African Journal of Advanced Pure and Applied Sciences (AJAPAS)

Online ISSN: 2957-644X

Volume 3, Issue 1, January-March 2024, Page No: 1-10

Website: *https://aaasjournals.com/index.php/ajapas/index*

معامل التأثير العربي 2023: (1.55)   SJIFactor 2023: 5.689   ISI 2022-2023: 0.557

Assessment of Historical and Projected Droughts at Siliana Watershed Catchment (Northern Tunisia)

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Received: October 28, 2023	Accepted: December 26, 2023	Published: January 05, 2024

Abstract:

Drought is one of the complex weather events affecting water resources and socio-economic conditions in arid environments that would be most exacerbated by climate change. Drought assessment can be useful in implementing strategies and measures to mitigate drought. This study focuses on the potential use of the Standardized Precipitation Index (SPI) based on precipitation and the Martonne Aridity Index (MAI) based on temperature to reproduce the meteorological and hydrological droughts observed in the Siliana watershed. The determination of these indices was evaluated for different time scales (monthly, seasonal, biannual, and annual) during the period 1960–1989, considered as the reference period, and climate projections to 2041–2070, as a mid-term period for climate change. Thirteen rain stations were selected for this work, spread throughout the Siliana basin. The calculation of SPI at different times was used to provide drought characterization maps using inverse distance interpolation. The SPI analysis shows a good agreement with the drought episodes. SPI was also used to study the temporal evolution of drought and its severity. The most severe droughts in the basin occurred during the 1980s–89. The intensity of droughts was mild to moderate, despite the presence of severe to extreme droughts in 1987.

Keywords: Drought, SPI, MAI, Remote Sensing, Climate change, RCP8.5.

Cite this article as: A. Mlayah, A. Skhiri, S. Khlifi, “Assessment of historical and projected droughts at Siliana Watershed catchment (Northern Tunisia),” *African Journal of Advanced Pure and Applied Sciences (AJAPAS)*, vol. 3, no. 1, pp. 1–10, January-March 2024.

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1. Introduction

Drought, one of the most complex hydrological phenomena, has a significant impact on various sectors, such as agriculture, water resources, and ecosystems. It is considered one of the most devastating climatic hazards, affecting several regions worldwide [1]. It is regarded as one of the most costly natural disasters globally, causing an estimated total economic damage of 135 billion USD [2]. Generally, insufficient rainfall over extended periods leads to droughts. In its fourth report, the Intergovernmental Panel on Climate Change Expert Group (IPCC, 2007 reveals that episodes of drought will occur in the coming year with a higher recurrence. Numerous studies have focused on examining and evaluating drought in various regions of the world [3–7].

The variability of droughts has been examined in several research studies primarily focused on local and regional case studies, especially in drought-prone areas such as the Euro-Mediterranean region [8–10], Southeastern Europe [11–12], China [13–15], and North Africa [16–17]. Drought sequences could locally affect one or several areas or even a broader context. Droughts are characterized by different periods (months, seasons, or years). This natural phenomenon is so complex that there is no uniform method developed for its study, even though several drought indicators are commonly deployed [3, 6].

Various indices have been developed for monitoring and quantifying drought, such as the Standardized Precipitation Index (SPI) and the Martonne Aridity Index (MAI). Regarding the statistical analysis of precipitation distribution, SPI is the most commonly used index. Based on long-term precipitation data, McKee et al [18] introduced the SPI. It is increasingly being used as a powerful tool to assess the characteristics of drought variability and factors and to represent precipitation anomalies. It accurately shows and expresses the severity and duration of the drought.

In Tunisia, numerous studies have shown that the occurrence of a one-year drought is very common throughout the country, while consecutive droughts of 2 years or more are less frequent in the north, moderate in the center, and very frequent in the south [19]. When drought episodes were frequent and brief in duration, Ellouze and Abida [16] demonstrated a high variability of short-term SPI values. However, over the long term, the values stabilize and reveal less frequent but more prolonged sequences.

Considering the SPI and MAI as effective tools for the calculation and assessment of drought evolution and distribution, these indices were used in the present study to address the issue of identifying and characterizing drought in the Siliana Watershed Basin. Various time scales (1, 3, 6, and 12 months) over the period from 1960 to 1989 were evaluated using SPI for thirteen rainfall stations, uniformly distributed across the study area, in order to characterize drought episodes.

2. Material and methods

2.1. Study area

The Siliana Watershed Basin (SWB) is part of the Medjerda River Basin (MRB) which is the main hydrological basin in Tunisia, covering an area of approximately 23,000 km², with 16.4 thousand km² within Tunisia, representing 10% of the country's total area. The SWB covers an area of 2036 km² and is located in the Siliana Governorate (Figure 1).

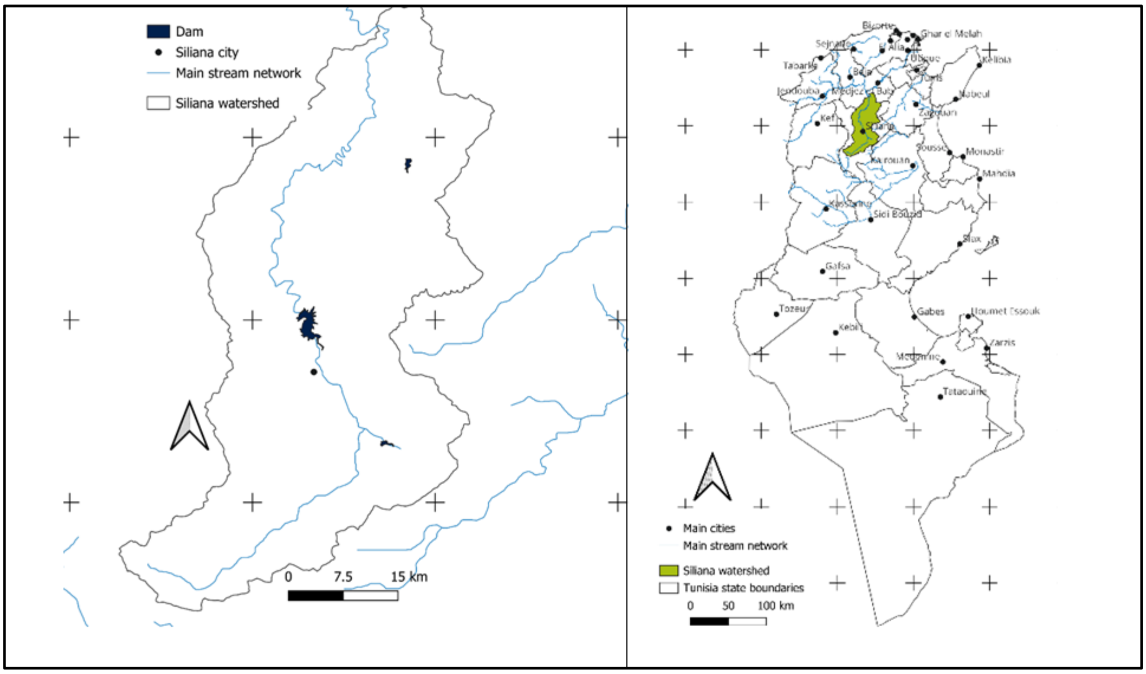

Figure 1: Localisation of the Siliana Watershed Basin (left) and Tunisian administrative boundaries (right).

The SWB primarily belongs to the upper semi-arid bioclimatic zone (73.0%), with an additional 23.8% classified under the bioclimatic zone of the middle semi-arid. Additionally, some micro-zones, representing 3.2% of the total surface area of the watershed, fall into the sub-humid. The average annual rainfall during the period from 1981 to 2010 is 428 mm [20]. The rainy season extends from September to April; peaking in January with 54 mm. July is the driest month. The average temperatures ranging from 9.0 °C in January to 11.5°C in March [20]. The average temperature indicates that summer temperatures can reach values around 31°C (in August), the hottest month. The average wind speed ranges from 17 to 26 km/h [20]. The relative humidity reaches its maximum during March at 86% and decreases to 52% in August (INM, 2020). The SWB is characterized by the presence of mostly fine-textured soils, rich in limestone, with varying levels of organic matter content. Annual crops, dominated by cereals, represent 46% of the total area of the SWB, accounting for 84% of the total agricultural land [21].

2.2. Data collection

The present study relies on an extensive rainfall dataset derived from stations spread across the entire SWB. The rainfall data used are sourced from the rainfall annals database of the General Directorate of Water Resources (D.G.R.E.) and encompass 33 stations distributed throughout the watershed and its vicinity. The lengths of the rainfall series observed at daily time intervals range from 9 years to 108 years. The selected reference period extends from 1960 to 1989 whereas climate change projections extend from 2041 to 2070. In Tunisia, the hydrological season starts in September and extends to august of the following year. The data were adjusted by gamma distribution, standardized as normal distribution.

2.3. Application of the Standardized Precipitation Index (SPI)

The SPI is a climate indicator that assesses precipitation anomalies over a specific period compared to the historical average. The SPI is widely used for monitoring and analysing droughts in various regions worldwide. It is preferable to have a time series of at least 30 years, even accounting for missing values. The SPI is calculated using the formula:

$$\mathrm{SPI} = \frac{(\mathrm{P_i} - \overline{\mathrm{P}}_\mathrm{m})}{\sigma_\mathrm{p}}$$

Where Pi is the precipitation value at a given time, $\overline{\mathrm{P}}_\mathrm{m}$ is the mean precipitation over a reference period, σ_p is the standard deviation of precipitation over the same reference period.

In this study, we aim to identify the presence of a potential temporal trend and assess the spatial variability of drought sequences in the SWB. Using the daily rainfall data from 33 stations, the SPI was applied based on precipitation series for various time scales: 3 months, 6 months, 9 months, and 12 months, with the objective of making a space-time analysis of drought behavior in the SWB.

2.4. Application of the Martonne Aridity Index (MAI)

The MAI is a climatic index used to assess the aridity of a region. It is calculated based on the ratio of annual precipitation to the annual temperature range, providing insights into the overall dryness or humidity of an area:

$$\mathrm{MAI} = \frac{\mathrm{P}}{\mathrm{T} + 10}$$

Where P is the average annual precipitation, T is the average temperature of the driest month. Semi-arid regions are those where index values between 10 and 20, with rainfall concentrated in a few months of the year.

After calculating the SPI at various time scales, we selected the time series with the maximum number of stations and the minimum amount of missing data. All gauges having more than 10% of missing observations were removed. Thus, the period from September 1960 to August 1989 was adopted for 13 stations across the entire SWB. The spatialization was performed, using QGIS 3.34.0 software, employing inverse distance weighting (IDW) interpolation. IDW interpolation determines cell values by the linearly weighted combination of a set of sample points, where the weights are inversely proportional to the distance. The same principle was applied to the MAI, except that the period and stations changed. Where climatic data were available, we calculated the MAI annually for the period from 1980 to 2009.

2.5. Precipitation projections for the period 2041-2070

To assess the impact of climate change on drought, precipitation projections from the Global National Oceanic and Atmospheric Administration's Geophysical Fluid Dynamics Laboratory (NOAA-GFDL) model were selected. The downscaling of the model was performed by the Swedish Meteorological and Hydrological Institute (SMHI-RC4) as part of the Coordinated Regional Downscaling Experiment (CORDEX). The spatial resolution was 0.22°, approximately 25 km for monthly projections, and the adopted scenario is RCP8.5. The data was downloaded from the SMHI website (www.esg-dn1.nsc.liu.se). Projected precipitation was bias-corrected using historical observations from the same model for the period 1960–1989, by applying linear scaling technique. The bias correction was performed using CMhyd [22, 23]. As climate projections correspond to regular grid cells of around 25 km and exhibit systematic errors compared to local observations, each entity was corrected based on the observed data from the nearest rain gauge station for each month. It appears that the projections are overestimated during the summer and underestimated during the winter.

3. Results and discussion

3.1. Characterization of rainfall regime

Figure 2 shows the variation of annual means, first quartile, third quartile, minima, and maxima of precipitation for the studied stations during 1960–1989. The study of the annual distribution of precipitation shows that the annual averages fluctuate between 360 and 603 mm over the 30-year period.

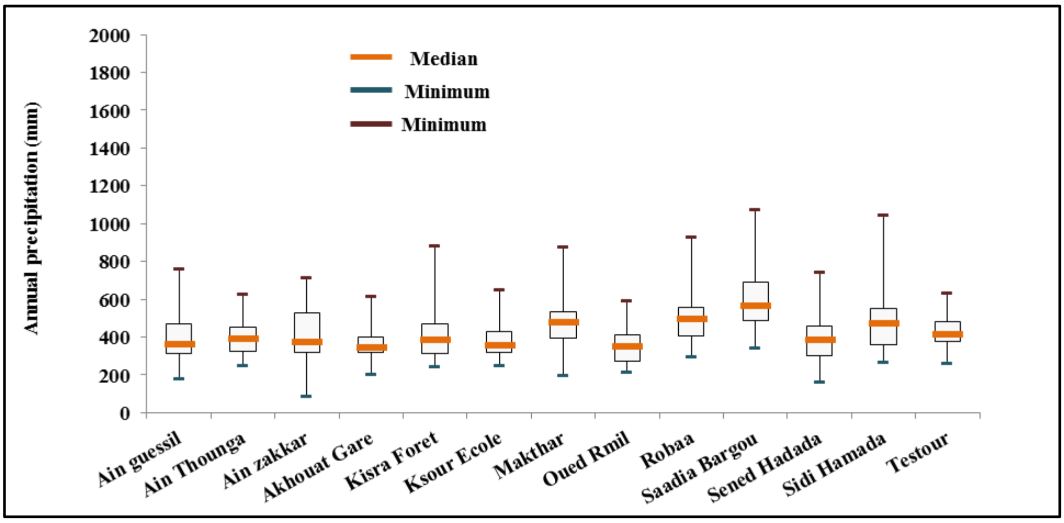

Figure 2: Variation of annual means, first quartile, third quartile, minima, and maxima of precipitation for the studied stations during 1960-1989.

The average precipitation in the SWB ranges from 366 to 603 mm/year at the Akhouat Gare and Saadia de Bargou stations, respectively. The coefficients of variation for annual precipitation are higher than 300% for the majority of stations, except for Sidi Hamada, with 172%, indicating their high variability. The absolute maximum was recorded at Saadia de Bargou, a mountainous station, in 1969–1970 with nearly 1200 mm, while the absolute minimum was observed at the Ain Zakkar station, a plain station, with less than 100 mm during the period 1960–1989. These extreme values indicate the high variability of precipitation in the SWB.

3.2. Historical estimation of SPI

Initially, we calculated monthly, quarterly, biannual (humid and dray seasons), and annual SPIs for the 13 rain stations. Subsequently, we obtained 132 series of SPI to characterize drought (short and medium-term), mainly hydrological drought, in the SWB. One or more consecutive negative SPI values with a value less than or equal to -1 are indicative of a dry sequence. By adopting this threshold, we extracted, for each series, dry sequences defined by the start, duration, and most significant intensity. Generally, the SWB is dominated by meteorological droughts (mainly in the short term) defined by the 3-month SPI, without neglecting the considerable presence of hydrological droughts (referred to as medium-term) marked by the 6-month SPI and the 9-month SPI.

3.2.1. 1-month SPI estimation

The calculation of the 1-month SPI for the studied rain stations during the study period between 1960 and 1989 reveals high temporal and spatial precipitation variability. The analysis of the obtained results indicates that the month of January is characterized by a wet trend in 1964 with a SPI of 3.43 at the Saadia Bargou station, which is extremely humid (Figure 3A). The downward trend was well observed in 1966, which is considered dry, as the stations Sened Hadada, Makhar, Ain Thounga, Testour, and Ain Guessil experienced drought in 1966/67 (Figure 3B). There were years with a very limited dry trend in space, as is well noted. For example, the year 1975 illustrates an average trend across all weather stations except for Makthar, Sened Hadada, and Akhouat Gare (Figure 3C). For the month of February, extreme humidity was observed in 1962/63 and 1965/66. The highest SPI value was recorded at the Sidi Hamada station, reaching 4.006 in 1962 (Figure 3D). A moderate drought was well observed in 1960/61, 1961/62, 1966/67, and 1974/75. Among them, 1960/61 was the most affected by the drought. This year is considered dry as the majority of stations in the watershed recorded SPI values below -1 (Figure 3E). In March, the year 1973 depicts extreme humidity covering the majority of the SWB, except for the Ain Thounga Testour and Kisra Forêt stations, which indicate humid year an average, 1973/74. The maximum SPI value recorded at the Saadia Bargou station in the same year is 4.75 (Figure 3F).

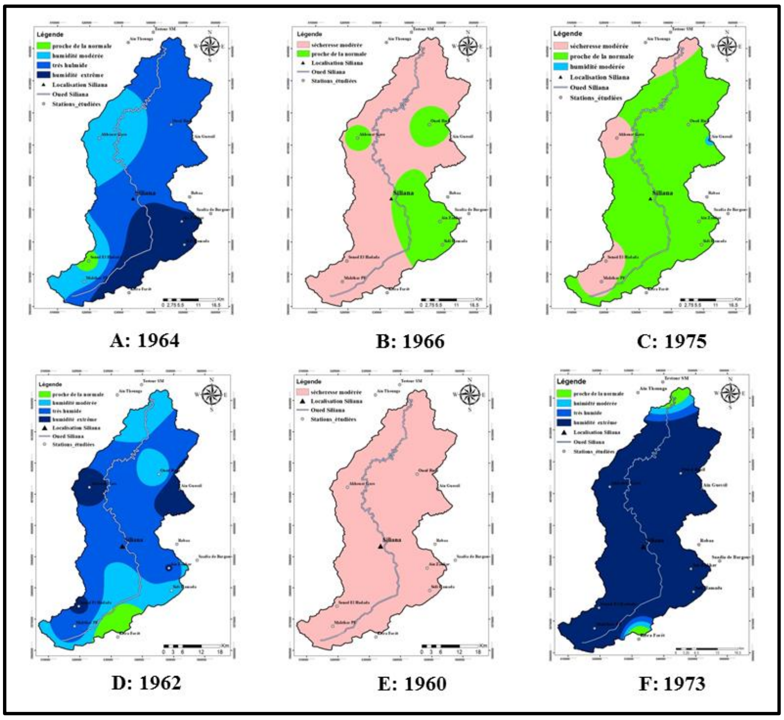

Figure 3: Spatial and temporal variability of 1-month SPI in the SWB during the study period.

3.2.2. 3-month SPI estimation

A 3-month SPI specifies medium-term moisture and provides an estimation of seasonal precipitation. A 3-month SPI is more useful for highlighting existing moisture conditions in major agricultural regions than many other hydrological indices. Figure 4 shows the spatial and temporal variability of the 3-month SPI in the SWB during the study period.

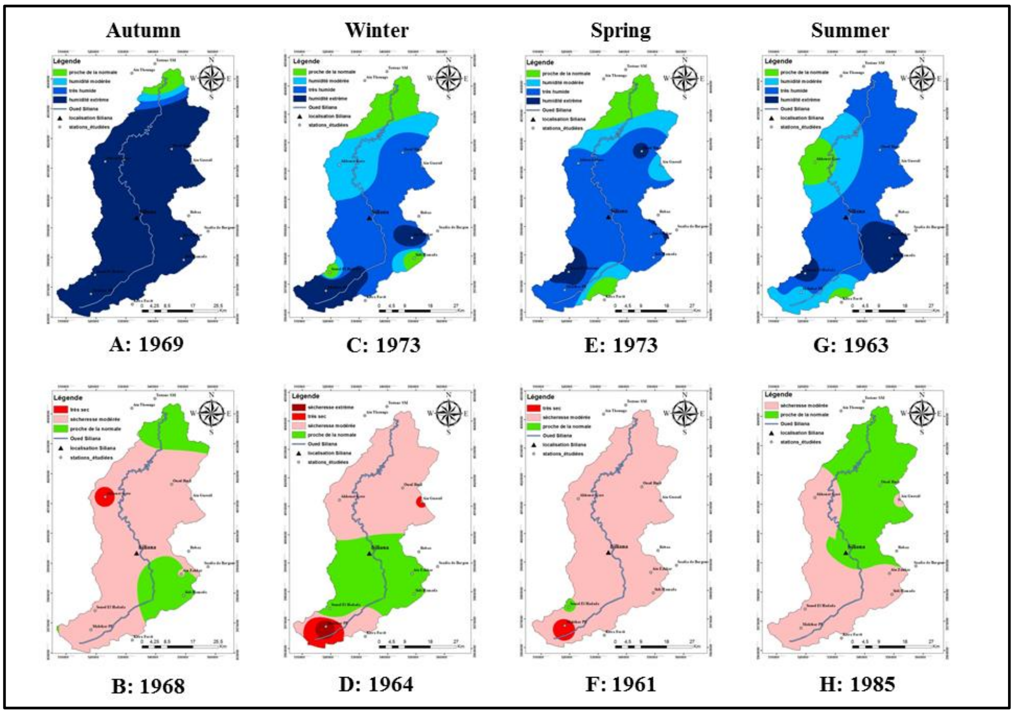

Figure 4: Spatial and temporal variability of 3-month SPI in the SWB during the study period.

The calculation of the 3-month SPI for the autumn season (September–October–November) during the period from September 1960 to August 1989 indicates that the highest 3-month SPI, representing the wettest year, corresponds to the year 1969/1970 (Figure 4A). It exceeds 4 at the Sidi Hamada and Saadia de Bargou stations. The driest year is 1968/69, which recorded moderate droughts in several stations (Figure 4B). For the same study period, the calculation of 3-month SPI showed that the winter (December-January-February) was extremely wet in 1973/74 (Figure 4C) and dry in 1961/62 (Figure 4D). The highest 3-month SPI value is 7.57, recorded in 1973/74 at the Makther station. The spring season (March–April–May) of the same study period (1960–1989) experienced extreme humidity in the year 1973/74 (Figure 4E), while the year 1961/62 was marked by moderate drought extending throughout the SWB (Figure 4F). The summer season (June–July–August) was humid in 1963/64 (Figure 4G) and dry in 1985/86 (Figure 4H). The maximum SPI value recorded was 3.90 in 1989/90.

3.2.3. 6-month SPI estimation

The 6-month SPI specifies the seasonal patterns of medium-term precipitation; it is very effective in illustrating precipitation for different seasons. In our case, for the first half, the lowest SPI is -2.32 (extremely dry) observed in 1962/63 (Figure 5). The second half also recorded its minimum in the same year, around -2.09 (extremely dry). The 6-month SPI, at the semiannual scale, shows the presence of many dry sequences throughout the analyzed period. For example, from 1977/78 to 1981/82 at the Ksour Ecole station, from 1960/61 to 1966/67 at the Kisra Forêt and Oued Rmil stations, and from 1962/63 to 1968/69 at the station Robaa, this was for the humid season (Figure 5).

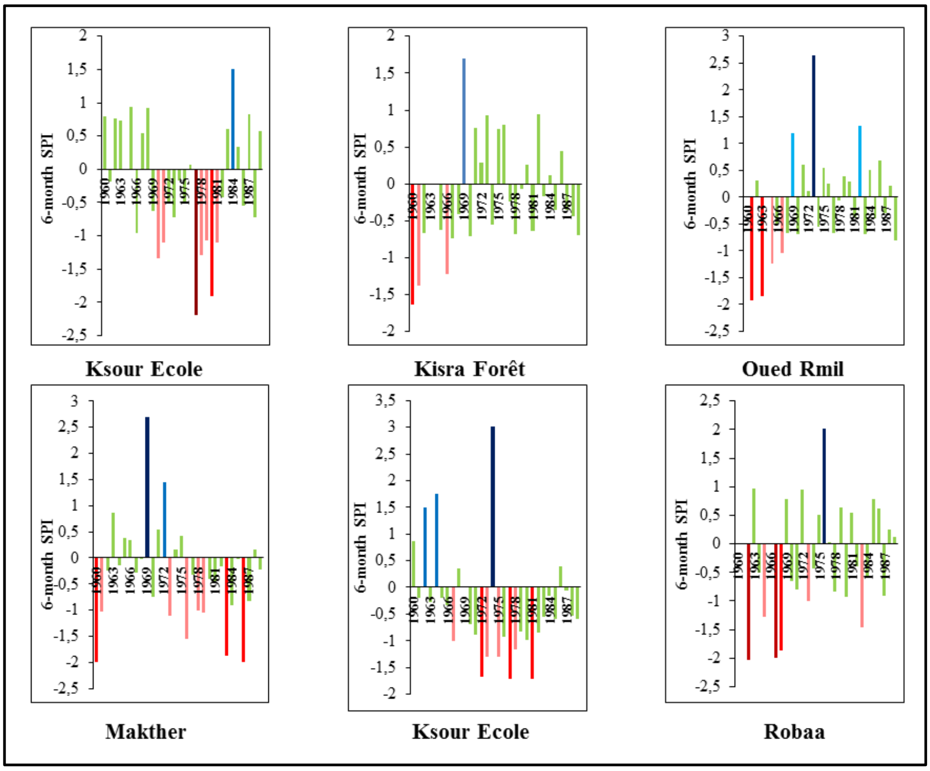

Figure 5: Spatial and temporal variability of 6-month SPI in the SWB during the study period.

For the dry season, the sequences are longer, with the high recorded between 1973/74 and 1986/87 at the Makther station. Additionally, Ksour Ecole recorded a sequence of 10 years from 1972/73 to 1981/82 and from 1962/63 to 1968/69 at the Robaa station.

3.2.4. 12-month SPI estimation

The 12-month SPI has highlighted the main drought years in the SWB for the study period from 1960 to 1989 for the stations under consideration. The first decade (1960–1969) showed a wet trend in the years 1963/64, 1969/70, and 1972/73, as depicted in Figure 6. The 1969/70 year was marked by extreme humidity, with the highest SPI recorded at 5.42 at the Sidi Hamada station (Figure 6A). However, a very dry trend occurred in 1960/61 at the Makthar and Sidi Hamada stations, with a recorded SPI of -2.11 (Figure 6B). For the second decade (1970–1979), the year 1972/73 was marked by a wet trend over the majority of the watershed (Figure 6C). The third decade (1980–1989) is notably drier, with the years 1983/84, 1987/88, and 1989/90 experiencing the severe droughts. The SPI is below -1.5 in several stations and sometimes exceeds -2.0, with certain years standing out for the low occurrence of drought, 1988/89 (Figure 6D).

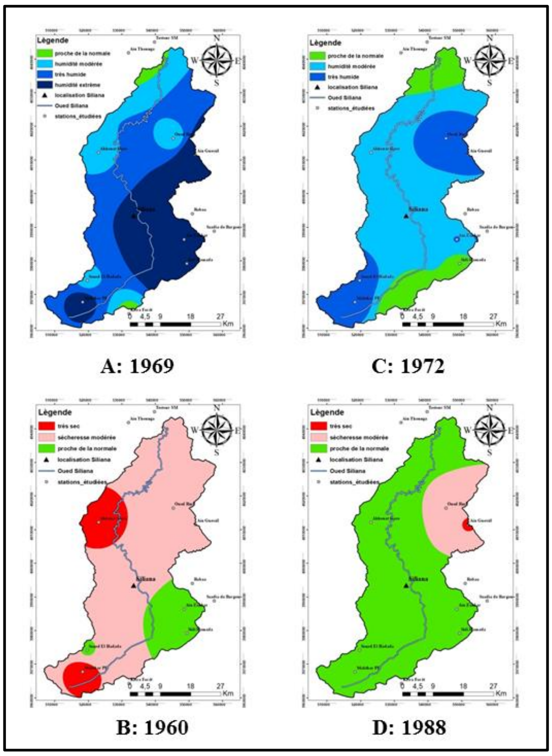

Figure 6: Spatial and temporal variability of 12-month SPI in the SWB during the study period.

3.3. Estimation of historical Martonne Aridity Index (MAI)

The calculation of the MAI on an annual scale (12 months) for the 21 rainfall stations during the period from 1980 to August 2009 reveals that the dominant climate type is semi-arid.

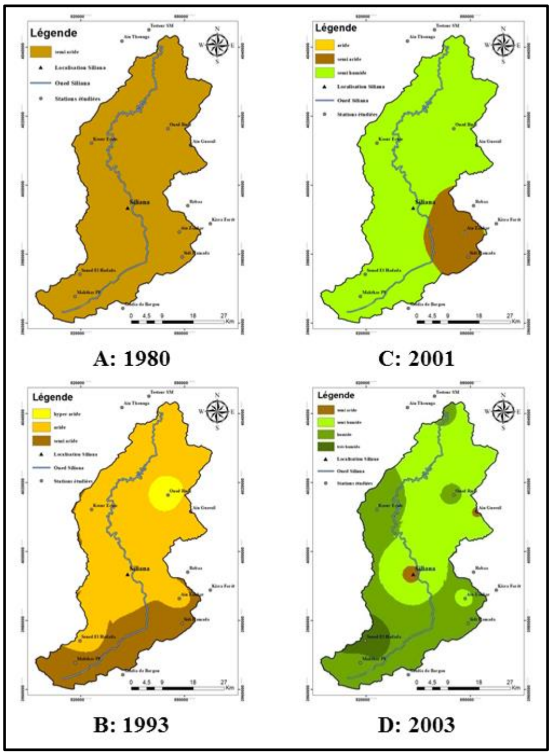

Figure 7: Spatial and temporal variability of the MAI in the SWB during the study period.

Upon a deep analysis of the results, climatic variability is observed for each decade: The first decade from 1980 to 1989 was characterized by a semi-arid climate overall. The trend that was close to normal and discovered through the SPI's annual analysis (Figure 7A) explains this climate. For the second decade (1990–1999), an arid trend was recorded for the years 1993/94. The drought Tunisia experienced during this time period (Figure 7B) explains these results. For the last decade (1990–2009), a very humid climate was observed in 2001/02 and 2002/03. This trend is attributed to the exceptionally high precipitation during the winter of 2003, reaching 428 mm, which is 240% of the average for that period and nearly 90% of the annual total (Figures 7C and 7D).

3.4. Projected SPI

3.4.1. Projected 6-month SPI

The estimation of the projected 6-month SPI indicates that high variability of precipitations will be expected. The humid season generally exhibits an average trend, except for the years 2047/48 to 2051/52, which will be characterized by a wet trend (Figures 8A and 8B). For the period from 2042/43 to 2070/71, a dry trend will be dominant. Drought during the last three years will be quite noticeable (Figures 8C and 8D). The SPI calculation for the dry season (from April to September) indicates that the first half of the projection (2041–2056) will be characterized by a wet trend. The years 2053/54 to 2056/57 are expected to be the most affected (Figures 8E and 8F). The remaining years (2057/58–2070/71) are expected to be dry. There will be a severe to extreme drought throughout the Oued Siliana SWB in the years 2059/60 and 2063/64 (Figures 8G and 8H).

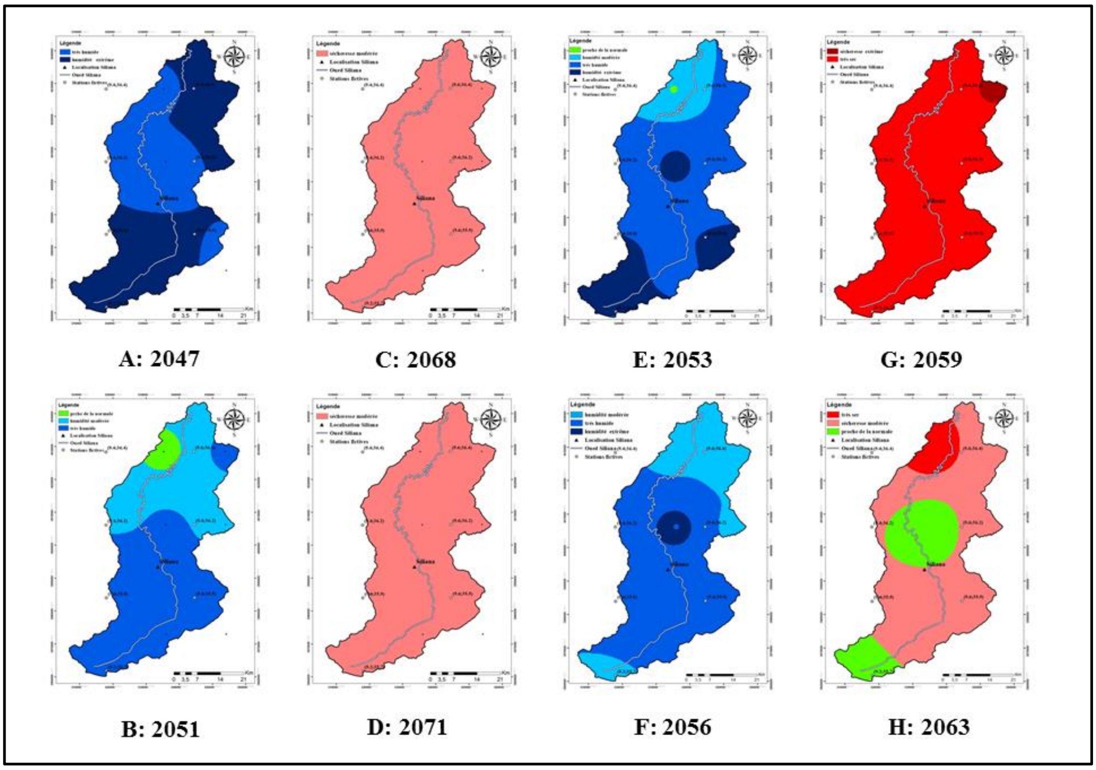

Figure 8: Characterization of precipitation trends over the period 2040/41-2070/71 in the SWB during the study period using the 6-month SPI projections

3.4.2. Estimation of the projected 12-month SPI

The 12-month SPI calculated for the period from 2041 to 2070 shows that the first 6 years (2040/41–2046/47) are characterized by an average trend, with a wet trend occurring in 2043/44 and 2047/48. This wetness will be expected by the end the first projection decade in almost all stations of the watershed (Figure 9A). From 2048/49 to 2056/57, wet trend will be expected. This trend will affect the entire SWB and fluctuate from moderate humidity to extreme humidity, especially in 2050/51 and 2053/54 (Figures 9B and 9C). The remaining years, from 2057/58 to 2069/70 (14 years), show an average trend. By the end of second decade, severe drought will be expected, for example the year 2059/60 (Figure 9D).

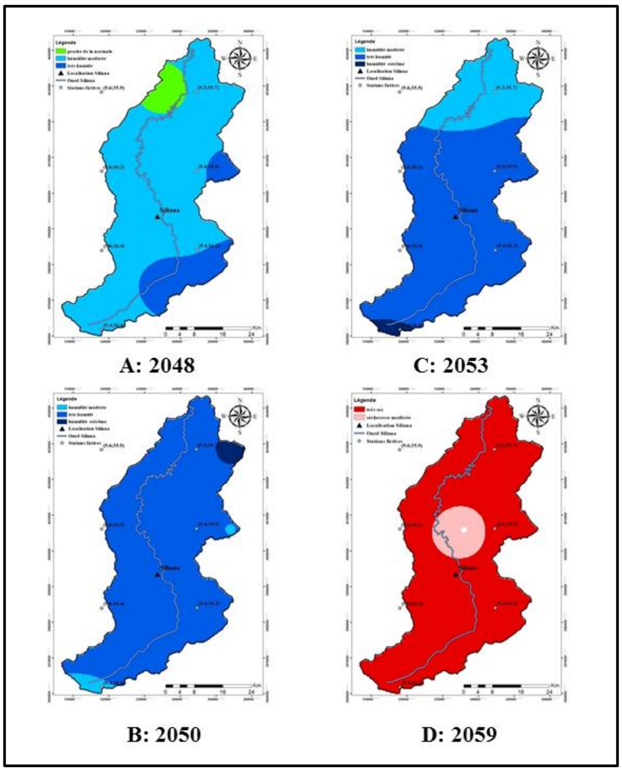

Figure 9: Characterization of precipitation trends over the period 2040/41-2070/71 in the SWB during the study period using the 12-month SPI projections

Conclusion

The main objective of this study is to delineate the pattern of drought occurrences in the SWB during the reference period from 1960 to 1989 and in the future for the period 2041–2070. It was achieved through a spatiotemporal characterization of drought episodes at various time scales. The study is based on the SPI by aggregating daily rainfall records from 13 stations covering the entire SWB; this straightforward and easy-to-use approach provides an effective means.

We calculated SPI for 1, 3, 6, and 12 months to capture trends in short- and medium-term droughts and to assess the impact of drought on the availability of different types of water resources. The SPI calculated in the short term is significantly sensitive to precipitation anomalies and is used to study short-duration moisture conditions. Consequently, for a 3-month SPI, droughts events are very frequent and do not last long. The return period for these droughts is very short. In the medium term, we consider the variability of SPI for 6 and 12 months, characterized by increasingly longer durations and more severe impacts. Their variability affects the water system deeply, defining hydrological droughts. Indeed, drought sequences (in the short and medium term) primarily affect the autumn months (September, October, and November), with the development of increasingly intense autumn heatwaves. The recurrence of this phenomenon implies an extension of summer warmth and a prolongation of the hot season at the expense of autumn, considered the starting phase of the agricultural season in Tunisia.

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