Open Access Library Journal
2024, Volume 11, e11897
ISSN Online: 2333-9721
ISSN Print: 2333-9705

Exploratory Analysis of Algeria Meteorological Drought Using SPI and SPEI

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How to cite this paper: Choutri, I. and Hussien, A. (2024) Exploratory Analysis of Algeria Meteorological Drought Using SPI and SPEI. *Open Access Library Journal*, **11**: e11897.
https://doi.org/10.4236/oalib.1111897

Received: July 2, 2024
Accepted: August 27, 2024
Published: August 30, 2024

Abstract

Drought frequency has increased worldwide in recent years due to global warming, causing famine, water shortage, and economic loss. This paper aimed to assess the meteorological drought in Algeria, using two globally accepted drought indices, Standardized Precipitation Index (SPI) and Standardized Precipitation Evapotranspiration Index (SPEI). The SPI and SPEI at 3-, 6-, 9-, and 12-month timescale were obtained to analyze the temporal variability of different drought levels. Pearson correlation was employed to explore relationships between SPI and SPEI values. The results show that the period 1999 to 2001, 2009, 2010 and 2016 years are observed as drought periods by both indices for all timescales. As indicated by both SPI and SPEI indices at different timescales the year after which the intensity and duration of drought notably increased was 1999. A negative trend of both the indices has been observed in all timescales, which clearly shows a transition from near normal to moderately dry during the selected time period. The highest correlation between both indices is for the 3-month scale with (r = 0.73). The main outcome of this study is that both SPI and SPEI show a strong correlation at the same time scales adopted in this study. The dependency of SPEI on temperature is also observed in this study. These findings highlight the consistency in identifying severe drought periods by both SPI and SPEI indices.

Subject Areas

Climate Change

Keywords

Algeria, Famine, SPI, SPEI, Thornthwaite Method

1. Introduction

Drought is one of the main natural causes of agricultural, economic, and environmental damage [1], it is a complex, naturally occurring hazard, resulting from climate variability and change, leading to a change in the water balance, due to drastic decreases in precipitation over an extended period of time [2] [3]. With ongoing global warming, the frequency and severity of droughts have been steadily increasing, exerting notable impacts on human survival and the sustainable development of societies. Hence, one needs to realize the context in which drought and its impacts are expressed. Wilhite and Glantz (1985) [4] identified more than 150 realizations of drought in the literature; while from those, drought can be classified into four major types: 1) meteorological, as a reduction in precipitation; 2) agricultural, as a lack of moisture in soil; 3) hydrological, tracked down considering the decline in stream-flows and runoffs; and finally 4) socioeconomic droughts in human water use while there is also another definition of drought based on ecological water deficit in the environment as ecological drought [5]. Based on these definitions, there are diverse and different realizations of drought types which have several impacts on different sectors. All types of drought initiate with a deficit in precipitation over time and/or space. An early stage of accumulating precipitation deficiency is commonly referred to as a meteorological drought. The persistence of this phenomenon over time, considering factors such as above-normal temperatures, high winds, and low relative humidity, has great impacts on socioeconomic and environmental cycles. Since regions have various climatic patterns, meteorological droughts are expressed with changes in the local hydro-meteorological, geographical, and climatological situation which plays an important role in the definition of the meteorological drought. However, these types of droughts may also linger into a multi-seasonal event and/or develop into other types of droughts [6].

Unlike other natural disasters, the onset and end of droughts are challenging to predict [7], and understanding the impacts of droughts is complicated due to their spatial and temporal variability [8], that's why drought indices are very important for monitoring droughts continuously in time and space, and drought early warning systems are based primarily on the information that drought indices provide [9]. The majority of drought indices have a fixed time scale. Since 1900, several indices have been developed to identify and assess the severity of drought, such as the rainfall anomaly index (RAI) [10], and the Palmer drought severity index (PDSI) [11] which has a time scale of about 9 months [12]. However, this time scale does not allow identification of droughts at shorter time scales. Moreover, this index has many other problems related to calibration and spatial comparability [13]. In contrast, the standardized precipitation index (SPI) [14] [15], when developed following a careful procedure [16], can be calculated at different time scales to monitor droughts in various usable water resources [17]-[19]. SPI It is recommended by many organizations such as the World Meteorological Organization (WMO) and the United States National Oceanic and Atmospheric Administration (NOAA) for characterizing meteorological droughts as well as the other categories of droughts [20]. There is also the

Standardized Precipitation Evapotranspiration Index (SPEI) [1], like the PDSI and the SPI, it can measure drought severity according to its intensity and duration, and can identify the onset and end of drought episodes. The SPI uses precipitation data as input variables, while the SPEI looks at how temperature affects water needs and takes global warming into account and it involves monthly climatic water balance (difference between precipitation and potential evapotranspiration). Global warming could increase evaporation more than precipitation. The SPEI comprises PET which is an essential factor of the hydrologic water cycle [21].

Severe droughts have been occurring in North Africa for several decades now [22], and Algeria was not an exception, drought had already been observed at the beginning of the twentieth century, through the 1940s and since the 1970s [23]-[25]. Over 80% of its land is desert and the north of the country, along the Mediterranean coast, boasts fertile lands, mountains, and hilly regions while the vast, arid Sahara Desert occupies the southern regions. The country already knows an accentuation of droughts and thus worsening of desertification, soil salinization, and pollution of surface water and therefore progressive degradation of water resources, The incidence of rainfall will be less frequent but more intense, while droughts more common and longer. Similarly, floods that continue to serve north and south would be greater in frequency, especially in spring and autumn [26].

Globally, many studies have used SPI and SPEI to study meteorological drought [27]-[33], and several studies in the Mediterranean area have demonstrated that SPI is an effective indicator for detecting drought-related impacts on reservoir storage, vegetation activity, agriculture, crop yields and forest fire risk [1] [34]-[37]. In Algeria, the persistent meteorological drought that it has suffered for several decades [38] has been the subject of several scientific articles. Most of the research on drought and climate change in Algeria has been based in the northern part of the country [39]-[42]. According to the studies in reference [43], the North West of Algeria experienced in the two last decades a severe drought characterized by rainfall deficits varying from 12% to 20%. The studies of [44] conducted for the period between 1980 and 1990 noted a rainfall deficit of about 50% in the central regions of Algeria, while it came up to 30% in the western and the eastern parts. [45] Found a correlation between the rainfall variability in northern Algeria and the variation in the number of wet days ranging from 10 to 50 mm, leading to a negative/positive rainfall trend in the west/east direction since the 1970s. At a larger regional scale, [46] studied rainfall data of 120 stations in Northern Algeria, the results indicated an alternation of wet and dry sequences; 1) a long wet sequence from 1922 to 1938 characterized by rainfall excess of about 6%. 2) A dry sequence from 1939 to 1946 in the eastern and central parts of Algeria with a rainfall deficit of about 11%. 3) A wet sequence from 1947 to 1972 4) and a long dry sequence that starts from 1973. All these studies and research aim to characterize the meteorological drought and climate variability in Algeria, highlight the spatio-temporal variability of drought. Some studies applied SPI to identify drought conditions in Algeria [47]-[49]. [47] Identified historical drought events in Northwest Algeria during 1982/83, 1983/84, 1989/90, 1992/93, 1993/94, 1996/97, 1998/99, 1999/00, 2004/05, and 2006/07 using SPI analysis. [48] Assessed the spatiotemporal meteorological drought pattern in northern central Algeria, and the analysis, conducted at seasonal and annual scales with the Standardized Precipitation Index (SPI), revealed a prolonged drought starting in the late 1980s. [49] Monitored the spatiotemporal evolution of meteorological drought in Northwestern Algeria, using the Standardized Precipitation Index (SPI), the analysis indicated significant inter-annual variability and a general decline in annual rainfall, with a notable shift observed between 1974 and 1980, and analysis of SPI trends using Mann-Kendall test, highlighted that drought events intensified significantly after 1976, showing increased intensity, duration, and frequency. Very few studies have been conducted using SPEI to monitor drought in Algeria [50] [51]. [50] showed that SPEI indicates greater drought impact than SPI. In Algeria, extreme drought was notably observed in 1983 based on SPI, the highest drought impacts occurred in 1983 and 2002 based on SPI and SPEI. [51] indicated a significant level of agreement between SPI and SPEI values at different timescales, and a positive linear correlation ($r > 0.75$, $p < 0.0001$) further supported this finding.

Generally speaking, there is indeed sufficient knowledge of the variation of droughts in Algeria using the SPI, unlike the use of the SPEI, which justifies the choice of our study, and as we mentioned previously, most studies related to drought were based on the Northern regions of Algeria (Western and Eastern), in this study we focus on the entire country. A systematic analysis of the meteorological drought pattern in Algeria would help in identifying drought scenarios and provide aid to drought management, the advancement of drought monitoring and early warning systems, anticipated to provide valuable insights for future comparisons and selections of drought indices. Timely determination of the level of drought will help in an effective decision-making process in mitigating the environmental, social and costly economic impacts of drought. The main objective of this study is to assess the temporal variation of meteorological drought, identify drought years over the observation period (1950-2020), and examine the drought severity in Algeria using Standardized Precipitation Index (SPI) and Standardized Precipitation Evapotranspiration Index (SPEI) at different time scales (3, 6, 9, and 12) (The main advantage of using the SPI and SPEI is that it allows comparison of droughts at any regional scale), using the long-term monthly precipitation and temperature data, covering the period of (1950-2020), obtained from the Climate Research gridded time series (CRU TS v.4.05). Mann-Kendall test and Sen's slope estimator have also been applied to find out the significance of drought characteristic trend and detect if there is a statistically significant trend in SPI, SPEI and precipitation. The primary aim of this study is to analyze temporal pattern of meteorological drought over Algeria using SPI and SPEI which can examine the characteristics of drought and can give an indication of drought at various levels of severity.

2. Data and Methods

2.1. Study Area

Algeria is a country in the subtropical zone of North Africa (Latitude: 28˚N · Longitude: 2˚E) (**Figure 1**). Its climate is very different between regions (North-South, East-West). It is of the Mediterranean type over the entire northern fringe which includes the coast and the Tell Atlas (hot and dry summers, wet and cool winters), semi-arid on the high plateaus in the center of the country, and desert as soon as one crosses the chain of the Saharan Atlas. It is distributed into five levels based on thermal and precipitation thresholds: saharien arid, semi-arid, sub-humid, and humid, which occupy 89.5%, 4.78%, 4.12%, 1.42%, 0.32%, and 0.08% of the total area, respectively [52]. In Algeria, a range of studies have projected a decrease in rainfall and an increase in temperature [45] [53] [54]. The rainfall is characterized by a very marked spatio-temporal variability, it diminishes southward, dropping below 100 mm south of the Saharan Atlas, marking the desert's onset, with a decline also from east to west; the northern, central, and eastern borders receive annual precipitation averaging 600 to 1150 mm, making them wetter than other regions, while the northwestern borders average around 250 to 500 mm annually. The spatial distribution of annual precipitation data from 1950 to 2020 used in this study is represented in **Figure 2**.

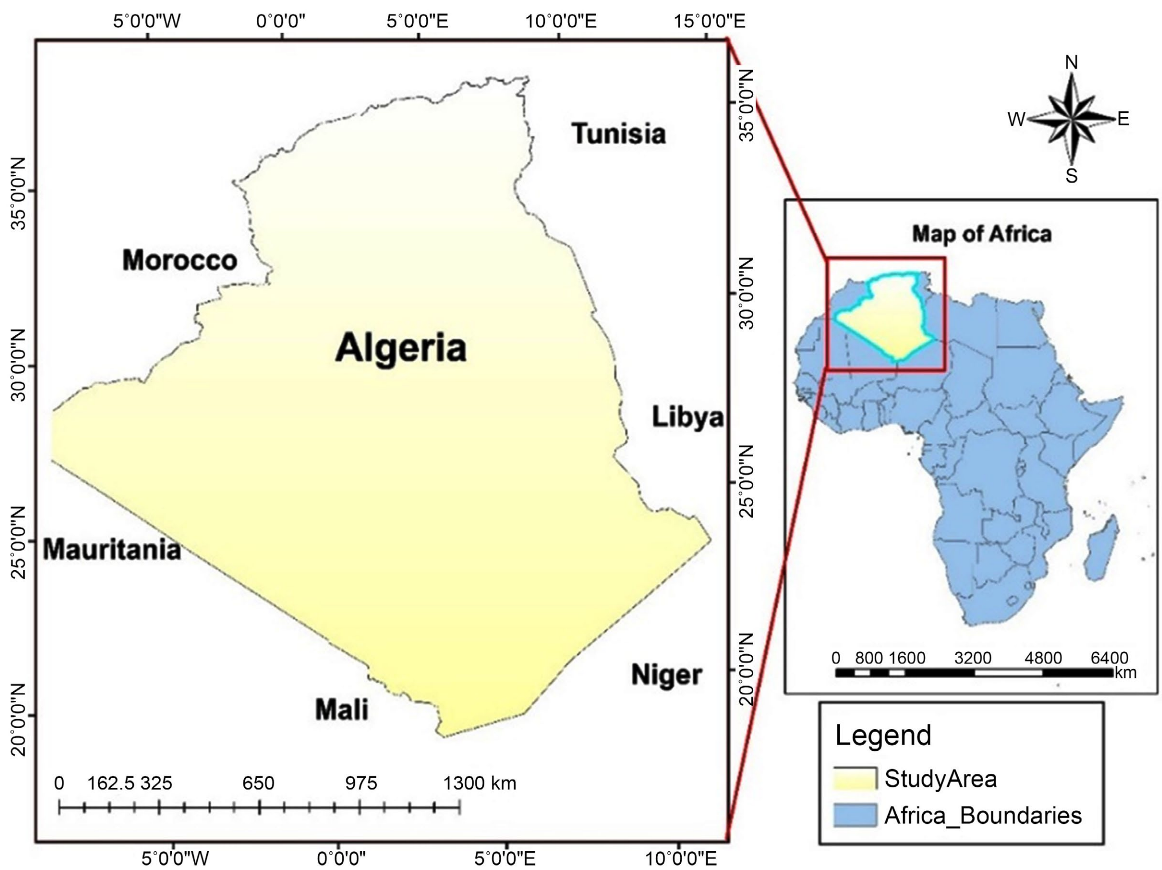


Figure 1. Location map of the study area.

2.2. Datasets

Monthly precipitation and Temperature data used in this study were obtained from the Climatic Research Unit (CRU) TS dataset [55]. We have used 70 years of data (1950-2020) for the SPI and SPEI calculations. The CRU TS v4 dataset used in this study is the new version of CRU datasets which are developed by the CRU of the University of East Anglia, U.K. It is comprised of monthly grids of observed climate data for the period 1901-2022 and covers the global land surface on a 0.5˚ × 0.5˚ latitude-longitude grid, including oceanic islands but excluding Antarctica. It is derived by the interpolation of monthly climate anomalies from extensive networks of weather station observations. There are no missing values in the defined domain. Since its first release in 2000 [56], CRU TS has been used widely by many classes of users, in diverse research areas and applications. These include those in the domain of climate research (e.g., [27] [52] [57]).

2.3. Methods

2.3.1. Standardized Precipitation Index (SPI)

The Standardized Precipitation Index (SPI) reflects the impact of drought on the availability of different water resources. It is designed to quantify the impacts of precipitation deficit on groundwater, reservoir storage, soil moisture, snowpack, and stream flow for multiple time scales. Soil moisture conditions respond to precipitation anomalies on a relatively short scale. Groundwater, stream flow, and reservoir storage reflect the longer-term precipitation anomalies [8]. Therefore, SPI was originally calculated for 3, 6, 12, 24, and 48-month time scales. The SPI is used operationally to monitor drought conditions globally [15]. The SPI calculation for any location is based on the long-term precipitation record for a desired period. This long-term record is fitted to a probability distribution, which is then transformed into a normal distribution so that the mean SPI for the location and desired period is zero [58]. The SPI formula is:

$$\text{SPI} = \frac{x_i - x_m}{\sigma} \quad (1)$$

where x_i precipitation in year, x_m average precipitation, and σ its standard deviation.

Positive SPI values indicate greater than median precipitation, and negative values indicate less than median precipitation. Because the SPI is normalized, wetter and drier climates can be represented in the same way. While the SPI can monitor wet periods, it is typically used to assess the length and magnitude of drought events. A drought event occurs when the SPI continuously reaches an intensity of −1.0 or less (**Table 1**). The event ends when the SPI becomes positive. Each drought event, therefore, has a duration defined by its beginning and end, and an intensity for each month that the event continues. Drought magnitude is the positive sum of the SPI for each month during the drought event [14]. In this study the Standardized Precipitation Index (SPI) at different time scales (3, 6, 9 and 12) was calculated by using SPEI package in R software using the monthly precipitation data from 1950 to 2020. Different values of SPI have significant meanings (Table 1).

Table 1. SPI values range [14].

SPI Values	Drought Classification
2.0+	Extremely Wet
1.5 to 1.99	Very Wet
1.0 to 1.49	Moderately Wet
−0.99 to 0.99	Near Normal
−1.0 to −1.49	Moderately Dry
−1.5 to −1.99	Severely Dry
− 2 and less	Extremely Dry

2.3.2. Standardized Precipitation Evapotranspiration Index (SPEI)

One of the more recently developed drought indices is the Standardized Precipitation Evapotranspiration Index (SPEI), which catches the basic premise of the SPI and adds a temperature component to capture a simplified water balance [1] [59]. Like the SPI, the SPEI can be calculated on a range of timescales from 1 - 48 months. The SPEI uses a simple water balance calculation that is based on several methods, such as the Thornthwaite (1948) model, Hargreaves or Penman-Monteith equation for evaluating the potential evapotranspiration (PET). The Thornthwaite method can be considered a rather simplified model if compared with other formulations [60], basing PET on temperature-driven models may exaggerate the effect of the current global warming [61]. Reference evapotranspiration (ET0) is the amount of evaporation and transpiration from a reference vegetation of grass, and they are usually considered equivalent. Several studies have shown that good estimates of PET can be obtained with various meteorological parameters, but in the context of drought index, they are not needed since a general estimation of the water balance is adequate. This also keeps the calculations stingy while giving the additional data requirements needed for determining actual evapotranspiration. [62] Thus, SPEI is calculated as

$$D_i = P - \text{PET} \tag{2}$$

where D_i is the difference between precipitation (P) and PET for the month (i), and the calculated D values at different timescales are as follows:

$$D_n^k = \sum_{i-0}^{k-1} P_{n-1} - \text{PET}_{n-1} \tag{3}$$

where k is the number of months over which the sum is taken, and n is the month for which the sum is taken.

The formula of the SPEI can be represented as

$$\text{SPEI} = W - \frac{C_0 + C_1 W + C_2 W^2}{1 + d_1 W + d_2 w^2 + d_3 w^3} \tag{4}$$

where

$$W = \sqrt{-2\ln(P)} \quad \text{for } P \le 0.5 \tag{5}$$

The constants are: C_0 = 2.515517, C_1 = 0.802853, C_2 = 0.010328, d_1 = 1.432788,

$d_2 = 0.189269$, $d_3 = 0.001308$.

In this study to calculate the Standardized Precipitation Evapotranspiration Index (SPEI) at different time scales (3, 6, 9 and 12), we calculate Potential Evapotranspiration PET by Thornthwaite method using SPEI package in R software, which requires average temperature between 1950-2020 and latitude of the site (our case Algeria latitude = 28.026876). SPEI has the same significant meanings as SPI [63] (Table 1).

2.3.3. Trend Analysis

Trend analysis determines whether the measured values of a variable show a consistent increase or decrease during a time period. Many statistical methods can be used for trend detection in a time series of meteorological and hydrological records. In the present study, Mann–Kendall's test (MK) [64] [65], was applied to identify statistically significant trends in precipitation, SPEI and SPI in different time scales for the period of 1950-2020, using CRU data. It is the most widely used nonparametric method for trend detection. This means it can be applied to data no matter what the probability distribution is [66], and it's recommended by World Meteorological Organization (WMO) to analyze various hydrological and meteorological variables [67].

1) Mann–Kendall trend test

The Mann-Kendall Test [64] [65] is used to determine whether a time series has a monotonic upward or downward trend of various hydro-meteorological data. It does not require that the data be normally distributed or linear. It does require that there is no autocorrelation. The null hypothesis for this test is that there is no trend, and the alternative hypothesis is that there is a trend in the two-sided test or that there is an upward trend (or downward trend) in the one-sided test. For the time series $x_1, \cdots, x_n$, the MK test uses the following statistic:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn\left(x_j - x_i\right). \tag{6}$$

where $sgn\left(x_j - x_i\right) = \begin{cases} 1 & \text{if } \left(x_j - x_i\right) > 0 \\ 0 & \text{if } \left(x_j - x_i\right) = 0 \\ -1 & \text{if } \left(x_j - x_i\right) < 0 \end{cases}$.

In which x_j and x_i are the observations taken at times j and i (with $j > i$), respectively, and n is the dimension of the series.

The variance is computed as:

$$V\left(s\right) = \frac{n\left(n-1\right)\left(2n+5\right) - \sum_{i=1}^{p} t_i\left(t_i - 1\right)\left(2t_i + 5\right)}{18} \tag{7}$$

The standardized test statistic Z is calculated as follows:

$$Z = \begin{cases} \frac{s-1}{\sqrt{V_s}} & \text{if } s > 0 \\ 0 & \text{if } s = 0 \\ \frac{s+1}{\sqrt{V_s}} & \text{if } s < 0 \end{cases} \tag{8}$$

Positive Z values designate increasing trends while negative Z values designate decreasing trends. The trend's significance assessment was conducted by computing the corresponding p-values at the level of significance of 5%, at this level, a positive trend is significant when p-value > 0.05, and a negative trend is significant when its p-value < 0.05 [68].

2) Sen's Slope estimator

It is also possible to obtain a non-parametric estimate for the magnitude of the Sen's slope of trend. Sen's slope estimator has been used to flawlessly determine the degree of the trend in the dataset [69]. Sen's slope estimator is applied here to resolve the magnitude of the result values of the drought indices (**Table 2**).

Table 2. Trend analysis results of Precipitation, Temperature, SPI and SPEI from 1950 to 2020.

Parameters	Z	p-value	Sen's slope
Precipitation	−2.189	0.029	−0.193
Temperature	6.825	0.000	0.016
SPI-3	−3.089	0.002	0.000
SPI-6	−4.982	0.000	−0.001
SPI-9	−6.642	0.000	−0.001
SPI-12	−7.414	0.000	−0.001
SPEI-3	−14.429	<2.2e−16	−0.002
SPEI-6	−18.314	<2.2e−16	−0.002
SPEI-9	−20.866	<2.2e−16	−0.003
SPEI-12	−21.955	<2.2e−16	−0.003

$$b = Median\left[\frac{X_j - X_i}{j - i}\right], \text{ for all } i < j \quad (9)$$

where b is the slope between data points X_j and X_i; measured at times j and i; respectively.

In this study M-K statistical test was used to analyze the annual scale evolution of meteorological drought and to determine the significance of trend combined with slope estimator to obtain the magnitude of the trend, they have been applied over the outcome values of precipitation and Temperature (1950-2020), SPI and SPEI in different time scale (3, 6, 9 and 12). It is used to determine whether a set of data values is increasing or decreasing over time, and whether the trend in either direction is statistically significant. The whole process is carried out by R-software programming package.

2.3.4. Correlation Analysis

Correlation Analysis is a statistical method that is used to discover if there is a relationship between two variables/datasets, and how strong that relationship may be. Through the correlation analysis, we evaluate correlation coefficient that tells us how much one variable changes when the other one does. Correlation analysis provides us with a linear relationship between two variables. It is a method used to determine the direction and strength of the relationship between the two variables. Since drought indices are based on standardization, Pearson correlation analysis was used for correlation analysis in this study. It is used in several scientific research related to the drought [70]-[72].

1) Pearson correlation

The Pearson correlation method is the most common method to use for numerical variables; it assigns a value between −1 and 1, where 0 is no correlation, 1 is total positive correlation, and −1 is total negative correlation [73]. This is interpreted as follows: a correlation value of 0.7 between two variables would indicate that a significant and positive relationship exists between the two. A positive correlation signifies that if variable A goes up, then B will also go up, whereas if the value of the correlation is negative, then if A increases, B decreases [74]. Pearson correlation coefficients (R) were found between the SPI and SPEI indices using SPEI package in R software. R was computed using:

$$R_{xy} = \frac{\sum_{i=1}^{n}(x_i - x)(y_i - y)}{\sqrt{\sum_{i=1}^{n}(x_i - x)^2 (y_i - y)^2}} \tag{10}$$

where "n" indicates the number of observations, and "x" and "y" represent the SPI and SPEI, respectively.

2) Linear regression analysis

Linear regression analysis is a widely used statistical technique for modeling and predicting the relationship between variables [75]. It measures the association between two variables and is often used to predict a dependent variable based on one or more independent variables [76]. The technique can be applied in various forms, including single linear regression, multiple linear regression, and polynomial regression [77]. However, it is important to note that a statistically significant regression analysis does not imply a causal relationship between the independent and dependent variables [78]. In the context of the study on drought indices (SPI and SPEI) and climate variables (precipitation and temperature) in Algeria, linear regression can be applied to understand how these indices interact and predict changes over time. By examining these relationships, the study aims to understand how changes in climate variables contribute to drought severity and frequency, helping to inform drought mitigation and adaptation strategies in the region.

3. Results and Discussion

3.1. Trends of Drought Characteristics

The trends of Precipitation, Temperature, SPI and SPEI, obtained using the M-K test, and the Sen's slopes from 1950 to 2020 are shown in **Table 2**. With a level of confidence of 95%, the Mann-Kendall test (MK-test) and Sen's slope estimator were applied in order to evaluate the significance of the trend. The Precipitation showed a decreasing trend (significant decrease) with a Sen's slope of approximately −0.1929. The Temperature showed a significant increase with a positive Sen's slope (0.0161) indicating a clear upward trend. For SPI and SPEI at different time scales (3, 6, 9, and 12), all of them show decreasing trends, this indicates that the probability of drought occurrence is increasing (increasing drought severity), our results agreed with [79]. It has been found that the SPI and SPEI values with different time patterns (3, 6, 9, and 12 months) have faced a slide declining trend at a 5% level of significance (**Table 2**). Overall, the results indicate decreasing trends in precipitation, SPEI and SPI values over the specified time period (1950-2020), and increasing trends in temperature, and these trends are strong statistically significant based on the small p-values ($p < 0.05$).

3.2. Spatial Distribution of Precipitation from 1950 to 2020

The spatial distribution of annual precipitation (1950-2020) in Algeria, is represented in **Figure 2**. During the last decade, the time trend in rainfall has generally been in deficit for the southern Algeria. In contrast to the North, the annual rainfall generally ranges between 320 and 920 mm. We also note that the total annual precipitation in the Western regions of the country is less compared to the eastern regions, this lack of precipitation according to Meddi and Hubert (2003) has generated flow deficits ranging from 37% to more than 70% from the east towards the west of the country. In general, shows its decrease from north to south, and from West to East denoting the effect of the general circulation of the atmosphere. Meddi and Toumi (2013) show that the Rainfall decreases from north to south and from east to south. From **Figure 3**, analysis reveals that the average annual precipitation between 1950 and 2020 over Algeria was around 94 mm during the study period. The lowest precipitation was recorded in 1961 (70 mm), 1970 (70.1 mm), 1981 (67 mm), 1983 (56.5 mm), 2000 (65.3 mm) and 2020 (66.6 mm), while the highest average precipitation was recorded in 1957 (125.1 mm), 1976 (131.2 mm) and 2003 (117.5 mm).

3.3. Spatial Distribution of Temperature from 1950 to 2020

The spatial distribution of annual mean temperature in the period (1950-2020) over Algeria, is represented in **Figure 4**. It is observed that the maximum value of the mean temperature observed was 29˚C. **Figure 5** shows the monthly mean, minimum and maximum temperature variation over Algeria. The monthly temperature data from 1950 to 2020 in Algeria shows a clear seasonal variation, with temperatures peaking in July and August during the summer months and dropping to their lowest in January and December during winter. There is a noticeable increase in temperatures from winter to summer, with a gradual decrease observed from summer through to winter. Variability across the months reflects the influence of seasonal changes in solar radiation, atmospheric circulation patterns, and regional climatic factors.

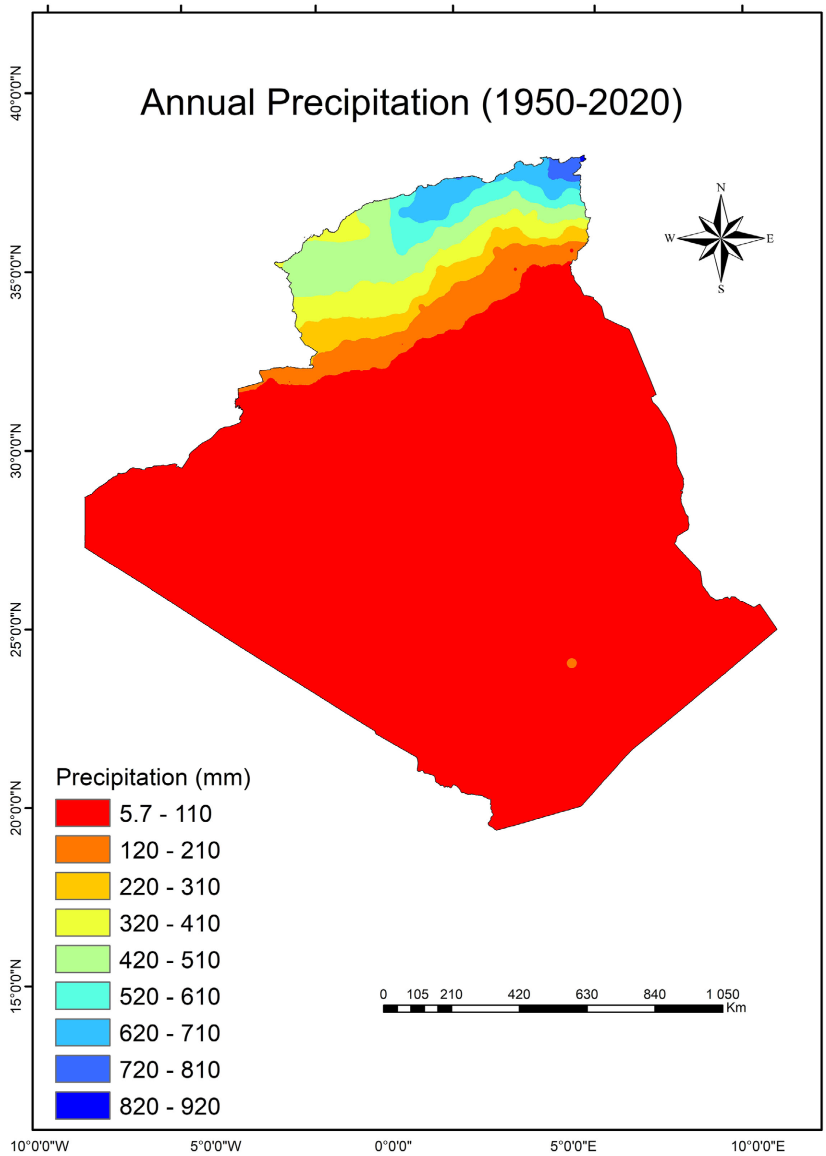


Figure 2. Spatial distribution of total annual Precipitation (1950-2020) over Algeria.

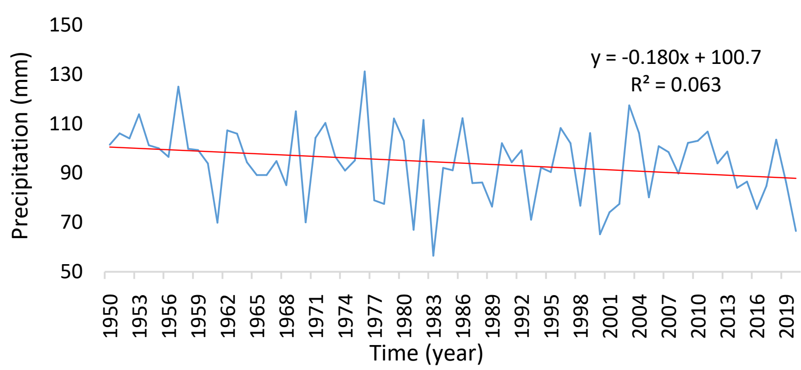


Figure 3. Variation of annual average precipitation over Algeria from 1950 to 2020 (CRU data).

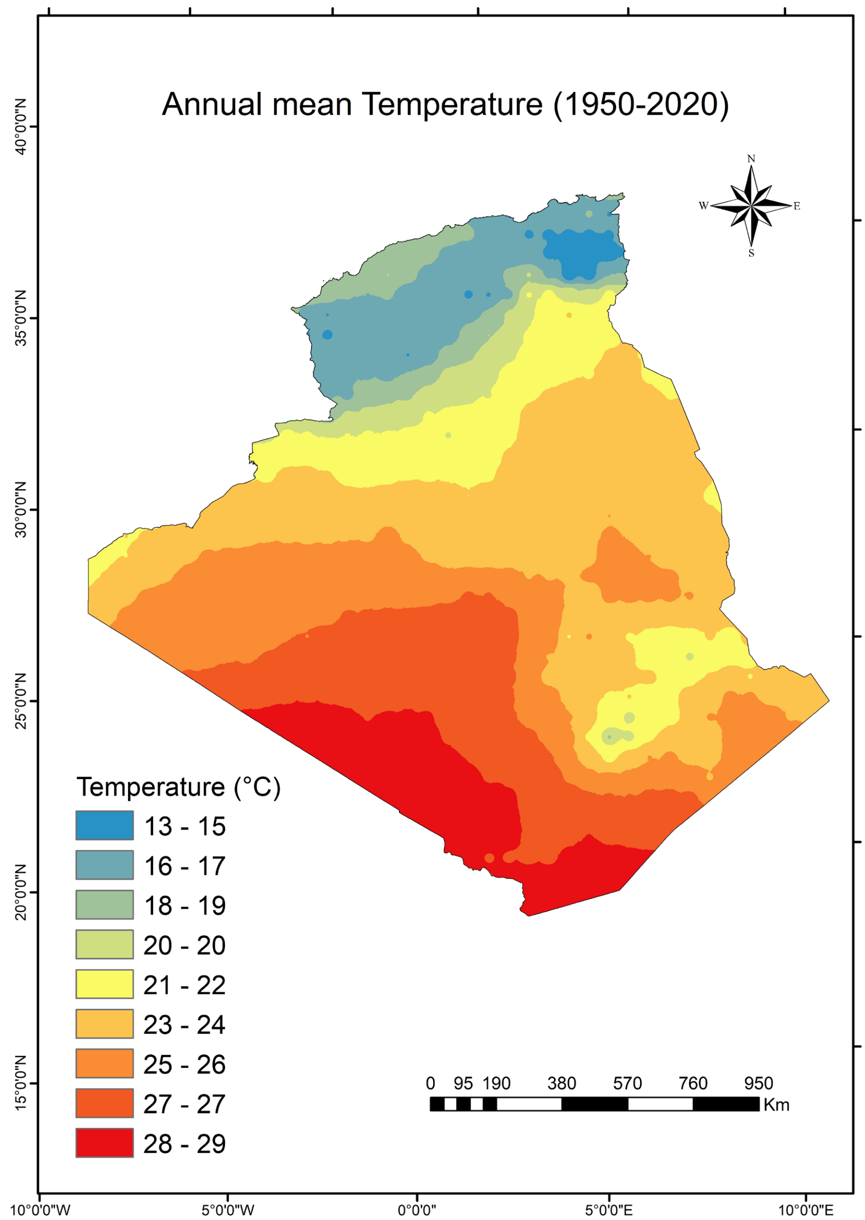


Figure 4. Spatial distribution of annual mean Temperature (1950-2020) over Algeria.

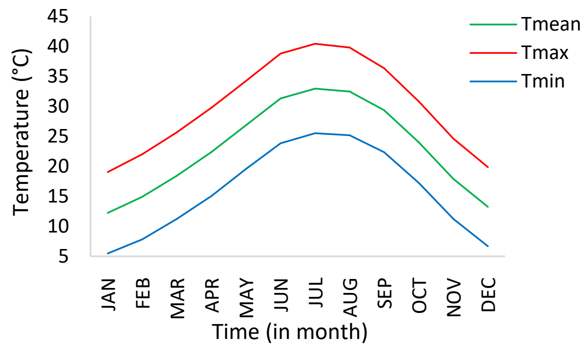


Figure 5. Variation of monthly mean, maximum and minimum temperature over Algeria from 1950 to 2020 (CRU data).

3.4. Temporal Variation of Drought

The SPI and SPEI were used to identify the historical drought which occurred in Algeria during the last seven (7) decades from 1950 to 2020 based on the 3, 6, 9, and 12-month timescales (Figure 6 and Figure 7), can show seasonal, semi-annual, and annual droughts. In Algeria, in general the dry period is 3 months in the summer season each year (JJA). Then, considering the 9-month time scale is necessary (SON, DJF and MAM). Moreover, a 3-month period may be significantly useful for medium drought pattern extraction which may help in cropping activities, and long-term droughts are identified by 9, 12 and 24 months periods that can aid agricultural productions, and drought mitigation strategy development [32]. Drought is defined when the SPI and SPEI reach a negative value and continue progressively until they become positive. Positive values are defined as wet periods (Table 1). According to Figure 5 and Figure 6, the indices had large fluctuations at short time scales, which reduced as the time scale increased, which means, an increase in the time scale reduced the number of drought events and enhanced the drought duration. In this study drought has been classified into four classes such as normal, moderate, severe and extreme drought.

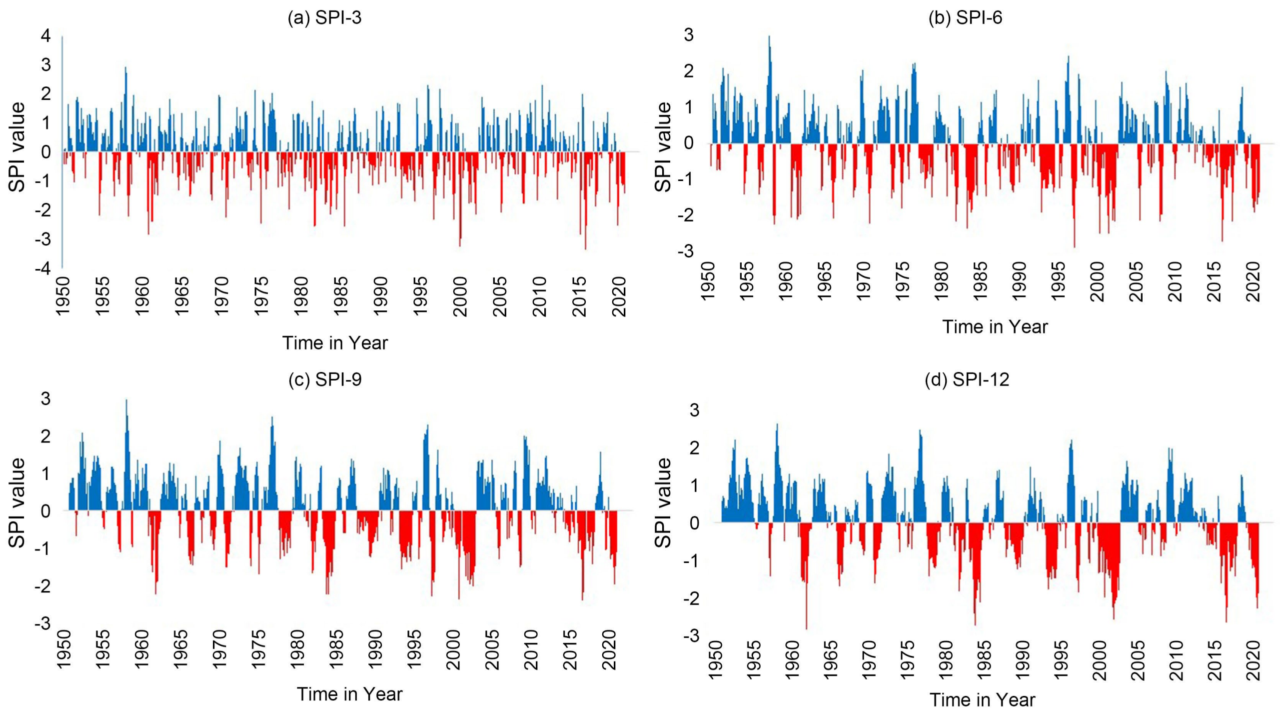


Figure 6. SPI values from 1950 to 2020 calculated for the time scales: (a) 3 months, (b) 6 months, (c) 9 months, and (d) 12 months.

3.4.1. Temporal Variation of SPI

Figure 6 presents the temporal variation of SPI for timescale (3, 6, 9 and 12 months), which have been computed using 70 years (1950 to 2020) of monthly precipitation data. The variation of the SPI was visible at various timescales, indicating a distinct change in the dry and wet degrees of each month in the study area and the dry and wet month periods have a high temporal frequency. Extreme drought has been observed during the years 1954, 1958, 1960, 1961, 1970, 1975, 1981, 1983, 1985, 1996, 1999, 2000, 2002, 2015, 2016 and 2020 having 3-month SPI less than −2.0, with frequency of 2.70%. The computed SPI for a 3-month timescale revealed that Algeria experienced a serious extreme drought once in 2000 (SPI = −3.27) and 2016 (SPI = −3.36), this result agreed with [80], they found that the drought magnitude was higher over Algeria in 2000 and 2016. In case of extreme drought, occurred in 1958, 1960, 1961, 1962, 1966, 1970, 1981, 1983, 1984, 1997, 2000, 2001, 2002, 2005, 2008, 2016, 2017, and 2020 according to 6, 9 and 12 month SPI with intensity less than -2.0 also these results contracted with [47], showed that the SPI was able to detect historical droughts in 1983, 1984, 1996, 1997, 1999, 2000 and 2005. From the calculation of the SPI, the lowest value (the peak drought intensity) for a 3-month time scale is −3.36 in January 2016, −2.86 for a 6-month time scale in Marsh 1997, −2.84 for a 12-month time scale in January 1962, −2.43 for 9-month time scale in July 2016 (**Figure 6**). From **Figure 6**, it can be seen that in the shorter time scale, the dry and wet month periods have a high temporal frequency, the frequency decreases with increasing time scale, and extreme drought conditions can be seen in Algeria [80].

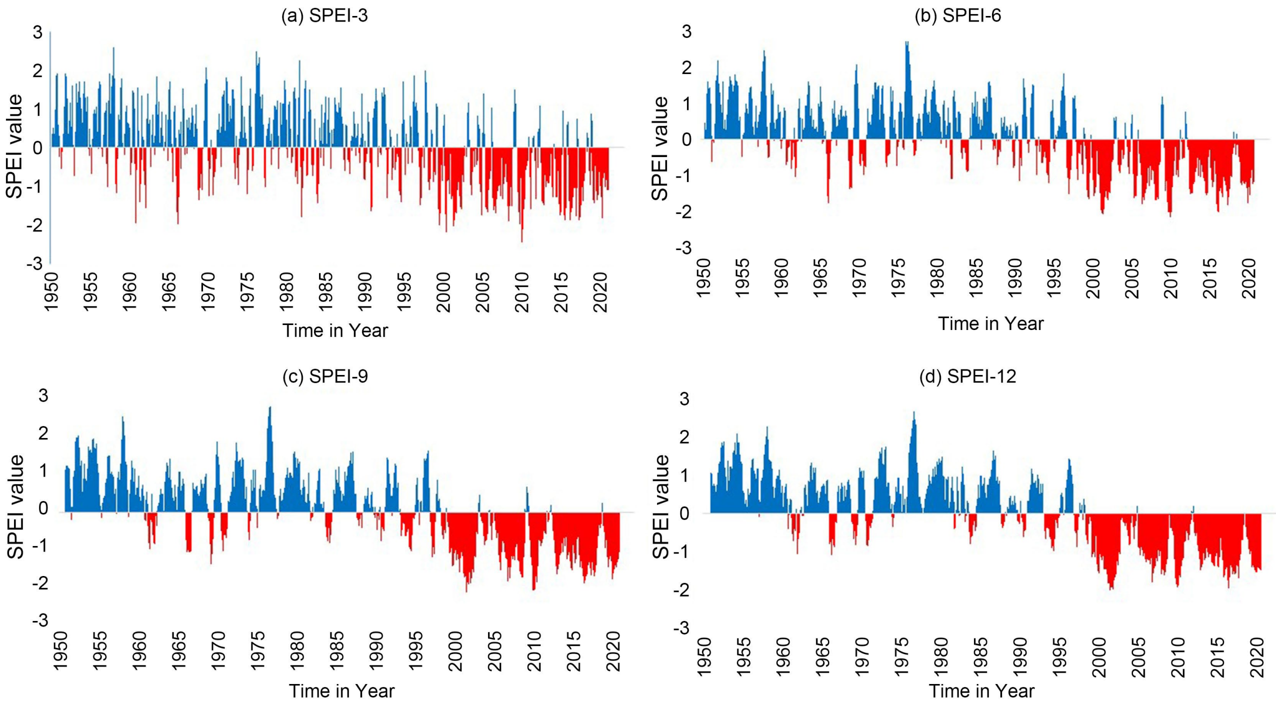


Figure 7. SPEI values from 1950 to 2020 calculated for the time scales: (a) 3 months, (b) 6 months, (c) 9 months, and (d) 12 months.

3.4.2. Temporal Variation of SPEI

Figure 7 presents the temporal variation of monthly SPEI for different timescales (3, 6, 9 and 12-month), which have been computed using 70 years (1950 to 2020) of precipitation and temperature data. Almost in all timescales, 2001-2010 has SPEI less than −2.0 which suggests that this duration is an extreme drought period. The 3-month SPEI data shows that 1999, 2000, 2001, 2009 and 2010 had extreme drought with intensities −2.00, −2.18, −2.04, −2.46 and −2.10 respectively, the peak intensity of the drought was in December 2009 with SPEI-3 = −2.46.

Extreme drought occurred in 2001, 2009, 2010 and 2016 according to 6 and 9-month SPEI with intensity less than −2.0, the peak intensity of the drought was in March 2010 with SPI-6 = −2.12, and in July 2001 with SPI-9 = −2.09. Whereas [81], they selected 2002, 2009, 2010 and 2016 as dry years, in North and West Africa. There is no extreme drought event observed for the 12-month SPEI but the negative value of the index shows moderate and severe drought. The years 1999 to 2001 are observed as drought periods for almost all all-time series calculated. 2009 to 2010 has also been observed as drought duration but it is not as severe as 1999 to 2001 duration drought. The intensity and duration of drought have increased after 1999.

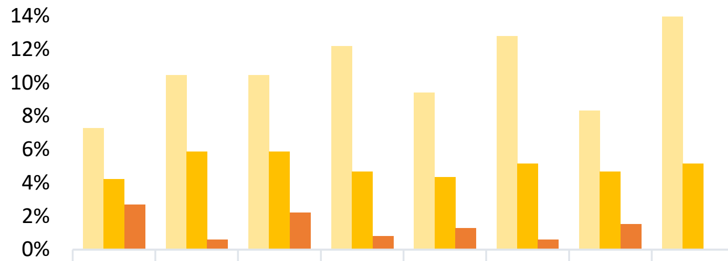
3.5. SPI and SPEI Drought Frequency

Table 3 presents the number and frequency of moderate, severe and extreme drought events (with SPI and SPEI ≤ −1.0) that have occurred at different timescales over Algeria in the period 1950-2020. We did not take mild drought into consideration as it showed only a slight variation from the normal rainfall distribution [82] [83]. In terms of moderate and severe drought, it is obvious that the SPEI number is higher than the SPI number at each timescale. The SPI frequency of extreme drought is larger than the SPEI frequency of extreme drought (**Figure 8**). From **Table 3** and **Figure 8**, It can be determined that the frequencies of moderate droughts are higher than those of severe and extreme droughts for both indices, which means that the probability of occurrence or the return period of moderate droughts is the highest, [84] find the same result using SPI and RDI (the Reconnaissance Drought Index) and this index (RDI) is based on ratio of precipitation and potential evapotranspiration. In the case of long-term droughts, both SPI and SPEI have identified around 26 events as severe and extreme droughts and 47 events as moderate, severe and extreme droughts in Algeria between 1950 and 2020. The reason for more drought events in the SPEI than in the SPI is that the increasing temperature is causing an increase in the rate of evapotranspiration, and SPI only uses precipitation variables to calculate its index [85]. As a result, the highest drought frequencies were obtained for moderate and severe drought events using the SPEI and for extreme drought events using the SPI.

Table 3. The number and frequency of severe and extreme drought in Algeria (1950-2020) on different timescales of the SPI and SPEI.

		SPI-3	SPEI-3	SPI-6	SPEI-6	SPI-9	SPEI-9	SPI-12	SPEI-12
MD	NB	62	89	89	104	80	109	71	119
	DF (%)	7.28	10.45	10.45	12.21	9.39	12.79	8.33	13.97
SD	NB	36	50	37	40	38	44	38	44
	DF (%)	4.23	5.87	5.87	4.69	4.34	5.16	4.69	5.16
ED	NB	23	5	19	7	11	5	13	0
	DF (%)	2.70	0.59	2.23	0.82	1.29	0.59	1.53	0

MD: Moderate drought, SD: Severe drought, ED: Extreme drought, NB: Number of appearance, DF: Drought frequency.

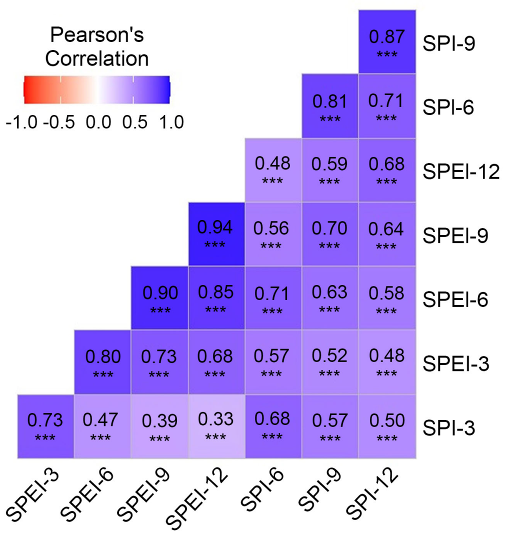


	SPI-3	SPEI-3	SPI-6	SPEI-6	SPI-9	SPEI-9	SPI-12	SPEI-12
Moderate drouht	7.28%	10.45%	10.45%	12.21%	9.39%	12.79%	8.33%	13.97%
Severe drought	4.23%	5.87%	5.87%	4.69%	4.34%	5.16%	4.69%	5.16%
Extreme drought	2.70%	0.59%	2.23%	0.82%	1.29%	0.59%	1.53%	0%

Figure 8. The frequency (%) of moderate, severe and extreme drought in Algeria (1950-2020) on different timescales of the SPI and SPEI.

3.6. Correlation Analysis of SPI and SPEI

Figure 9 shows the Pearson correlation matrix of SPI and SPEI at different timescales (3, 6, 9 and 12). According to the correlation matrix, there is a high relationship between the indices in the same timescale [31] [86]. The correlation coefficient observed between SPEI-3 and SPI-3 was r = 0.73 and it's the strongest correlation coefficient observed between indices of the same timescale; the lowest correlation coefficient (r = 0.33) observed was between SPI-3 and SPEI-12. It was observed that the correlation between SPI and SPEI decreased as the timescale increased reliability with earlier studies [1] [86]. We can say there is a high positive correlation between SPI and SPEI during the study period.



	SPI-3	SPI-6	SPI-9	SPI-12	SPEI-3	SPEI-6	SPEI-9	SPEI-12
SPI-3	1.00	0.68	0.57	0.50	0.73	0.47	0.39	0.33
SPI-6		1.00	0.81	0.71	0.57	**0.71**	0.57	0.48
SPI-9			1.00	0.87	0.52	0.63	**0.70**	0.59
SPI-12				1.00	0.48	0.58	0.64	**0.68**
SPEI-3					1.00	0.80	0.73	0.68
SPEI-6						1.00	0.90	0.85
SPEI-9							1.00	0.94
SPEI-12								1.00

ns p ≥ 0.05; * p < 0.05; **p < 0.01; and *** p < 0.001

Figure 9. Pearson's correlation matrix of SPI and SPEI.

3.7. Linear Regression Analysis

Regression analysis has been used in this study to compare drought indices of same timescale (3, 6, 9 and 12). For the comparison of drought indices, scatter diagram has been drawn and statistically evaluated by using the coefficient of determination (R^2) which explains the amount of variation by correlation. (Figure 10). There was a linearly significant Pearson's correlation coefficient between the SPI and SPEI at the same timescale. Strongest fit has been shown by values of SPI-3 and SPEI-3, and the results of statistical indicators show that the value of SPI gives close results with SPEI in the same timescale. Greatest value of R^2 is 0.52 for SPI-3 and SPEI-3, which indicates that those indices give close results.

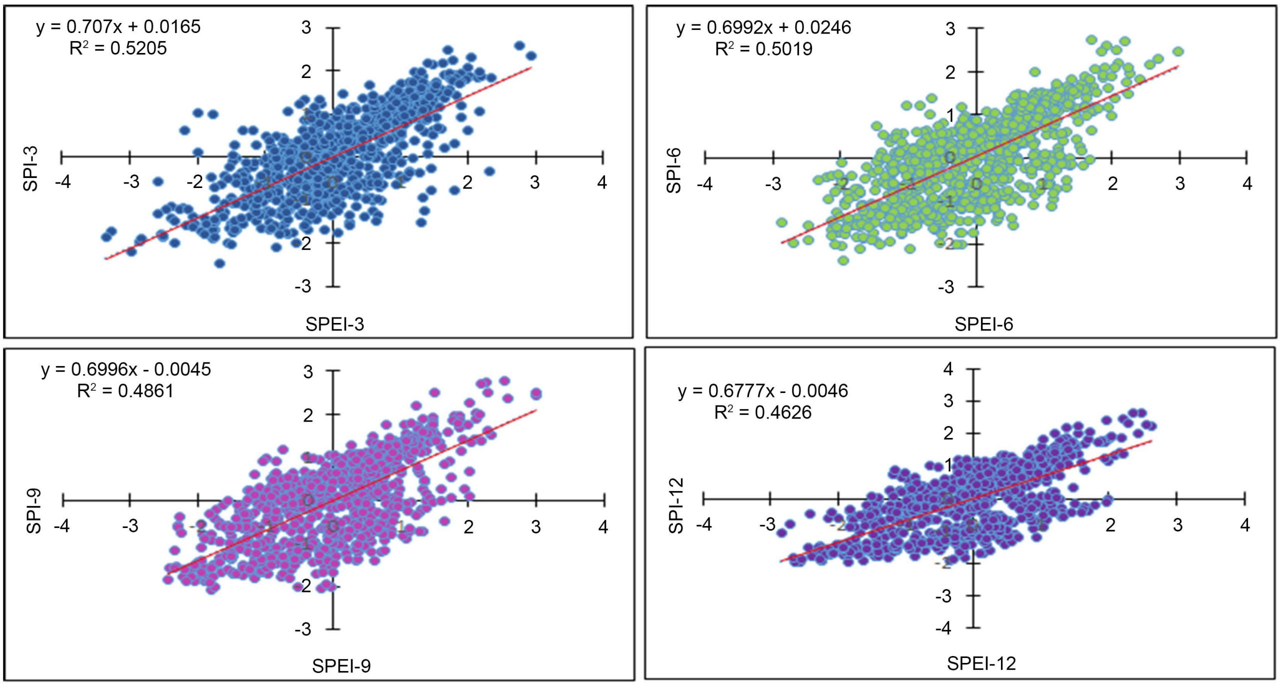


Figure 10. Scatter diagrams of SPI and SPEI at different time scales (3, 6, 9 and 12).

4. Conclusions

The principal aim of this study is to evaluate the temporal dynamics of meteorological drought, identify drought years within the observational span (1950-2020), and investigate drought severity in Algeria using SPI and SPEI at different time scales (3, 6, 9, and 12 months). The primary findings of this research are presented as follows:

- The trend analysis conducted from 1950 to 2020 using the Mann–Kendall test and Sen's slope estimator revealed significant findings regarding precipitation, temperature, SPI, and SPEI in Algeria. Precipitation exhibited a notable decreasing trend with a Sen's slope of approximately −0.1929, indicating a consistent decline over the study period. Conversely, temperature showed a significant increase with a positive Sen's slope of 0.0161, reflecting a clear upward trend. Both SPI and SPEI across various timescales (3, 6, 9, and 12 months) demonstrated decreasing trends, suggesting an increasing probability of drought occurrence and severity.

- Spatially, the distribution of annual precipitation from 1950 to 2020 indicated a gradient from north to south and from east to west, with the northern, central, and eastern borders receiving higher average annual precipitation (600 - 920 mm) compared to the rest of the country. The western regions recorded lower totals (320 - 510 mm), highlighting significant precipitation deficits moving westward.
- Temporal variations in drought conditions, analyzed using SPI and SPEI, identified numerous drought events over the decades. Shorter timescales (3 months) exhibited higher frequency and intensity of drought events, notably in years such as 1954, 1958, 1960, 1961, 1970, 1975, 1981, 1983, 1985, 1996, 1999, 2000, 2002, 2015, 2016, and 2020. Extreme drought conditions, with SPI and SPEI values less than -2.0, were observed particularly in 2000 and 2016. These findings highlight the consistency in identifying severe drought periods by both SPI and SPEI indices, emphasizing the utility of both indices in assessing drought severity over different timescales in Algeria
- Furthermore, correlation analysis between SPI and SPEI showed a strong positive relationship across similar timescales, with the strongest correlation observed between SPI-3 and SPEI-3 (r = 0.73). Linear regression analysis confirmed this relationship, with SPI-3 and SPEI-3 demonstrating the closest agreement (R^2 = 0.52), indicating that both indices provide consistent assessments of drought severity at shorter timescales. Overall, there is a statistically significant positive correlation between SPI and SPEI across all timescales, indicating that both indices generally track drought conditions similarly over the study period (1950-2020).

In conclusion, the study underscores the declining trend in precipitation and increasing trend in temperature over Algeria from 1950 to 2020, contributing to more frequent and severe drought conditions as evidenced by SPI and SPEI. These findings are crucial for informing drought monitoring strategies, water resource management, and agricultural planning in the region. Algeria can enhance drought management and sustainable agriculture by employing remote sensing for real-time monitoring, updating drought indices, investing in water storage infrastructure, reducing water wastage, promoting drought-tolerant crops, and utilizing precision agriculture. Further advanced research is needed to understand the links between atmospheric circulation and drought in Algeria. Therefore, researchers should focus on identifying the advantages of different precipitation data to reduce the data bias of individual precipitation products for studying drought in Algeria.

Acknowledgements

Many thanks to the Chinese Ministry of Commerce.

Conflicts of Interest

The authors declare no conflicts of interest.

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