

## Comparison of meteorological indices for drought assessment and monitoring: A case study from the Tafna watershed, Northwestern Algeria

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### RESUMEN

La sequía es un fenómeno complejo que incluye aspectos meteorológicos, agrícolas e hidrológicos. Se caracteriza por un periodo prolongado de lluvias insuficientes que afecta negativamente los aspectos económicos, sociales y ambientales de la civilización. Este estudio compara cuatro índices meteorológicos, incluyendo el Índice de Precipitación Estandarizado (SPI), el Índice China-Z (CZI), el Índice Modificado China Z (MCZI) y el Índice Z-Score (ZSI) a fin de identificar los índices de sequía (DI) más adecuados para evaluar la sequía en la cuenca del Tafna. Se utilizaron datos mensuales de precipitación de 14 estaciones (1970-2019) para calcular los eventos de sequía en escalas de tiempo de 1, 3 y 12 meses. En las escalas de tiempo de 1 y 3 meses, la frecuencia de sequía total para SPI-1 y CZI-1 es mayor que para MCZI-1 y ZSI-1. En la escala de 12 meses, todos los DI mostraron la misma frecuencia de sequía total para la mayoría de las estaciones. El mayor coeficiente de correlación de Pearson se observa entre SPI-1 y CZI-1 en la escala de 1 mes, con valores superiores a 0.939 en todas las estaciones. Además, el 57 y 71 % de las estaciones muestran la mayor correlación entre SPI y CZI, con coeficientes superiores a 0.963 y 0.999 en las escalas de 3 y 12 meses, respectivamente. La mayoría de las estaciones no muestran alguna tendencia (aumento o disminución) utilizando la prueba de tendencia de Mann-Kendall en todos los valores de los índices en las escalas de 1 y 3 meses. En la escala de 12 meses, la mayoría de las estaciones mostraron un aumento en los valores de todos los DI. Los resultados reportados en este estudio proporcionan valiosas ideas que pueden mejorar la gestión de los recursos hídricos y mejorar la preparación para los eventos de sequía en la cuenca del Tafna, particularmente en el contexto del cambio climático.

### ABSTRACT

Drought is a complex phenomenon that includes meteorological, agricultural, and hydrological aspects. It is characterized by an extended period of insufficient rainfall that adversely impacts civilization's economic, social, and environmental aspects. This study compares four meteorological indices, including the Standardized Precipitation Index (SPI), China-Z index (CZI), MODIFIED China Z Index (MCZI), and Z-Score Index (ZSI), to identify the most suitable drought indices (DIs) for assessing drought in the Tafna watershed. Monthly rainfall data from 14 stations (1970-2019) were used to calculate drought events on 1-, 3-, and 12-month time scales. On the 1- and 3-month time scales, the frequency of total drought for SPI-1 and CZI-1 is higher than for MCZI-1 and ZSI-1. At the 12-month time scale, all DIs showed the same frequency of total drought for most stations. The highest Pearson correlation coefficient is observed between SPI-1 and CZI-1 on a 1-month scale, with values exceeding 0.939 across all stations. Additionally, 57 and 71% of stations exhibit the highest correlation between SPI and CZI, with coefficients exceeding 0.963 and 0.999 at 3- and 12-month scales, respectively. Most stations do not show any trend (increase or decrease) using the

Mann-Kendall trend test in all index values at 1- and 3-month scales. On a 12-month scale, most stations showed an increase in the values of all DIs. The results reported in this study provide valuable insights that can enhance the management of water resources and improve preparedness for drought events in the Tafna watershed, particularly in the context of climate change.

**Keywords:** drought, trend analysis, SPI, CZI, MCZI, ZSI.

## 1. Introduction

Drought is a meteorological phenomenon characterized by an extended period of insufficient rainfall, leading to a water shortage for human, animal, and plant needs. However, drought is also influenced by socio-economic and environmental factors, with significant impacts on water systems, agriculture, and ecosystems. It can occur in almost any region but primarily affects arid and semi-arid areas. Drought can trigger adverse effects, including crop failures, reduced water availability, increased wildfire risk, and economic hardship (Adisa et al., 2020). Given the wide-ranging impacts of drought, it is essential to have reliable tools, such as drought indices, to quantify, monitor, and analyze this phenomenon, enabling effective mitigation and adaptation strategies. Understanding drought is crucial for sustainable water management and climate change adaptation. Various drought indices (DIs) have been developed worldwide to assess drought, with some tailored to specific climatic conditions, such as arid, semi-arid, or humid regions. Comparison studies of DIs under different climatic conditions are always exciting and maybe insightful. Comparing DIs is necessary to assess their sensitivity to timestep, to choose a DI, and to evaluate its impact on selecting an effective value (Dogan et al., 2012). Wu et al. (2001) studied the evaluation of the Standardized Precipitation Index (SPI), China Z Index (CZI), and Z-Score Index (ZSI) in different regions in China at various time scales. The results revealed that both CZI and ZSI provided similar results to the SPI throughout all time ranges, and the calculations for CZI and ZSI were relatively easy compared to the SPI. This suggests that CZI and ZSI might be more effective tools for monitoring moisture conditions due to their reliability and applicability in drought monitoring. Morid et al. (2006) compared seven DIs, including SPI, ZSI, CZI, Modified China Z Index (MCZI), Percent of Normal (PN), Deciles

Index (DI), and Effective Drought Index (EDI) in Tehran province, Iran. These DIs are all capable of evaluating hydrological conditions, including wet and dry periods. The findings indicate that SPI, ZSI, and CZI have comparable performance concerning drought detection and respond slowly to drought onset. Comparisons showed that SPI and EDI outperformed in detecting drought. They were more effective due to their higher sensitivity to precipitation changes, making them more responsive to the onset of drought events. Additionally, their ability to adapt to various climatic conditions, including arid and semi-arid regions like Tehran, further highlights their suitability. These DIs were recommended for Tehran's drought monitoring system.

Shahabfar and Eitzinger (2013) compared six meteorological DIs, including SPI, PNPI, CZI, MCZI, and ZSI, and the aridity index of E. de Martonne (I) in different regions in Iran. The findings suggested that CZI, MCZI, and ZSI could serve as effective indicators of meteorological drought. Jain et al. (2015) compared SPI, EDI, ZSI, CZI, Rainfall Decile Drought Index (RDDI), and Rainfall Departure (RD) to determine their suitability in districts vulnerable to the drought of the Ken River basin in central India. The study revealed a strong correlation between DIs at the same time scales. Mahmoudi et al. (2019) compared seven DIs, including SPI, EDI, ZSI, DI, PN, CZI, and MCZI at different timescales. The results demonstrated that the EDI index outperforms other indices in accurately representing the various drought classes. The SPI, CZI, and ZSI exhibited the highest level of consistency in their behavior. Katipoğlu et al. (2020) compared five meteorological DIs, including SPI, ZSI, Rainfall Anomaly Index (RAI), Standardized Precipitation Evaporation Index (SPEI), and reconnaissance drought index (RDI), across seasonal and annual time scales to monitor drought. The findings indicated that precipitation and temperature-based

SPEI and RDI are consistent patterns, and there is a similarity in the patterns of precipitation-based SPI and ZSI. RAI was more accurate in detecting extreme drought or wet periods than the other DIs. Sridhara et al. (2021) compared five DIs including SPI, DI, PN, CZI, and ZSI. The findings revealed that SPI, CZI, and ZSI had a high similarity in detecting drought conditions. Ng et al. (2023) studied an evaluation of five DIs, including SPI, DI, PNPI, RAI, and ZSI, in Peninsular Malaysia. The findings showed that ZSI had the highest accuracy among all DIs. Kartal and Nones (2024) analyzed the drought conditions in the Konya Closed basin in Türkiye using different DIs such as meteorological (SPI, CZI, MCZI, ZSI), hydrological, and hydrogeological. The results showed that the frequency of total drought (the sum of different drought categories) of SPI and CZI was greater than that of MCZI and ZSI.

In Algeria, Bougara et al. (2021) compared four DIs, namely SPI, PN, DI, and RAI, in the Tafna watershed. A comparable frequency for dry and wet categories was found between SPI and DI. In addition, the RAI and PN could identify more drought categories than the other DIs. Bettahar and Şener (2022) conducted a study comparing five drought-monitoring indices (SPI, DI, ZSI, RAI, and PN) in the Wadi Righ area. The findings confirmed a positive correlation between the researched DIs and precipitation. Achite et al. (2023) studied seven DIs to monitor and assess drought conditions in the Wadi Ouhrane basin. Among these, they found a high similarity in the behavior of SPI, CZI, MCZI, and ZSI, with a correlation coefficient exceeding 0.97 as the time scale increased from 1 to 24 months. Berhail and Katipoğlu (2023) conducted a study comparing SPEI and SPI as drought assessment tools in the Wadi Mekerra basin (northwestern Algeria). The findings revealed a substantial agreement between SPI and SPEI values at different timescales.

This study examines drought conditions in the Tafna watershed using four DIs: SPI, CZI, MCZI, and ZSI. Data from 14 rainfall stations over 50 years were analyzed to compare these indices. This research aims to measure drought on multi-month scales to better understand drought patterns in the region. This research has the following objectives for the Tafna watershed: (1) to determine the correlation between

DIs using the Pearson correlation coefficient (PCC), (2) to assess the drought frequency categories for all DIs, and (3) to indicate the trends of the DIs by using the Mann-Kendall (MK) test.

## 2. Study area and data

The research area is located in the Tafna watershed in northwestern Algeria, which is characterized by a Mediterranean climate, covering an area of 7200 km<sup>2</sup>. It is located at 34° 3'–35° 9' N, 1°–2° W, with an altitude between 0 and 1773 masl (Fig. 1). The National Hydraulic Resources Agency (ANRH) provided monthly precipitation data from 14 rainfall stations from 1970 to 2019. The names of the stations, their IDs, coordinates (longitude, latitude), and elevation are presented in Table I. The selection of stations was based on the duration of the time series and their geographical distribution, ensuring extensive coverage

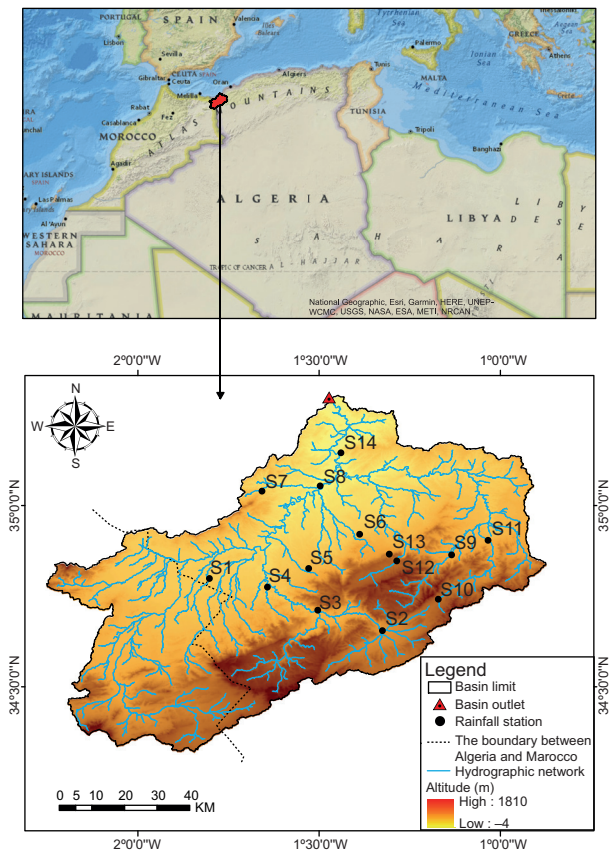


Fig. 1. Location of the Tafna watershed in Algeria and rainfall stations used in this study.

Table I. Rainfall stations used in this study.

Station	Name	ID	Longitude	Latitude	Elevation (m)
S1	Maghnia	160302	-1,80254	34,79900	395
S2	Sebdou	160401	-1,32548	34,65515	875
S3	Beni Bahdel	160403	-1,50369	34,71165	660
S4	Sidi Medjahed	160407	-1,64262	34,77520	360
S5	Sebra	160502	-1,52886	34,82671	600
S6	Hennaya	160516	-1,38812	34,92100	515
S7	Zaouia Ben Amar	160517	-1,65752	35,03999	370
S8	Djebel Chouachi	160518	-1,49698	35,05436	110
S9	Oued Lakhdar	160601	-1,13454	34,86408	700
S10	Meurbah	160602	-1,17134	34,74197	1100
S11	Ouled Mimoun	160607	-1,03406	34,90429	705
S12	Mefrouche	160701	-1,28586	34,84734	1110
S13	Lalla Setti	160705	-1,30650	34,86604	1020
S14	Pierre Du Chat	160802	-1,43970	35,14572	80

of the study area. The timeframe of analysis for the selected sites spanned 50 years, commencing with the hydrological year 1970-1971, which begins in September and ends in August. The selected stations are well distributed across the study area, ensuring adequate spatial coverage for the analysis.

### 3. Methodology

#### 3.1 Meteorological drought index

##### 3.1.1 SPI drought index

The SPI index developed by McKee et al. (1993) is based only on precipitation data, which is widely used. It is a useful tool for detecting drought occurrences in various regions. Identifying the appropriate probability distribution is the first step in calculating the SPI. According to a study by McKee et al. (1995), gamma family functions are the best probability distribution function for fitting precipitation data, as described in Eq. (1):

$$g(x) = \frac{1}{\beta^\alpha \Gamma(\alpha)} x^{\alpha-1} e^{-\frac{x}{\beta}} \quad (1)$$

In the equation above,  $\Gamma(\alpha)$  is the gamma function,  $X$  is the precipitation amount,  $\alpha > 0$  is the shape parameter, and  $\beta > 0$  is the scale parameter. The parameters of the gamma probability density function are determined using the maximum likelihood method separately for each station and time scale, as defined by:

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

$$\alpha = \frac{1}{4A} + \left[ 1 + \sqrt{1 + \frac{4A}{3}} \right] \quad (3)$$

$$\beta = \frac{\bar{x}}{\alpha} \quad (4)$$

$$A = \ln(\bar{x}) - \frac{\sum \ln(x)}{n} \quad (5)$$

and  $n$  represents the number of precipitation observations. A mathematical cumulative probability function can accurately describe the distribution of precipitation at stations as follows:

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

When the gamma function is undefined for  $x = 0$ , and the precipitation distribution is zero, the cumulative probability is obtained in the following manner:

$$H(x) = q + (1 - q)G(x) \quad (7)$$

Here,  $q$  is the probability of a zero. The cumulative probability  $H(x)$  is then converted to the standard normal distribution to give the SPI. According to Wu et al. (2007), the calculation of the SPI is presented based on the following equations :

$$\text{SPI} = \begin{cases} - \left( t - \frac{c_0 + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3} \right); & t = \sqrt{\ln\left(\frac{1}{(H(x))^2}\right)}; \text{ for } 0 < H(x) \leq 0.5 \\ + \left( t - \frac{c_0 + c_1 t + c_2 t^2}{1 + d_1 t + d_2 t^2 + d_3 t^3} \right); & t = \sqrt{\ln\left(\frac{1}{(1-H(x))^2}\right)}; \text{ for } 0.5 < H(x) \leq 1.0 \end{cases} \quad (8)$$

$$\varphi_j = \frac{x_j - \bar{x}}{\sigma} \quad (11)$$

$$\sigma = \sqrt{\frac{1}{n} \sum_{i=1}^n (x_i - \bar{x})^2} \quad (12)$$

In the equations above,  $C_s$  is the coefficient of skewness,  $n$  is the number of observations, and  $\sigma$  is the standard deviation.

where  $c_0, c_1, c_2, d_1, d_2,$  and  $d_3$  are coefficients whose values are 2.515517, 0.802853, 0.010328, 1.432788, 0.189269, and 0.001308, respectively.

3.1.3 MCZI drought index

Wu et al. (2001) calculated the MCZI index using the median precipitation value (Med) instead of the mean value in the CZI calculation. Eq. (9) remains unchanged, while in Eqs. (10), (11), and (12), the mean is replaced by the median. The MCZI follows the same classification of drought categories as the CZI, as shown in Table II.

3.1.2 CZI drought index

The CZI index was developed by the National Climate Center of China in 1995. The cube-root transformation used in this method comes from the Wilson-Hilferty transformation (Kendall and Stuart, 1977). Under the assumption that precipitation data follows the Pearson type III distribution, the index is calculated as follows:

$$\text{CZI} = \frac{6}{C_s} \left( \frac{C_s}{2} \varphi_j + 1 \right)^{\frac{1}{3}} - \frac{6}{C_s} + \frac{C_s}{6} \quad (9)$$

$$C_s = \frac{\sum_{i=1}^n (x_i - \bar{x})^3}{n \times \sigma^3} \quad (10)$$

3.1.4 ZSI drought index

ZSI is commonly calculated in numerous drought studies such as Wu et al. (2001), Dogan et al. (2012), Jain et al. (2015), Mahmoudi et al. (2019), and Ng et al. (2023). It does not require any modification of index data, such as type III Pearson distributions or gamma distributions, as performed in CZI and SPI. The equation used to determine ZSI is as follows:

$$\text{ZSI} = \frac{X_i - X_m}{\sigma} \quad (13)$$

where  $i$  represents the current month,  $X_i$  is the precipitation of the  $i$  month,  $\sigma$  represents the standard deviation, and  $X_m$  is the mean monthly precipitation.

Table II. Classification and value ranges of DIs (Morid et al., 2006; Achite et al., 2023; Kartal and Nones, 2024).

Class numbers	Symbol	Category	SPI, ZSI, CZI, and MCZI
-3	EW	Extremely wet	$\geq 2$
-2	VW	Very wet	1.5 to 1.99
-1	MW	Moderately wet	1 to 1.49
0	N	Normal	-0.99 to 0.99
1	MD	Moderately dry	-1.49 to -1
2	SD	Severely dry	-1.99 to -1.5
3	ED	Extremely dry	$\leq -2$

DIs: drought indices; SPI: Standardized Precipitation Index; ZSI: Z-Score Index; CZI: China-Z Index; MCZI: Modified China Z Index.

### 3.2 Correlation and trend test analysis

#### 3.2.1 Pearson correlation coefficient (PCC)

The PCC, often called the product-moment correlation coefficient, was developed by Karl Pearson (1896). According to Adler and Parmryd (2010) and Hauke and Kossowski (2011), PCC is the most frequent statistical method used to measure the strength of the relationship between two variables. PCC ranges from  $-1$  to  $+1$ , where  $-1$  indicates a perfect negative linear relationship, and  $+1$  indicates a perfect positive linear relationship between the variables. The PCC value of  $0$  means no linear relationship between the variables.

#### 3.2.2 Mann-Kendall (MK) trend test

One of the non-parametric tests used to detect trends is the MK test (Mann, 1945; Kendall, 1975), which is particularly useful for meteorological, climatological, and hydrological time series (Akçay et al., 2023; Jafarpour et al., 2023). The following equations give the MK test statistic ( $S$ ):

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^n \text{sgn}(x_j - x_i) \quad (14)$$

$$\text{sgn}(x_j - x_i) = \begin{cases} +1 & \text{if } (x_j - x_i) > 0 \\ 0 & \text{if } (x_j - x_i) = 0 \\ -1 & \text{if } (x_j - x_i) < 0 \end{cases} \quad (15)$$

where  $x_i$  and  $x_j$  represent the data points in periods  $i$  and  $j$ , while the amount of data series is larger than or equivalent to  $10$  ( $n \geq 10$ ), since  $n \geq 10$ , the MK test is then categorized by a standard distribution with the mean  $E(S) = 0$  and variance  $Var(S)$  given as:

$$Var(S) = \frac{n(n-1)(2n+5) - \sum_{k=1}^m t_k(t_k-1)(2t_k+5)}{18} \quad (16)$$

where  $m$  is the number of the tied groups in the time series and  $t_k$  is the number of ties in the  $k_{th}$  tied group. From this, the test  $Z$  statistics is obtained using an approximation as follows:

$$Z = \begin{cases} \frac{s-1}{\sqrt{Var(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{s+1}{\sqrt{Var(S)}} & \text{if } S < 0 \end{cases} \quad (17)$$

In a  $Z$  test, the null hypothesis ( $H_0$ ) indicates no trend in the time series, and the alternative hypothesis ( $H_a$ ) indicates a significant change. At the 5% significance level, negative values indicate decreasing trends, and positive values indicate an increasing trend. If  $|Z| > 1.96$ ,  $H_0$  is rejected (Sneyers, 1990).

## 4. Results and discussion

### 4.1 Correlation of SPI with CZI, MCZI, and ZSI

Figs. S1, S2, and S3 in the supplementary material illustrate the variation of all indices over the 1-, 3-, and 12-month time scales, respectively. This variation allows us to identify dry and wet events at different timescales. These can be determined by referencing the position of the indices within the drought classification categories defined in Table II.

To better understand the relationship between DIs, the PCC was used to compare the SPI with CZI, MCZI, and ZSI. According to the findings of many researchers, the SPI is a highly precise measure of drought and serves as a basis for comparing with other indices in several countries, such as Algeria (Bougara et al., 2021; Achite et al., 2023), Mauritania (Yacoub and Tayfur, 2017), Iran (Shahabfar and Eitzinger, 2013; Khanmohammadi et al., 2022), Turkey (Katipoğlu et al., 2020; Zeybekoğlu and Aktürk, 2021; Gumus, 2023; Zeybekoglu et al., 2023; Simsek et al., 2024), Ethiopia (Tefera et al., 2019), Philippines (Salvacion, 2021), and Malaysia (Ng et al., 2023).

Table III shows the PCC values between SPI and CZI, MCZI, and ZSI on multi-monthly timescales for all stations. Figs. 2, 3, and 4 present scatter plots of the highest correlations between SPI and other DIs at a 1-, 3-, and 12-month time scales for all stations. On a 1-month timescale, all stations demonstrate the highest correlation (0.939 to 0.984) between SPI-1 and CZI-1. On a 3-month timescale, most stations exhibit the highest correlation (0.963 to 0.996) between SPI-3 and CZI-3, except for the Sebdou, Hennaya, and Ouled Mimoun stations, which display the highest correlation (0.964 to 0.993) between SPI-3 and MCZI-3, and the Maghnia, Sidi Medjahed, and Pierre Du Chat stations, which exhibit the highest correlation (0.949 to 0.957) between SPI-3 and ZSI-3. On a 12-month timescale, most stations show the highest correlation (0.999 to 1.0) between SPI-12 and CZI-12, except for Beni

Table III. PCC between SPI and the other DIs at different time scales.

Station	1-month			3-month			12-month		
	CZI	MCZI	ZSI	CZI	MCZI	ZSI	CZI	MCZI	ZSI
Maghnia	<b>0.944</b>	0.917	0.918	0.947	0.919	<b>0.952</b>	0.919	0.864	<b>0.982</b>
Sebdou	<b>0.971</b>	0.936	0.943	0.953	<b>0.964</b>	0.956	<b>1.000</b>	0.989	0.993
Beni Bahdel	<b>0.939</b>	0.909	0.929	<b>0.963</b>	0.912	0.951	0.997	<b>0.999</b>	0.991
Sidi Medjahed	<b>0.955</b>	0.933	0.914	0.947	0.894	<b>0.957</b>	<b>1.000</b>	0.998	0.991
Sebra	<b>0.967</b>	0.942	0.893	<b>0.996</b>	0.957	0.963	0.998	<b>0.999</b>	0.991
Hennaya	<b>0.984</b>	0.943	0.935	0.976	<b>0.977</b>	0.949	0.996	<b>0.999</b>	0.982
Zaouia Ben Amar	<b>0.984</b>	0.953	0.919	<b>0.990</b>	0.937	0.965	<b>1.000</b>	0.986	0.994
Djebel Chouachi	<b>0.954</b>	0.931	0.896	<b>0.996</b>	0.907	0.957	<b>1.000</b>	0.991	0.992
Oued Lakhdar	<b>0.952</b>	0.943	0.935	<b>0.986</b>	0.983	0.962	<b>1.000</b>	0.996	0.995
Meurbah	<b>0.954</b>	0.935	0.944	<b>0.993</b>	0.966	0.962	<b>1.000</b>	0.982	0.993
Ouled Mimoun	<b>0.970</b>	0.943	0.940	0.985	<b>0.993</b>	0.965	<b>0.999</b>	0.999	0.994
Mefrouche	<b>0.940</b>	0.907	0.934	<b>0.993</b>	0.933	0.964	<b>0.999</b>	0.998	0.990
Lalla Setti	<b>0.977</b>	0.934	0.944	<b>0.991</b>	0.968	0.964	<b>1.000</b>	0.996	0.995
Pierre Du Chat	<b>0.945</b>	0.918	0.865	0.924	0.876	<b>0.949</b>	<b>1.000</b>	0.995	0.990

SPI: Standardized Precipitation Index; DIs: drought indices; CZI: China-Z Index; MCZI: Modified China Z Index; ZSI: Z-Score Index.

Bold characters indicate the highest correlation values.

Bahdel, Sebra, and Hennaya stations, which show the highest correlation (0.999) between SPI-12 and MCZI-12, and Maghnia station, which shows the stronger correlation (0.982) between SPI-12 and ZSI-12.

Overall, the best correlation is found between SPI and CZI on the 1-month timescale for all stations, highlighting their strong agreement in capturing short-term drought conditions. This high correlation signifies the reliability of both indices in detecting drought conditions. Around 57 and 71% of stations show the best correlation between SPI and CZI on 3- and 12-month timescales, respectively. These percentages underline the robustness of SPI and CZI in reflecting both short-term and long-term drought patterns, making them valuable tools for drought monitoring. Achite et al. (2023) demonstrated a high correlation between those DIs in Algeria's Mediterranean climate. They found that the correlation coefficient exceeds 0.97 when the timescales increase. These results are consistent with the present study, reinforcing the efficacy of SPI and CZI in assessing drought across different time scales.

#### 4.2 Drought categories

Fig. 5 compares the frequency of drought categories across DIs and timescales. On a 1-month timescale:

- Moderate drought frequency: SPI-1: 7.0 to 9.5%; CZI-1: 6.3 to 10.7%; MCZI-1: 1.0 to 8.7%; and ZSI-1: 4.7 to 10.7%.
- Severe drought frequency: SPI-1: 2.5 to 4.7%; CZI-1: 0.3 to 3.0%; MCZI-1: less than 1.7%; and ZSI-1: no severe drought at any station, except for Djebel Chouachi (4.7%).
- Extreme drought frequency: SPI-1: less than 0.8%; CZI-1: less than 2.3%; MCZI-1: less than 2.0%; and ZSI-1: no extreme drought, except for Djebel Chouachi (2.0%).

On a 3-month timescale:

- Moderate drought frequency: SPI-3: 4.5 to 11.5%; CZI-3: 4.0 to 12.5%; MCZI-3: 1.0 to 9.0%; and ZSI-3: 6.5 to 13.0%.
- Severe drought frequency: SPI-3: 1.0 to 4.5%; CZI-3: 2.0 to 6.0%; MCZI-3: 1.0 to 4.0%; and ZSI-3: 0.0 to 4.0%.
- Extreme drought frequency: SPI-3: 1.0 to 4.5%; CZI-3: the highest frequencies were observed at the Sebdou and Beni Bahdel stations (6.5 and 5.0%, respectively), while other stations ranged from 0.5 to 3.5%; MCZI-3: a high frequency (5.5%) was recorded at Sebdou station, with

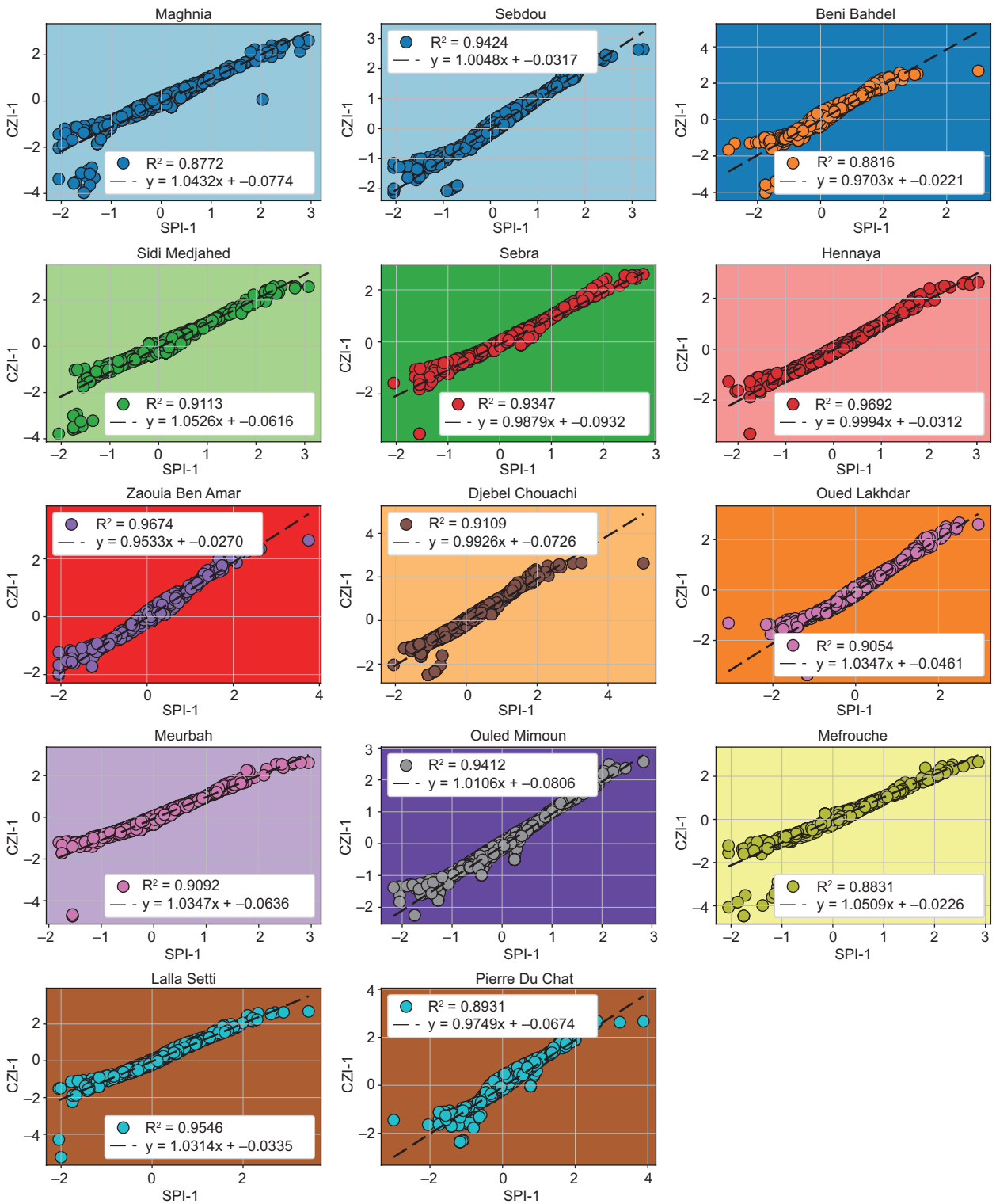


Fig. 2. Scatter plots of the highest correlations between the Standardized Precipitation Index (SPI) and other Drought Indices (DIs) at a 1-month time scale for all stations.

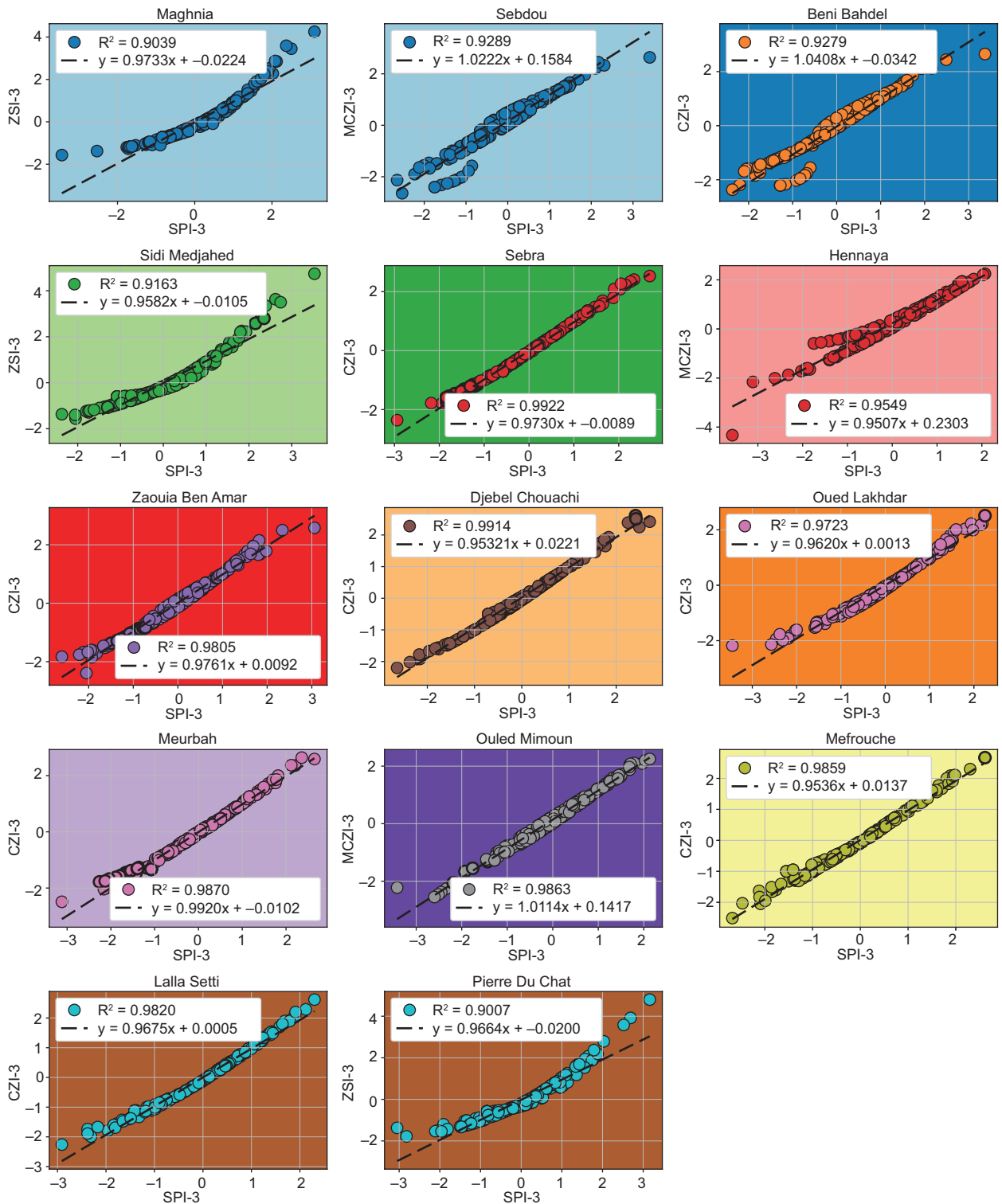


Fig. 3. Scatter plots of the highest correlations between the Standardized Precipitation Index (SPI) and other Drought Indices (DIs) at a 3-month time scale for all stations.

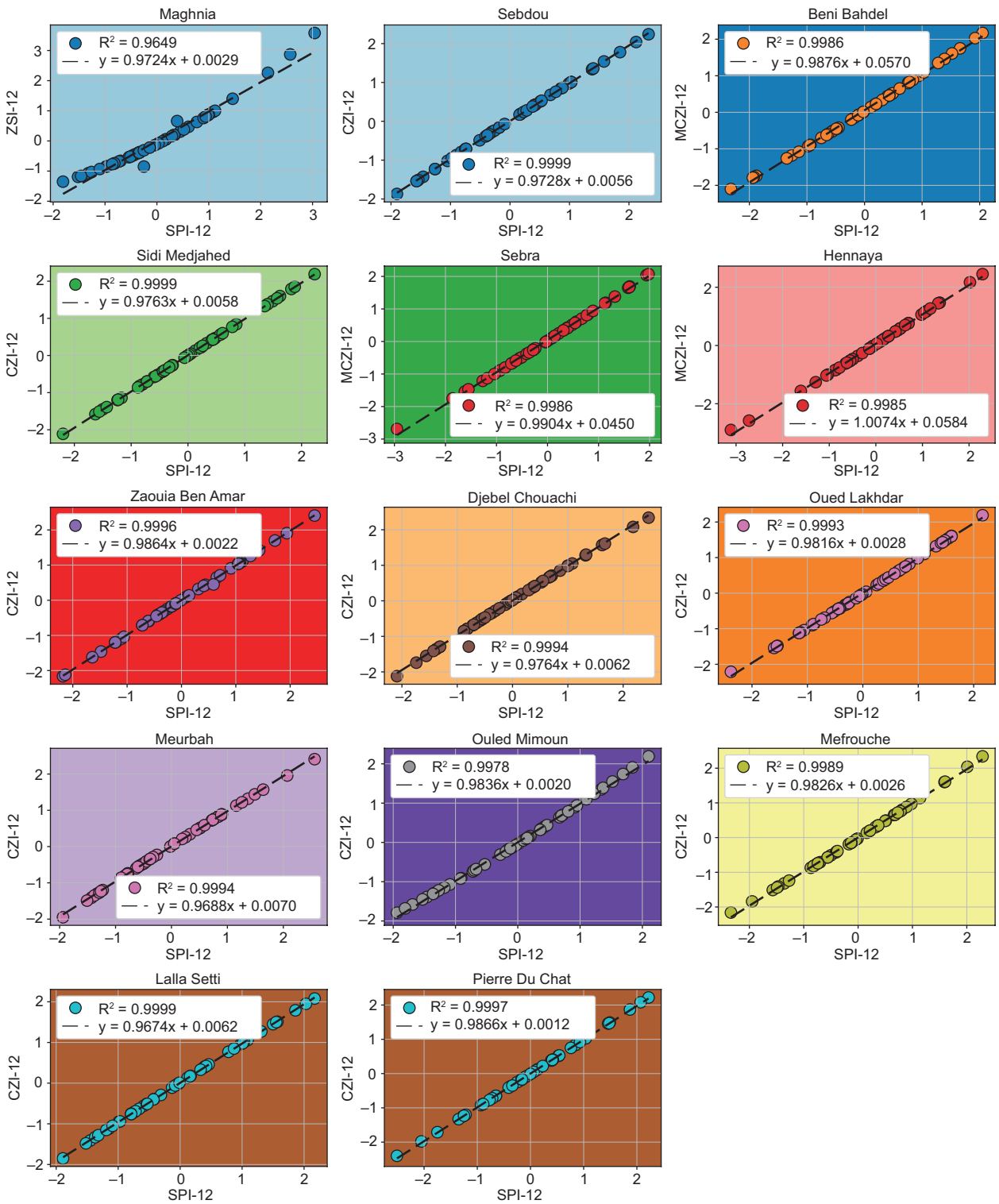


Fig. 4. Scatter plots of the highest correlations between the Standardized Precipitation Index (SPI) and other Drought Indices (DIs) at a 12-month time scale for all stations.

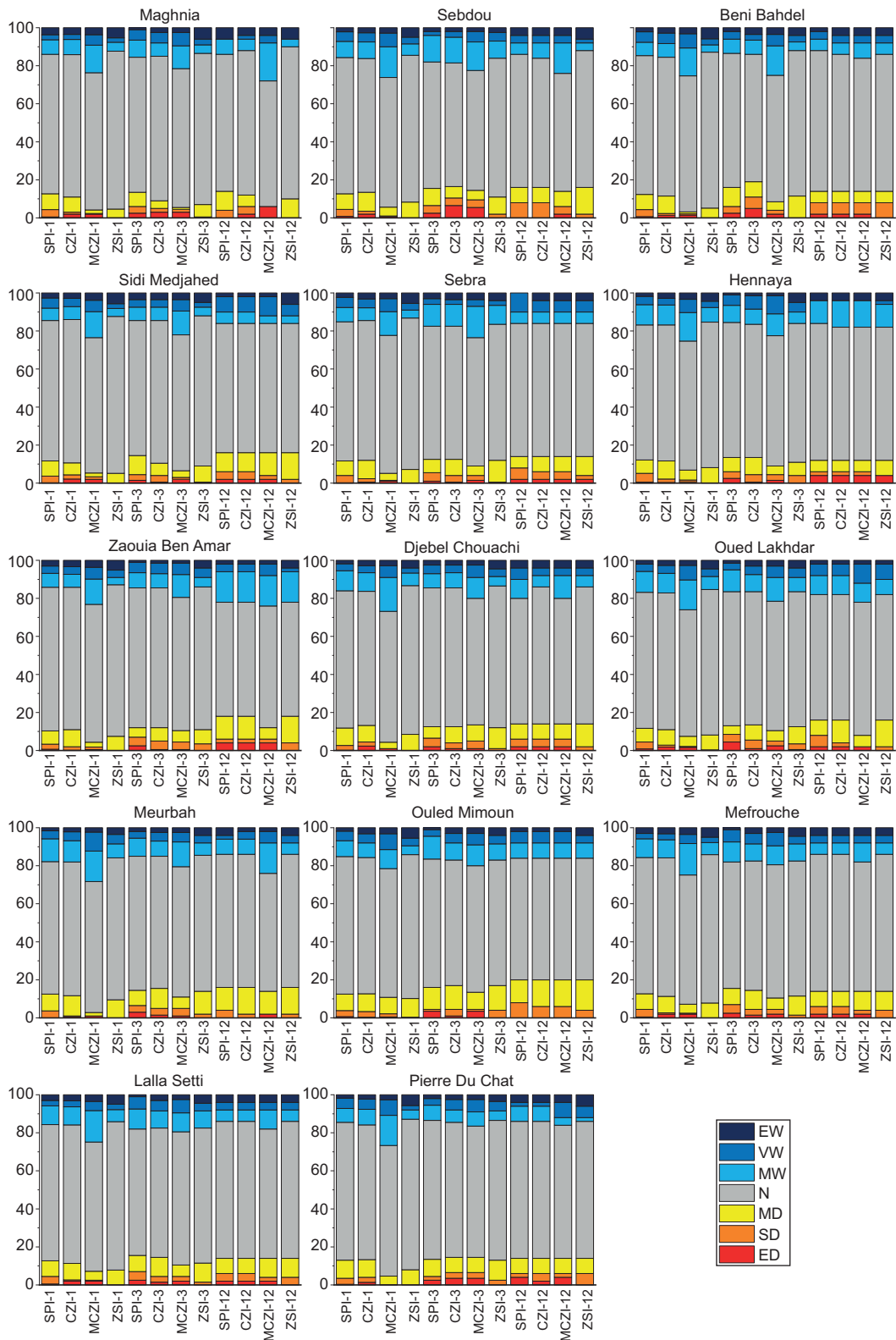


Fig. 5. Drought frequency categories for the Standardized Precipitation Index (SPI), China-Z Index (CZI), Modified China Z Index (MCZI), and Z-Score Index (ZSI) at different time scales.

other stations ranging from 0.5 to 4.5%; ZSI-3: no extreme drought occurrences were identified.

On a 12-month timescale:

- Moderate drought frequency ranged from 6.0 to 12.0% for SPI-12. For CZI-12, MCZI-12, and ZSI-12, the highest frequency was observed at Ouled Mimoun station (16.0% for ZSI-12), while Maghnia station did not record any occurrences of moderate drought. Other stations reported frequencies ranging from 6.0 to 14.0%.
- Severe drought frequencies ranged from 2.0 to 8.0% for SPI-12 and CZI-12, and from 0.0 to 6.0% for MCZI-12 and ZSI-12, except for Beni Bahdel Station, where ZSI-12 recorded a frequency of 8.0%.
- Extreme drought frequencies for SPI-12 and CZI-12 ranged from 0.0 to 4.0%. For MCZI-12, the highest frequency was observed at Maghnia Station (6.0%), while other stations reported frequencies ranging from 0.0 to 4.0%. ZSI-12 identified extreme drought only at Sebra and Hennaya stations (2.0 and 4.0%, respectively), with no occurrences recorded at the remaining stations.

These results reveal that the occurrence of moderate droughts is more frequent than severe and extreme droughts across most of the 14 meteorological stations for all the indices at different time scales. Therefore, the probability or return period of moderate droughts is the highest. On a 1-month timescale, Figure 2 shows that the frequency of total drought (ED + SD + MD) of SPI-1 and CZI-1 is greater than that of MCZI-1 and ZSI-1 for all stations. These results were explained by Jain et al. (2015), who found that erroneous estimates of drought duration in DIs could be produced on a 1-month time scale. In addition, on a 3-month time scale, the frequency of total drought in MCZI-3 and ZSI-3 is less than that of SPI-3 and CZI-3 in many stations such as Maghnia, Beni Bahdel, Sidi Medjahed, Hennaya, Mefrouche, and Lalla Setti. Higher frequencies at this timescale indicate that SPI and CZI may be more sensitive to short-term climatic variations, making them useful for detecting rapid changes in drought conditions. On a 12-month timescale, SPI-12, CZI-12, MCZI-12, and ZSI-12 showed the

same frequency of total drought for most stations. This consistency across indices at longer timescales highlights their reliability for identifying long-term drought conditions, which are critical for strategic water resource management. Based on Achite et al. (2023), the agreement between drought classes for SPI, CZI, MCZI, and ZSI increases with the increase in timescale.

### 4.3 Trend analysis

Table IV presents the Z-values of the Mann-Kendall test for SPI, CZI, MCZI, and ZSI, obtained on different time scales for all stations. On a 1-month timescale, the results showed no significant trend for all indices in most stations, indicating no apparent increase or decrease in index values. However, Maghnia station exhibited a decrease in both SPI-1 and ZSI-1 index values.

On a 3-month timescale, significant decreases in index values were observed at Maghnia and Mefrouche stations for all indices, Sebdou station for CZI-3, and Pierre Du Chat station for ZSI-3. The remaining stations exhibited non-significant trends. These findings suggest that some regions in the Tafna watershed experienced more pronounced seasonal dryness, characterized by reduced precipitation or extended dry periods. This could potentially affect water resource management in these regions, such as through reduced water availability, increased demand, and risk of overexploitation.

On a 12-month timescale, all stations except Maghnia exhibited significant increases in the values of all DIs. Maghnia station showed a non-significant trend. These findings differ from the study by Bougara et al. (2021), who did not find significant trends in any indices (SPI, RAI, PN, and DI) on a 12-month time scale in the Tafna watershed in stations such as Beni Bahdel, Sebdou, Djbel Chouachi, Hennaya, Meurbah, or Ouled Mimoun. The study by Bougara et al. (2021) spanned 33 years (1979-2011), while the current research covers a more extended period of 50 years (1970-2019). The extended timeframe of this study may capture prolonged climatic cycles and trends that were not apparent in the shorter study period of Bougara et al. (2021).

It can be concluded that most stations showed an increase in all index values on a 12-month time

Table IV. Z values obtained by the Mann-Kendall test for all stations at different time scales.

Station	1-month				3-month				12-month			
	SPI	CZI	MCZI	ZSI	SPI	CZI	MCZI	ZSI	SPI	CZI	MCZI	ZSI
Maghnia	<b>-1.98</b>	-1.94	-1.79	<b>-1.97</b>	<b>-2.93</b>	<b>-3.11</b>	<b>-2.86</b>	<b>-2.86</b>	-1.46	-1.46	-1.63	-1.46
Sebdou	-0.09	-0.10	-0.16	-0.07	-1.33	<b>-3.03</b>	-1.33	-1.41	<b>2.50</b>	<b>2.50</b>	<b>2.93</b>	<b>2.37</b>
Beni Bahdel	1.61	1.70	1.21	1.53	0.18	0.44	0.14	-0.11	<b>3.47</b>	<b>3.57</b>	<b>3.57</b>	<b>3.06</b>
Sidi Medjahed	1.77	1.77	1.58	1.84	0.79	0.73	0.78	0.60	<b>4.63</b>	<b>4.63</b>	<b>4.51</b>	<b>4.21</b>
Sebra	0.64	0.75	0.72	0.75	0.34	0.36	0.38	0.29	<b>3.19</b>	<b>3.77</b>	<b>3.76</b>	<b>3.65</b>
Hennaya	-0.80	-0.83	-0.74	-0.63	-1.45	-1.35	-1.43	-1.40	<b>2.48</b>	<b>2.46</b>	<b>2.46</b>	<b>2.52</b>
Zaouia Ben Amar	0.45	0.56	0.49	0.61	-0.07	-0.16	-0.14	-0.28	<b>3.56</b>	<b>3.56</b>	<b>3.56</b>	<b>3.21</b>
Djebel Chouachi	-0.22	-0.29	-0.15	-0.14	0.04	-0.07	-0.08	-0.15	<b>3.98</b>	<b>3.96</b>	<b>3.92</b>	<b>3.46</b>
Oued Lakhdar	0.08	0.13	0.02	0.04	-0.79	-0.82	-0.85	-0.84	<b>3.43</b>	<b>3.28</b>	<b>2.78</b>	<b>2.94</b>
Meurbah	1.30	1.45	1.32	1.35	0.38	0.52	0.83	0.36	<b>3.77</b>	<b>3.71</b>	<b>3.48</b>	<b>3.84</b>
Ouled Mimoun	-0.23	-1.02	-0.62	-0.94	-0.96	-1.00	-0.95	-1.01	<b>3.41</b>	<b>3.44</b>	<b>3.45</b>	<b>3.53</b>
Mefrouche	-1.06	-0.92	-0.83	-0.95	<b>-2.15</b>	<b>-2.07</b>	<b>-2.10</b>	<b>-2.05</b>	<b>3.05</b>	<b>3.06</b>	<b>2.89</b>	<b>2.57</b>
Lalla Setti	-1.41	-1.39	-1.11	-1.42	-1.88	-1.89	-1.80	-1.85	<b>2.83</b>	<b>2.59</b>	<b>2.45</b>	<b>2.76</b>
Pierre Du Chat	-0.29	-0.48	-0.61	-0.59	-0.62	-0.83	-0.35	<b>-2.97</b>	<b>3.78</b>	<b>3.80</b>	<b>3.90</b>	<b>3.44</b>

SPI: Standardized Precipitation Index; CZI: China-Z Index; MCZI: Modified China Z Index; ZSI: Z-Score Index. Bold characters indicate significant values at the  $\leq 0.05$  level of significance.

scale, which suggests more frequent wet periods in the long term. Most stations do not exhibit any significant trends in index values on 1- and 3-month time scales, which indicates stability in short-term drought and wet conditions. These findings highlight the necessity for water resource managers to adopt a multi-timescale approach when planning drought mitigation and water resource allocation, ensuring that strategies are responsive to short-term and long-term variability.

## 5. Conclusion

In this study, we compared four rainfall-based DIs, namely SPI, CZI, MCZI, and ZSI, in the Tafna watershed using 14 rainfall stations from 1970 to 2019. The most important results of this research are as follows:

1. On a 1-month timescale, the frequency of total drought (ED + SD + MD) of SPI-1 and CZI-1 is greater than that of MCZI-1 and ZSI-1 for all stations. On a 3-month time scale, in many stations such as Maghnia, Beni Bahdel, Sidi Medjahed, Hennaya, Mefrouche, and Lalla Setti, the frequency of total drought in MCZI-3 and ZSI-3 is less than that of SPI-3 and CZI-3. On a 12-month timescale, the SPI-12, CZI-12, MCZI-12, and ZSI-12 showed the same frequency of total drought for most stations.
2. The highest correlation is found between SPI-1 and CZI-1 on a 1-month time scale for all stations using the PCC. Around 57 and 71% of stations show the best correlation between SPI and CZI on 3- and 12-month scales, respectively.
3. On a 12-month time scale, most stations showed an increase in all index values using the MK test, which suggests more frequent wet periods in the long term. On a 1- and 3-month time scale, most stations do not exhibit significant index value trends, indicating stability in short-term dry and wet conditions. These results highlight the need to analyze climatic data at multiple timescales to better understand regional climate dynamics.

In conclusion, this study's results show that the SPI and CZI indices performed best in drought assessment and monitoring at different time scales. These DIs are preferable for assessing drought in the Tafna watershed. These findings highlight the importance of using SPI and CZI for more accurate drought forecasting and assessing current climatic conditions, enabling better preparation and response strategies for water resource management in the region.

## Acknowledgments

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# Supplementary material



Fig. S1. Variations between all indices at 1-month time scale.

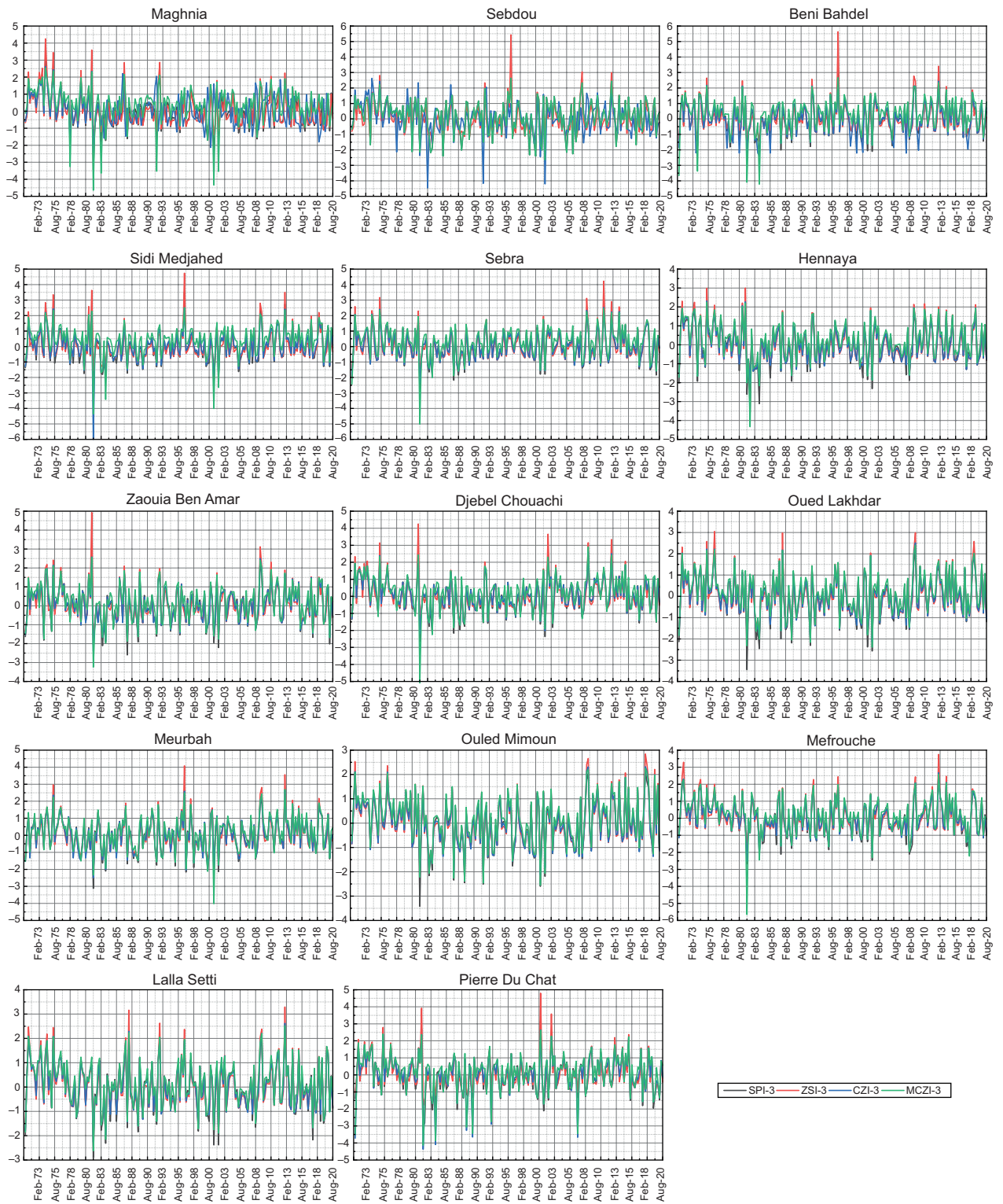


Fig. S2. Variations between all indices at 3-month time scale.

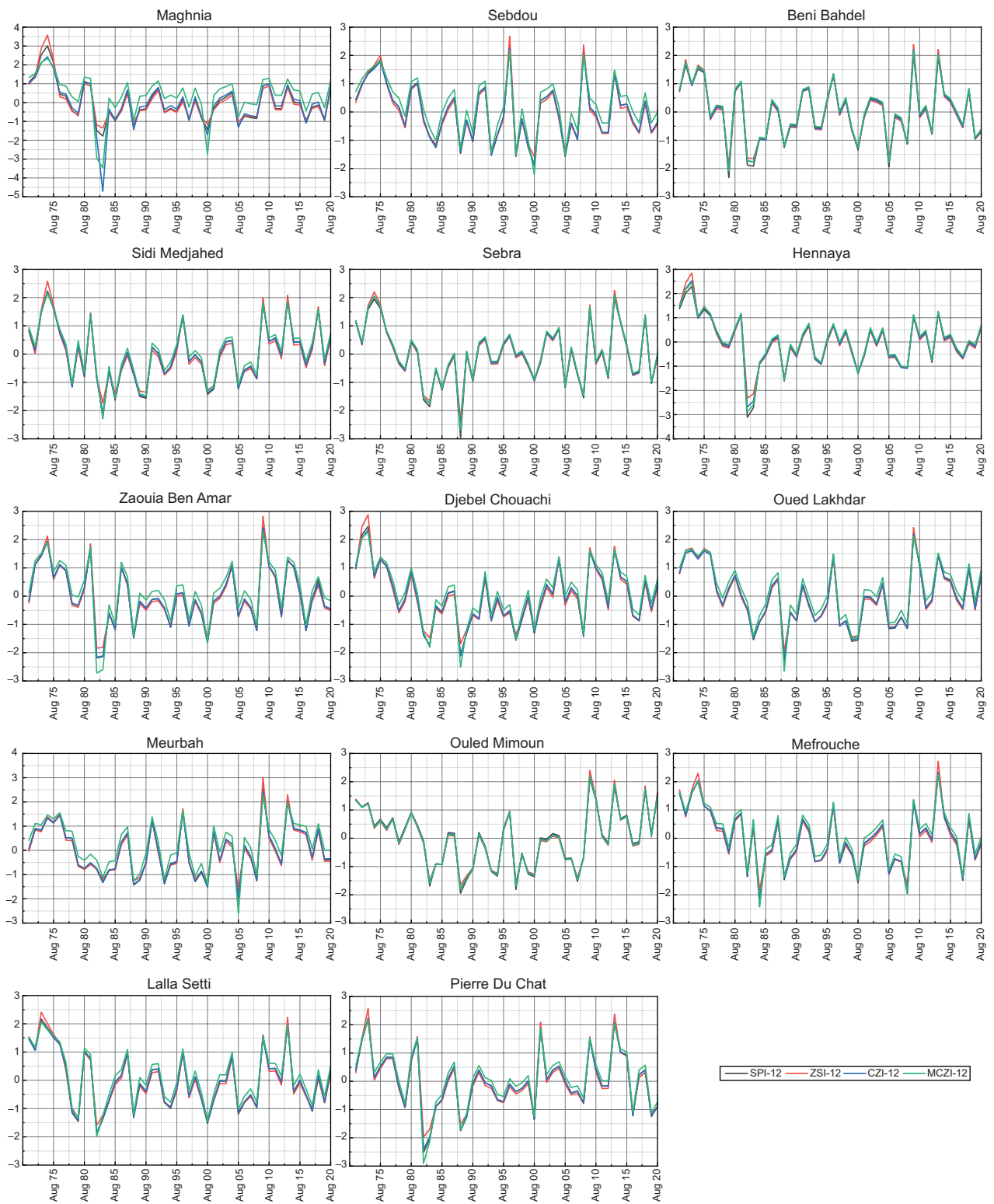


Fig. S3. Variations between all indices at 12-month time scale.