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Drought impact on rainfall and water storage in Tunisian semi-arid context

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Abstract

Despite the great progress made to strengthen resilience to drought, Tunisia still faces many challenges in developing effective monitoring of this phenomenon. So, during the last decade, the impact of climate change and the overuse of water caused a significant reduction in the capacity of some dams, such as the Rmel dam semi-arid Tunisia.

So, the targeted goal is to assess the drought impact on rainfall and water storage using a climatolic and hydrologic index, as defined by the Standardized Precipitation Index (SPI) and the Standardized Runoff Indices (SRI). These indices were computed on annual and 3- months time scales in Rmel watershed covering an area of 675 Km2 and having dam targeting agricultural use.

Results showed that an acceptable correlation exists between SPI, as a climatological index, and SRI, as a hydrologic drought index. Analyses revealed that the basin suffered from a succession of dry years especially in the last decade, accompanied by sever and moderate years.

Key Words*:* SPI, SRI, Rmel watershed, Tunisian semi-arid region, drought

Impact de la sécheresse sur les précipitations et le stockage de l'eau dans le contexte semi-aride Tunisien

Résumé

Malgré les grands progrès accomplis pour renforcer la résilience à la sécheresse, la Tunisie est encore confrontée à de nombreux défis pour développer une surveillance efficace de ce phénomène. Ainsi, au cours de la dernière décennie, l'impact du changement climatique et la surexploitation des ressources en eau ont entraîné une réduction significative de la capacité de certains barrages, comme ceux existant dans la région semi-aride (Barrage Rmel).

Ainsi, l'objectif visé est d'évaluer l'impact de la sécheresse sur les précipitations et le stockage de l'eau à l'aide de deux indices climatolique et hydrologique, tel que défini par l'indice de précipitation normalisé (SPI) et l'indice de ruissellement normalisé (SRI). Ces indices ont été calculés sur des échelles de temps annuelles et de 3 mois dans le bassin versant du Rmel couvrant une superficie de 675 km2 et ayant un barrage destiné à l'utilisation agricole.

Les résultats ont montré qu'il existe une corrélation acceptable entre le SPI, en tant qu'indice climatologique, et le SRI, en tant qu'indice de sécheresse hydrologique. Les analyses ont révélé que la zone d'étude a souffert d'une succession d'années sèches, en particulier au cours de la dernière décennie, accompagnée par des années à sécheresse sevères (2017/2018) et modérées.

Mots clés : SPI, SRI, Bassin versant Rmel, Région semi-aride Tunisienne, Sécheresse

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Introduction

Water is fundamental for life and livelihoods. It's the key for a sustainable development [6]. Our planet contains only 2.5% of freshwater. This limited resource will be further threatened with population growth. In 2017, world's population is numbered nearly 7.6 billion and would be continues to grow to become 9.7 billion in 2050 [18]. [21] reported that by 2030, water demands will be increased until the world faces a 40% water deficit caused by the reduction of water storage in dams and depletion of runoff in rivers. In addition, 20% of the world's aquifers are overexploited [5], with serious consequences such as lowering of the piezometric level in the water table and the intrusion of marine water. But, the water insecurity can be exacerbated by drought [5] which is being one of the most extreme water-related natural hazards that result from lower amounts of precipitations [19]. The United Nations Convention to Combat Desertification (UNCCD) has defined drought as a naturally occurring phenomenon that exists when precipitation is significantly below normal recorded levels, causing serious hydrological imbalances that adversely affect land resource production systems. Also, droughts are generally classified as meteorological, agricultural, hydrological and socio-economic concepts ([19,20].

Extreme drought conditions affected at least 3 % of the global land area, but the severe drought represents about 11 % [14]. In the Mediterranean areas the frequency and intensity of drought have likely increased [8]. In Tunisia, during the last decades, the drought has been exacerbated by the magnitude of the rainfall deficit [1]. This has resulted in a significant decline in the dam's capacities; some of them have become dry. Several methods and indices have been developed to monitor and quantify drought intensity and impacts. These methods are based on climatic and hydrological variables, such as precipitation [13,11,4], runoff [15] and evapotranspiration condition [9].

In this study, we tried to use the Standardized Precipitation Index (SPI) as a widely used index to characterize meteorological drought on a range of timescales [7,9], and the Standardized Runoff Index (SRI), based on basin discharge. It's used to assess the hydrological drought index. The purpose is to provide quantitative information on meteorological and hydrological drought for North African semi-arid climatic conditions. Knowledge of the SPI and SRI index may be very useful to well monitoring the hydrological behavior of Tunisian semi-arid region and to facilitate the water resources management against the future climate change.

Materials and methods

Study area

The Rmel watershed is located in the north-eastern of Tunisia, between 36° 32.0.9' and 36° 14.20' Latitude North and between 10° 13.47' and 10° 13.4' Longitude East. It has a highly irregular terrain ranging from 20 to 1235 m.a.sl m. (Figure 1). The watershed covers an area of 675 km2 and drains into the Rmel dam, which has been built in 1998 [1]. It provides a transition between different regions: northern Tunisian ridge, the Sahel and the Cap Bon. It should be noted that the Rmel dam was built with the aim of promoting and intensifying irrigated area in the downstream. From 2004, an irrigated perimeter, extending over an area of 4952 ha [12], has been created in order to enhance the downstream area. This perimeter has benefited 1178 farms.

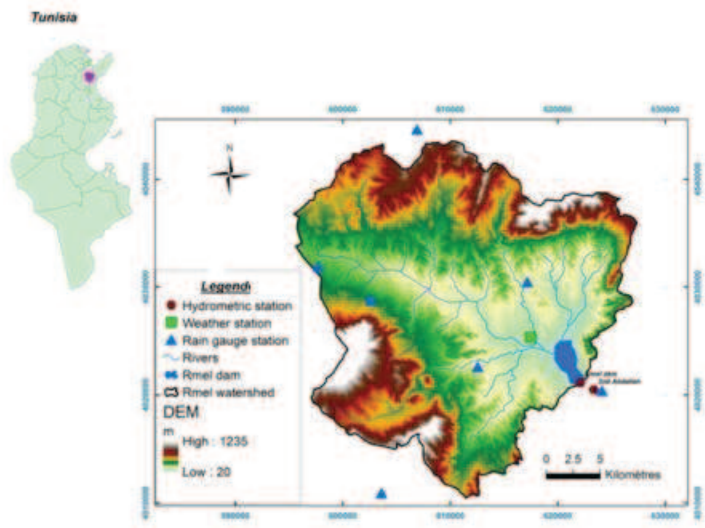


Fig 1 Location of Rmel watershed and the hydro-climatic stations

The average temperature of the studied area is about 19°C. Temperature peaksare recorded during July and August months with more than 35°C. Minimum values are observed during the months of January and February with 7°C.

Concerning observed annual evaporation in the Rmel dam, during the period from 1999 to 2019, the average value is about 1710 mm.

Data

Rainfall data used in this study were provided by the General Direction of Water Resources, Ministry of Agriculture in Tunisia (DGRE).

So, to characterize the rainfall regime in the Rmel watershed, we selected seven raingauges (Table 1), which will be used to assess the rainfall regime in the Rmel basin. Data are provided during the period from 1980/81 to 2018/19 and well selected based on their availability and quality.

Table 1 List of selected rainfall stations

STATION	X (m)	Y (m)	Elevation (m)
Bouchlaka	606912	4044638	235
Mograne	597730	4031956	155
Oued Ezzit	617176	4030502	100
Saouaf Agricole	603609	4010944	170
Sidi Abdallah	624120	4020428	32
Zaghouan PF	602599	4028807	230
Zeriba	612570	4022644	110

The homogeneity of rainfall data for all stations in Rmel watershed was checked using double-mass curve method [2]. Mograne raingauge has been selected as a reference station in the study area. This choice is based on the consistency of its data and the long-term of recorded rainfall. Results of this method revealed that the rainfall data records were found to be consistent in all stations.

Methods

Monthly rainfall and runoff data in Rmel watershed were used in this study to perform the drought analysis. It would help the monitoring of hydrological drought and its impact on water storage in the dam, considering that the stored waters are used to promote irrigated agriculture.

So, the SPI and SRI drought index calculation, based on the long-term precipitation and runoff record (39 years), at monthly scale, was done through Gamma distribution function [17]. The gamma distribution is defined by its frequency or probability density function:

$$f_{\gamma}(x/\alpha,\beta) = x^{\alpha-1}.\frac{1}{\beta^{\alpha}.\Gamma(\alpha)}.e^{\frac{-x}{\beta}};x \geq 0;\alpha,\beta > 0 \quad (1)$$

Where α >0 is the shape parameter; β >0 is a scale parameter; x > is the precipitation amount; $\Gamma(\alpha)$ defines gamma function as :

$$\Gamma(\alpha) = \int_0^{\infty} y^{\alpha-1}e^{-y}dy \quad (2)$$

Computation of the SPI involves fitting a gamma probability density function to a given frequency distribution of precipitation total for a station. From [17], the maximum likelihood solutions are used to optimally estimate α and β.

$$\hat{\alpha} = \frac{1}{4A}(1+\sqrt{1+\frac{4A}{3}} \quad (3)$$

Where, for n observation

$$A = \ln(\bar{x} - \frac{\sum \ln(x)}{n}) \quad (4)$$

$$\hat{\beta} = \frac{\bar{x}}{\hat{\alpha}} \quad (5)$$

The resulting parameters are then used to find the cumulative probability of an observed precipitation event for the given month and time scale for the station in concern. The cumulative probability is given by:

$$G(x) = \int_0^x g(x)dx = \frac{1}{\beta^{\alpha}\tau(\hat{\alpha})}\int_0^x t^{\hat{\alpha}-1}e^{-x/\hat{\beta}}dx \quad (6)$$

$$t = \frac{x}{\hat{\beta}} \quad (7)$$

$$G(x) = \frac{1}{\tau(\hat{\alpha})}\int_0^x t^{\hat{\alpha}-1}e^{-t}dx \quad (8)$$

Since Since gamma function is undefined for x=0 and precipitation distribution may contain zero, cumulative probability becomes:

$$H(x) = q + (1-q)G(x) \quad (9)$$

Where q is the probability of zero precipitation

The gamma distribution becomes undefined, for X = 0 and q = p(x = 0) (probability of zero precipitation is simply the number of observations of zero precipitation divided by the total number of observations).

To convert cumulative probability to the standard normal random variable Z as used by [4]:

$$Z = SPI = -[t - \frac{C_0 + C_1 t + C_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}] \quad (10)$$

For $0 < \mathrm{H(x)} \leq 0.5$

$$Z = SPI = [t - \frac{C_0 + C_1 t + C_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3}] \quad (11)$$

For $0.5 < \mathrm{H(x)} \leq 1$

Where, $t = \sqrt{\ln(\frac{1}{(H(x))^2})}$ $\quad 0 < H(x) \le 0.5$ (12)

$$t = \sqrt{\ln(\frac{1}{(1-H(x))^2})} \quad (13)$$

for $0.5 < H(x) \le 1$

C0= 2.515517, C1 = 0.802853, C2 = 0.010328,
d1 = 1.432788, d2 = 0.189269 and d3 = 0.001308.

The Standardized Precipitation Index (SPI-n) is a statistical indicator comparing the total precipitation received during a period of n months with the long-term rainfall distribution, for the same time-period. SPI is calculated on a monthly basis for a moving window of n months, where n indicates the rainfall accumulation period, which is typically of 1, 3, 6, 9, 12, 24 and 48 months. The Standardized Runoff Index is developed to assess hydrological drought considering stream flow data (Shukla and Wood 2008). The SRI is based on river runoff and its calculation procedure is similar to SPI index. The gamma distribution is also used, here, to fit the river runoff data. The SRI and SPI are similarly calculated. While the SPI for medium accumulation periods (3 and 12 months) can be used as an indicator for reduced stream flow and reservoir storage, we decide to calculate this index for two time-scales, i.e. 3 months (SPI-3) and 12 months (SPI-12) for each raingauge station and for average monthly rainfall. The SPI-3 was used to assess drought during mid-spring season (Februray- April), which is a reference period to judge agricultural yield. For SPI-12, it was used to assess the hydrological drought. The same approach was highlighted for the SRI drought index.

Calculated SPI and SRI will be compared with the classification values of dryness and wetness category to conclude about the drought in the study area. The status of hydrological droughts according to SPI values are defined in Table 2 [4].

Table 2. Dryness/wetness categories according to SPI values [4]

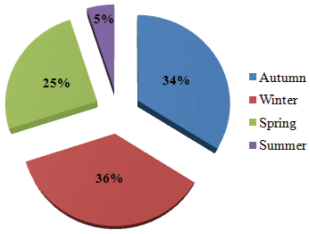
State	Drought Class	Standardized PrecipitationIndex
1	Extremely wet	SPI > 2
2	Severely wet	1.5 to 1.99
3	Moderately wet	1.00 to 1.49
4	Near normal	0.99 to -0.99
5	Moderately dry	-1.00 to -1.49
6	Severely dry	-1.50 to -1.99
7	Extremely dry	≤-2.0

In order to assess the extent of the space-time drought in the Rmel basin, it is necessary to compute SPI drought indices for the watershed using a Thiessen polygon method [16] to determine the average rainfall for each year and each month which lead to calculate SPI-3 months and SPI -12 months. This approach led to compare the relation between SPI and SRI drought indices.

Results and discussion

Rainfall variability

The hydrological year begin from September, it's characterized by intense events and finish in august. At the seasonal scale, winter and autumn, represent the wet period. They present 70%of the total annual rainfall. However, the summer season is characterized by a low rainfall amounts with 5% (Fig. 2).



Ben Khelifa and Chargui / JISTEE, Vol. (vi), Issue 1, April 2021, pp. 104-113

Fig. 2 Seasonal distribution of rainfall

The spatial variability of rainfall highlights an irregular distribution of rainfall in the Rmel watershed. It varies from the upstream to the downstream. In fact, this distribution shows that the Northeastern part (basin upstream) is the most watered area (450 to 490mm), whereas when going down to the South (basin downstream) rainfall knows a noticeable decrease (Fig. 3).

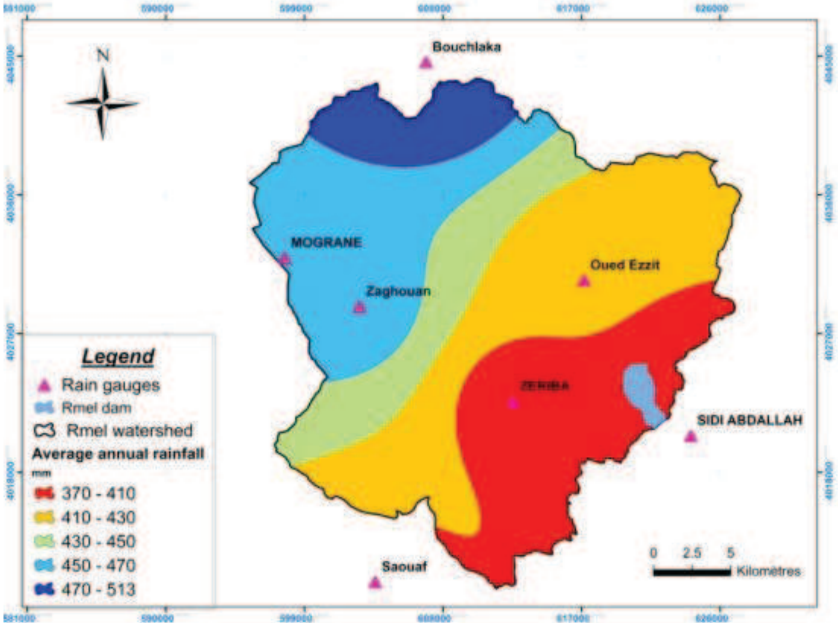


Fig 3 Spatial distribution of rainfall in the Rmel watershed

Some of the typical rainfall characteristics such as the average, minimum, maximum and the coefficient of variation at each of studied meteorological stations are given in Table 3. It should be noted that the study area is characterized by an average rainfall varying from 372.4 mm, in Sidi Abdallah raingauge, to 514.5 mm in Bouchlaka raingauge. The coefficient of variation fluctuates from 29 % (Oued Ezzit raingauge) to 36% (Bouchlaka, Souaf and Zaghouan raingauges) showing an irregular rainfall over time.

Table 3: Statistical characteristics of annual rainfall

Raingauge	Mean (mm)	Min.	Max.	STD	CV
Bouchlaka	514.5	203	930	185	36%
Mograne	469.4	255	811	153	33%
Oued Ezzit	407.3	184	750	121	29%
Souaf	407.8	193	871	146	36%
Sidi Abdallaha	372.4	193	758	131	35%
Zaghouan	455.0	220	861	167	36%
Zeriba	390.4	211	750	124	31%

Runoff characteristics

In term of runoff contribution, the Rmel reach was monitored by a hydrometric station during the period 1980/81-1997/98. Since 1999, Rmel dam was built and the runoff was monitored by another station implemented in the dam during the period from 1999/00 to 2018/19. The location of the hydrometric stations was shown in Fig. 1.

The observation period [1980/81-2018/2019] shows low to medium runoff values (Fig. 4), except, for 1995/96, this year was distinguished as a very wet year in Tunisia ([3].

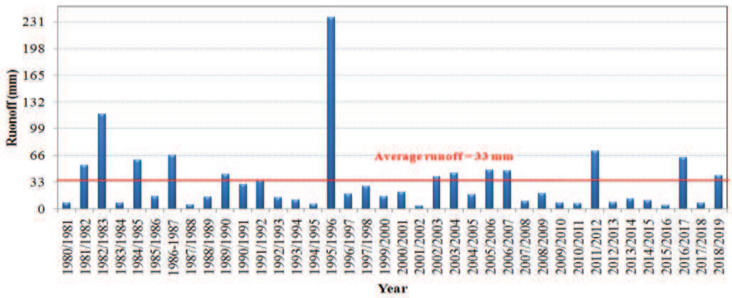


Fig 4 Annual runoff in Rmel watershed from 1980 to 2019

About monthly values (Figure 6), the low runoff values occur in general in June, July, and August. Maximum runoff was observed respectively in February, September, November, and December.

Drought characterization

- *Drought at annual scale (SPI-12)*

The assessment of calculated SRI -12 and SPI -12, over the 39 past years, in the Rmel watershed shows a fluctuation of dry and wet period (Fig. 5). Some dates appear as a severe drought when the SRI and SPI values are upper to (-1.5). This is the case of 1987/88, 2001/02, and 2017/18 years.

Also, three years present a moderate dry (1980/81, 1994/95 and 2015/16), there SPI and SRI values are between (-1) and (-1.49).

About wet year, we notice that most of values are lower than 1. They indicate a normal period. Except the year of 1995/96, it is an extremely wet year. Its SRI is above 2.5 and its SPI is upper to 1.5.

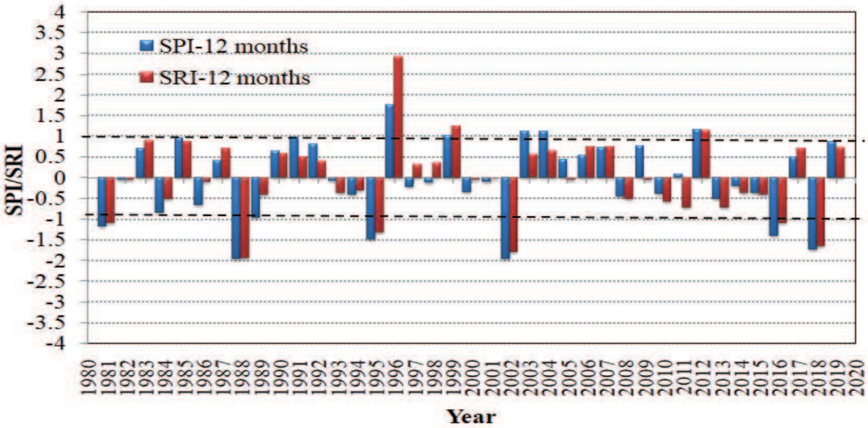


Fig 5 Annual distribution of SPIand SRI drought indices

Fig. 6 illustrates for all studied stations, that the drought categories (Near normal) represent 60 to 70% (23 to 27 years) of the assessed period. The wet period for all station represents about 16%. However, the dry period represents 84% if we consider the near normal as drought (Fig.6).

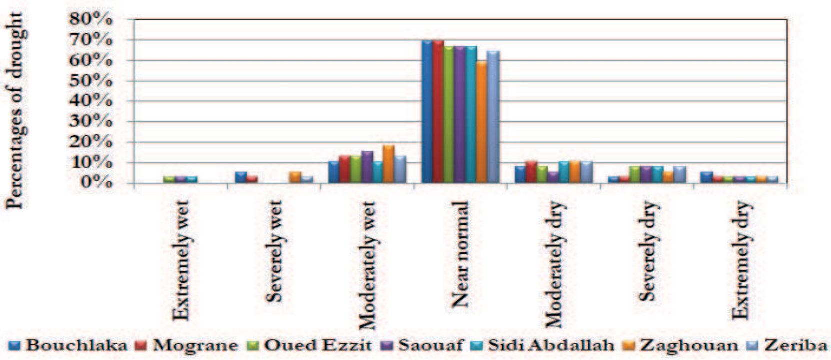


Fig 6 classification of SPI values on annual scale

The previous results were proven by the Fig.7, which shows the SPI-12 deduced from rainfall representing the watershed.

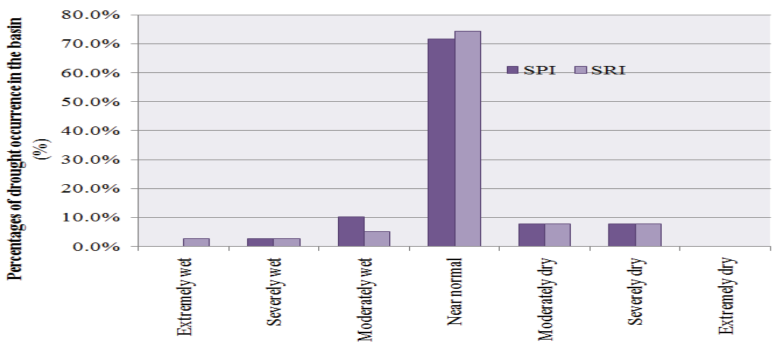


Fig. 7 The percentage of drought occurrences in SRI and SPI indices

- *Drought at 3 months scale*

The 3-month SPI values compare the precipitation over a specific 3-month (in our case we have chosen February, March and April months) with precipitation totals from the same three-month period. The SPI-3 can reflect short- and medium-term moisture conditions and provides an assessment of seasonal precipitation.

Fig. 9 indicates the 3-months indices for the reference period Feb-April.

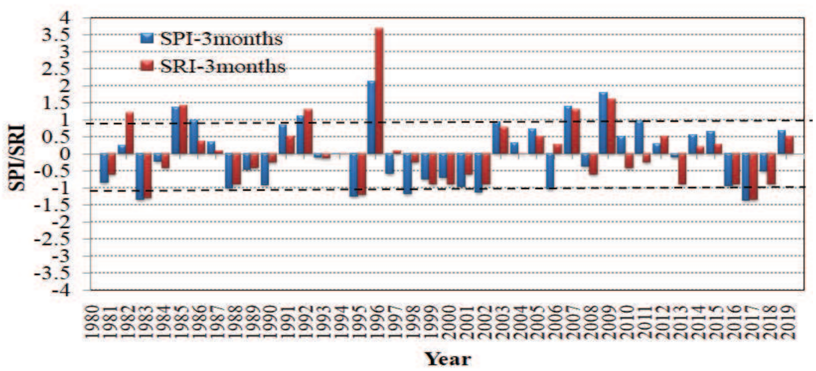


Fig. 8 Distribution of SPIand SRI drought indices on 3 months scale

As shown, SRI revealed that only three years were considered as moderately drought (1982/83, 1994/95 and 2015/16). But two dry periods can be marked. The first is from 1996/97 to 2002/03. The second begin in 2015/16 and finish in 2017/18. During the last two decades, the SRI proves a deficit in the runoff. So, from February to April, the dam should be filled to satisfy agricultural needs in summer.

Correlation between SPI and SRI

To investigate the relationship between the meteorological and hydrological drought, we have calculated the correlation coefficients of Pearson for the SPI and SRI indices. This coefficient is based on 3 and 12-month time scale (Table 4). On annual and 3 months scales, most SPIs stations revealed a significant relation with SRIs. Except Bouchlaka raingauge, it showed a correlation coefficient lower than 0.6. This is can be explained by its location, in the northern upper part of the study area.

Table 4. Correlation coefficient between SPI and SRI on 3 and 12-months' time scale

Station	12-month	3-month (Feb-April)
Bouchlaka	0.57	0.56
Mograne	0.68	0.71
Oued Ezzit	0.74	0.74
Saouaf	0.72	0.64
Sidi Abdallah	0.72	0.71
Zaghouan	0.68	0.73
Zeriba	0.73	0.72

Based on 3-months and annual time scale, for the studied period (1980/81 to 2018/19), the SPI and SRI for Rmel watershed illustrated a correlation coefficient of 0.75. They show and confirm a significant relationship between these drought indices (Fig 9 and Fig.10).

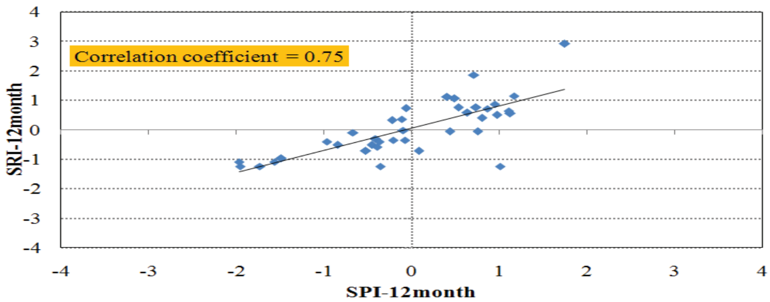


Fig. 9 Relationship between the average SPI and SRI on annual scale

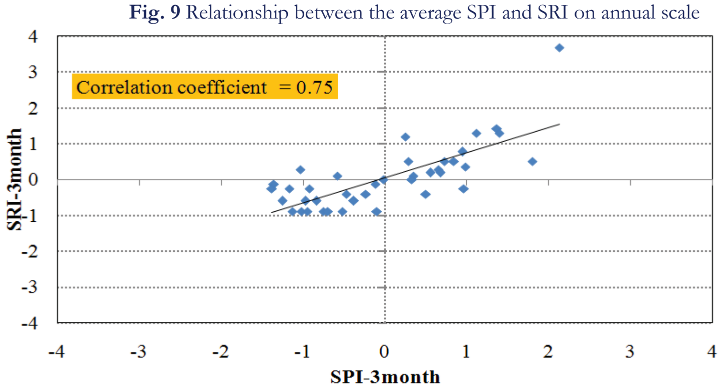


Fig. 10 Relationship between the average SPI and SRI on 3 months scale

Conclusion

Being a watershed of 675km2, the drought can be well characterized by a good spatially distributed five raingauges. Investigation of climatological and hydrological droughts was studied by the assessment of the standardized indices (SPI and SRI), over 39 years of observed data (1980 to 2019). The SPI and SRI were assessed at two-time scales: 3 and 12 months. Results illustrate that more drought events occurred at 3 months scales than 12 months scales. The assessment of calculated SRI -12 and SPI -12 shows a fluctuation of dry and wet period. Some periods (1987/88, 2001/02 and 2017/18) appear as a severe drought, with an SRI and SPI values are upper to (-1.5). Also, three years present a moderate dry (1980/81, 1994/95 and 2015/16). About the 3-months scale (February, March and April), results of SRI indices revealed that only three years were considered as moderately drought (1982/83, 1994/95 and 2015/16). Then, two dry period can be marked. The first is from 1996/97 to 2002/03. The second begin in 2015/16 and finish in 2017/18. During the last two decades, the SRI proves a deficit in the runoff. Also, a common extremely wet year was detected at 1995/96. Its SRI-3 and SRI-12 are above 2.5 and its SPI-3 and SPI-12are upper to 1.5. A high correlation between SPI and SRI was detected at the studied Rmel watershed (R2 ≥ 0.7), indicating a significant relationship between meteorological and hydrologicaldroughts at medium (3 and 12 months) timescales in semi-arid context.

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