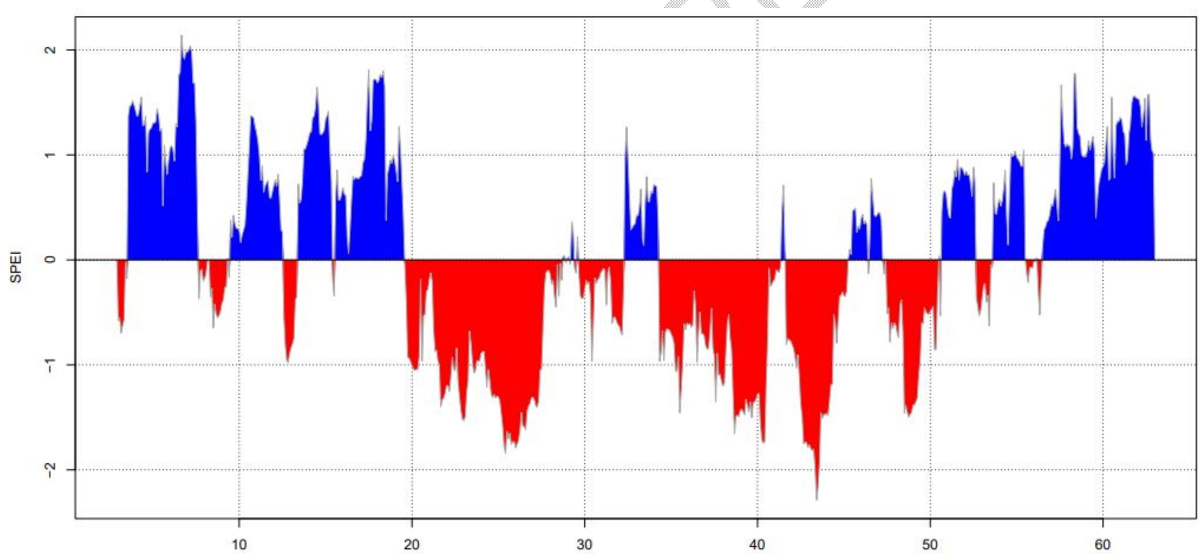
a) SPEI at 3 months accumulation time scales for Massili basin



b) SPEI at 6 months accumulation time scales for Massili basin



c) SPEI at 12 months accumulation time scales for Massili basin



d) SPEI at 24 months accumulation time scales for Massili basin

Figure 2: Massili basin SPEI at different time scale accumulation from 1960 to 2021

Table 3 shows that during the period 1960-1979, the mean value of SPEI varies from 0.06 to 0.71. Over 1980 to 2009, the mean value of the SPEI varies from -0.08 to -0.88. During the last decades (2010 to 2021), the mean value of the SPEI ranges from 0.05 to 0.75. Base on the classification of SPEI in table (02), normal to middle wet conditions over the period 1960-1979 within the Massili watershed can be identified. Conversely, the second period (1980-2009) presents a middle drought condition due to less precipitation and higher temperature in the bassin. However, in recent decades 2010-2021, a slight decreasing trend in drought frequency is observed. These findings are consistent with the existing literature, which indicates that in recent decades the Sahel is recovering from drought [37,38]. The slight return to wet conditions observed in the last years may have significant socio- economic implications since many people are involved in water related activities. In the field of agriculture for instance more than 90% of the population is engaged.

Table 3: Mean value of SPEI-3 SPEI-6 SPEI-12 and SPEI-24 from 1960 to 2021 over the Massili watershed

Period	SPEI-3	SPEI-6	SPEI-12	SPEI-12	SPEI-24
1960-1969	0,21	0,30	0,41	0,41	0,71
1970-1979	0,06	0,15	0,32	0,32	0,57
1980-1989	-0,08	-0,30	-0,62	-0,62	-0,88
1990-1999	-0,11	-0,21	-0,38	-0,38	-0,59
2000-2009	-0,12	-0,26	-0,40	-0,40	-0,59
2010-2021	0,05	0,29	0,62	0,62	0,75

Table 4 and table 5 provide the results of the Mann-kendall test and the estimation of the drought magnitude. The Mann Kendall test results show a decreasing trend of SPEI-3 and SPEI-24 with a Z of - 0.784 and -0.530 respectively. However, Mann Kendall test for SPEI-6 and SPEI-12 shows an increasing trend with Z ranging from 0.59792 to 1.9168 respectively. In addition, according to the Mann–Kendall test for historical monthly SPEI across Massili basin, the Kendall τ values vary from negative (SPEI-3, SPEI-24) to positive (SPEI-6, SPEI-12) indicating respectively decreasing and increasing trends in drought over time. The significance of the trends is non-significant (P > 0.05) as indicated by the associated p-values (Table 3). This result shows that the basin did not experience severe or extreme drought.

Table 4: Values of the Mann Kendall test for monthly SPEI (1960-2021) over Massili Basin

	MANN KENDALL		
	z	***P*-value**	**MK-tau**
SPEI-3	-0.78439	0.4328	-1.924623e-02
SPEI-6	0.59792	0.5499	1.470162e-02
SPEI1-2	1.91680	0.0553	4.731659e-02
SPEI-24	-0.53019	0.5960	-1.319926e-02

The magnitude of the decrease is indicated by the sens' slope value, which is -0.0014 for SPEI3 and -0.00010 for SPEI24 (Table 5). The magnitude of the increase ranges from 0.00011 (SPEI6) to 0.00037(SPEI12). It has come out from the study that since the rainfall break in 1970, there was sparse extreme drought event across the entire basin but moderate drought events were observed over the years. The negative trends can affect agriculture and water supply of the regions. In addition, based on the SPEI24 trends, the last two decades are marked by a return to normal rainfall.

Table 5: Values of the Sen's slope estimator for monthly SPEI (1960-2021) over Massili Basin

		SEN'S SLOPE	
	z	***P*-value**	**Sen's slope**
SPEI3	-0.78439	0.4328	-0.0001402821
SPEI6	0.59792	0.5499	0.0001114899
SPEI12	1.91680	0.0553	0.0003763441
SPEI24	-0.53019	0.5960	-0.0001080403

4. CONCLUSION

Historical drought signature was investigated by the Standardized precipitation Evapotranspiration index in this paper over the Massili watershed. The Mann–Kendall and Sen Slope estimation test were then used to detect the drought trends and magnitude. The results indicated three significant episodes. The first period standing from 1960 to 1979 is marked by an occurrence normal to wet conditions. The period 1980-2009 presents a middle drought condition due to less precipitation and higher temperature in the basin with repercussion on agricultural activities. From 2010-2021, a slight decreasing trend in drought frequency is observed with a tendency to recovery features. The result provides baseline information for climate policy making and drought responses. Indeed, in the context of climate change, there is an urgent need to develop a drought management strategy, policy framework, and action plane for the watershed. However, accurate adaptations strategies to climate change required historical information's on hydro-climatological parameters but also information related to their projections in the near and long term under climatic scenarios.

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