



Investigation of Drought Trend on the Basis of the Best Obtained Drought Index

Neda Khanmohammadi¹ · Hossein Rezaie² · Javad Behmanesh²

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Abstract

The drought phenomenon is a primary natural hazard in Iran. The drought can be analyzed using different indices. Therefore, the use of suitable indices will have an essential role in quantitatively investigating this phenomenon. Since precipitation is one of the most critical factors in drought analysis, different drought indices consist of precipitation and have been developed based on this parameter. In this study, the time series of nine precipitation-based drought indices were compared in 30 synoptic stations of Iran, and the superior index was determined during 1960–2014. Then, using the selected drought index, the annual trend of wet and dry periods was calculated by the modified Mann–Kendall test. Among studied indices, the SPI index was selected as the superior one. This index was well fitted by the Normal distribution and had a correlation coefficient of more than 0.92 with precipitation. Also, this index was sensitive to the amount of precipitation, and it could detect drought events corresponding to the minimum precipitation. In other words, the SPI had the best capability to determine extreme drought based on minimum precipitation. The results of drought analysis based on the SPI index showed that at least one drought event happened in the majority of studied years (82%). It reflects drought conditions in the studied area, especially in 2008 and 2010. The trend analysis of wet and dry periods showed the decreasing trend of the SPI index in the most studied stations. The decreasing trend of the mentioned index was significant (at 95% confidence level) in the northwest and west of Iran. The trend line slope values corresponding to the SPI index were negative in most studied stations. Tabriz and Esfahan stations had the maximum value of negative (−0.027) and positive (0.025) trend line slope, respectively.

Keywords Drought analysis · Modified Mann–Kendall test · SPI index · Trend analysis · Wet and dry periods

✉ Neda Khanmohammadi
n.khanmohammadi@urmia.ac.ir

¹ Urmia Lake Research Institute, Urmia University, Urmia, Iran

² Department of Water Engineering, Urmia University, Urmia, Iran

1 Introduction

Drought, as a destructive phenomenon, occurs in various climates, and its detrimental effect is considerable in arid and semiarid regions such as Iran. Due to the dependence of living organisms on water resources and attention to the harmful effect of extreme drought on soil and water resources, the trend analysis of dry and wet periods is vital to provide appropriate management principles. For quantitative and qualitative evaluation of drought in the whole world, different drought indices have been developed by researchers in the literature (Khanmohammadi et al. 2017a). Some indices such as Palmer Drought Severity Index (PDSI) (Palmer 1965), Crop Moisture Index (Palmer 1968), and Standardized Precipitation Evapotranspiration Index (SPEI) (Vicente-Serrano et al. 2010) utilize precipitation data combined with temperature. The precipitation data combined with soil moisture are used to calculate some indices such as the Moisture Adequacy Index (McGuire and Palmer 1957) and Keetch-Bryam Drought Index (Keetch and Byram 1968). Moreover, there are some standard indices that use only precipitation data. The Rainfall Anomaly Index (RAI) (Van Rooy 1965), Deciles Index (DI) (Gibbs and Maher 1967), Nitzche Index (Nitzche et al. 1985), SPI (McKee et al. 1993), Percent of Normal Precipitation Index (PNPI) (Willeke et al. 1994), Z-Score, China Z Index (CZI) (Ju et al. 1997) and Modified China Z Index (MCZI) (Wu et al. 2001) are some of them.

Due to the existence of various drought indices, comparing proposed indices and selecting the superior index have been current subjects in recent research (e.g. Quiring and Papakryiakou 2003; Morid et al. 2006; Adnan et al. 2018; Wable et al. 2019). Wu et al. (2001) compared the SPI, Z-score, and CZI in four regions of China based on the SPI index. In the mentioned study, the CZI index was more sensitive to dry conditions than the SPI index. Tsakiris et al. (2007) compared the SPI and RDI indices using recorded data in two river basins located in Greece. The results of the mentioned study showed the similarity of the SPI and RDI results. They also stated that the RDI index is more suitable for regions with environmental changes. Asadi-Zarch et al. (2011) compared the SPI and RDI indices for different scales. They used recorded data of 40 synoptic stations located in Iran. Based on obtained results, there was a considerable correlation between the RDI and SPI which were calculated in shorter time scales (such as three months) in comparison with longer ones. In the mentioned study, they suggested using the RDI index for drought analysis in Iran. In another study, the SPI and RDI indices were compared by Khalili et al. (2011). They used recorded data (39 to 53 years) at ten stations that had different climates in Iran. They suggested using the RDI index for drought assessment for agricultural purposes. Dogan et al. (2012), in their study, compared six different meteorological drought indices, including Percent of Normal (PN), statistical Z-Score, Rainfall Decile based Drought Index (RDDI), Standardized Precipitation Index (SPI), China-Z Index (CZI), and Effective Drought Index (EDI) to analyze the drought in Konya (a semiarid closed basin in Turkey). They used the data of 12 stations during 1972–2009. On the basis of the obtained results of the mentioned study, since the EDI index does not depend on time step and has good correlations with various time steps of other drought indices, they recommended EDI index for long term drought monitoring in arid or semiarid regions when monthly precipitation data were used for drought analysis. Paulo et al. (2012) compared the SPI, and PDSI indices with the modified PDSI developed for the Mediterranean conditions (MedPDSI) and the Standardized Precipitation Evapotranspiration Index (SPEI) in 27 stations of Portugal (1941–2006). The results showed that both the PDSI and MedPDSI drought indices, compared with the SPI and SPEI indices, identify more severe droughts

and have more ability to identify drought occurrence. Jain et al. (2015) compared six different meteorological drought indices, including Rainfall Departure (RD), CZI, Z-score, EDI, SPI, and RDDI, in 13 stations of Ken river basin (central India). Based on the results of the mentioned study, similar to the study of Dogan et al. (2012), the EDI was a more suitable drought index. The literature review shows that the SPI index was proposed by McKee et al. (1993) and is more acceptable and popular than other drought indices. In addition to mentioned studies, the SPI index alone or with other indices were used by Moreira et al. (2006), Silva et al. (2008), Asadi-Zarch et al. (2015), Al-Faraj and Tigkas (2016), Belayneh et al. (2016), Rawat and Tripathi (2016), Byakatonda et al. (2018), Mathbout et al. (2018), Tigkas et al. (2019), Shiau (2020), Khezri et al. (2021), Pham et al. (2021) and Yerdelen et al. (2021).

During recent years, besides drought analysis, the researchers have been focused on the trend of wet and dry periods. Several studies have shown an increase in droughts (Bonaccorso et al. 2003; Vicente-Serrano et al. 2004; Vicente-Serrano and Cuadrat-Prats 2007). Zhang et al. (2009) investigated the seasonal trends of wet and dry periods on the basis of the SPI index by the Mann–Kendall test during 1960–2005. They used 42 stations' data of a basin of China. Their results showed that the studied basin tends to be wet and dry in the winter and rainy seasons, respectively. In another study, the drought's trend was analyzed by Tabari et al. (2012) at ten stations of Iran (1966–2005). The trend results of the SPI, except the Zabul station, showed the reduction of the mentioned index at all studied stations. Nikbakht et al. (2013) analyzed the hydrological drought in Urmia Lake Basin (Iran) by Percent of Normal Index (PNI). They applied the recorded data at 14 stations during 1975–2009. The results of their study showed that over the past years, the value of hydrological drought in the studied area had been increased, and most of the studied stations had a significant decreasing trend. Khanmohammadi et al. (2017b) investigated the variation of wet and dry periods in 30 synoptic stations in Iran. Firstly, they calculated the values of RDI and SPI indices based on the best distribution. Then, they analyzed the trend of these two mentioned indices. The results of the mentioned study showed that in most studied stations, the trend of dry and wet periods was decreasing. Achite et al. (2021) evaluated the trend of 12-month SPI using the Theil–Sen, and Mann–Kendall test in the Wadi Cheliff Basin, Algeria. They found that the trend of northern and southern parts of the studied basin was different. The trend of 12-month SPI was negative on the northern side, and vice versa was positive at the south side of the basin. Mohammed and Yimam (2021) evaluated the trend of RDI during 1986–2019, using the Mann–Kendall trend test and data of ten stations located in the Lake's Region of Ethiopian Rift Valley. Their study showed that in most studied stations, the drought tends to increase.

According to the importance of drought and its destructive effect on different regions such as Iran, it is essential to conduct a more comprehensive study about this natural phenomenon on the basis of a suitable drought index. On the other hand, drought can affect water resources and their management. Misunderstanding of drought and its occurrence time can be costlier for governments and lead to unprincipled management by managers, experts, and engineers. Therefore, it is necessary to pay more attention to the selection of the best index. In fact, detecting drought periods using a suitable index leads to proper strategies for better drought management. Unfortunately, most researchers applied one index for drought analysis without selecting the best index among existing indices. But, for correct drought analysis, it is essential to use the best drought index. So, in the present study, nine drought indices (SPI3 index has been presented for the first time) were compared, and the most suitable index was introduced. Then, on the basis of relevant drought

index, the annual trend of wet and dry periods was determined by modified Mann–Kendall test (with removing all significant autocorrelation coefficients) in 30 stations which are located in four different climates of Iran.

2 Materials and Methods

2.1 Study Context and Data Set

Iran is a country located in West Asia with an area of about 1,648,000 square kilometers. A large part of Iran has an arid or semiarid climate. Because of finding a considerable area of Iran in a dry zone and consequently the importance of drought study in this country, the present study focuses on drought analysis on the basis of a suitable precipitation-based drought index. For this purpose, in the present study, daily precipitation data recorded in 30 synoptic stations of Iran (Fig. 1) was taken from the Iranian Meteorological Organization. The period of 1960–2014 was common for all selected meteorological stations. The characteristics of studied stations can be seen in Table 1. As seen in this table, the average annual precipitation in these stations varies from 56.277 mm (Yazd) to 1334.297 mm (Rasht).

It is necessary to mention that the selected stations are located in various climates. Stations located in 1–13 and 14–27 rows have an arid and semiarid climate, respectively. The climate of Babolsar is humid, and Ramsar and Rasht have a very-humid climate. Regarding the initial analysis of studied data, the Run test and Double Mass method were used to evaluate the homogeneity and randomness of data, respectively (Bars 1990; Adeloje and Montaseri 2002). The results which are reported in Table 1, confirmed the homogeneity of data and the hypothesis of data randomness. It should be noted that the reported results for the Double Mass method in Table 1 represent the determination coefficient values between an average of cumulative annual precipitation of all studied stations and cumulative annual precipitation recorded in each station. Also, it should be mentioned that the run test statistic is compared with ± 1.96 values. If the run test statistic value is between -1.96 and 1.96, it represents the randomness of data (precipitation in this study).

2.2 Drought Indices

In the present study, nine drought indices, including SPI, SPI2, SPI3, RAI, DI, PNPI, Z-score, CZI, and MCZI, which are determined on the basis of precipitation data, were compared each other, and the superior index was determined.

2.2.1 Standardized Precipitation Index (SPI)

The SPI was introduced by Mckee et al. (1993) for drought analysis. This index only needs precipitation data. To obtain the SPI index, first, a suitable distribution (such as Gamma) is fitted to the precipitation time series, and then the cumulative probability is transformed to the Standard Normal distribution (with a variance of unity and mean zero) (Dogan et al. 2012). In other words, this transformation was carried out at the same probability level. The obtained values with Standard Normal distribution will be the SPI index (Mckee et al. 1993; Edwards and Mckee 1997). The PDF (Probability Density Function) of Gamma distribution is defined as:

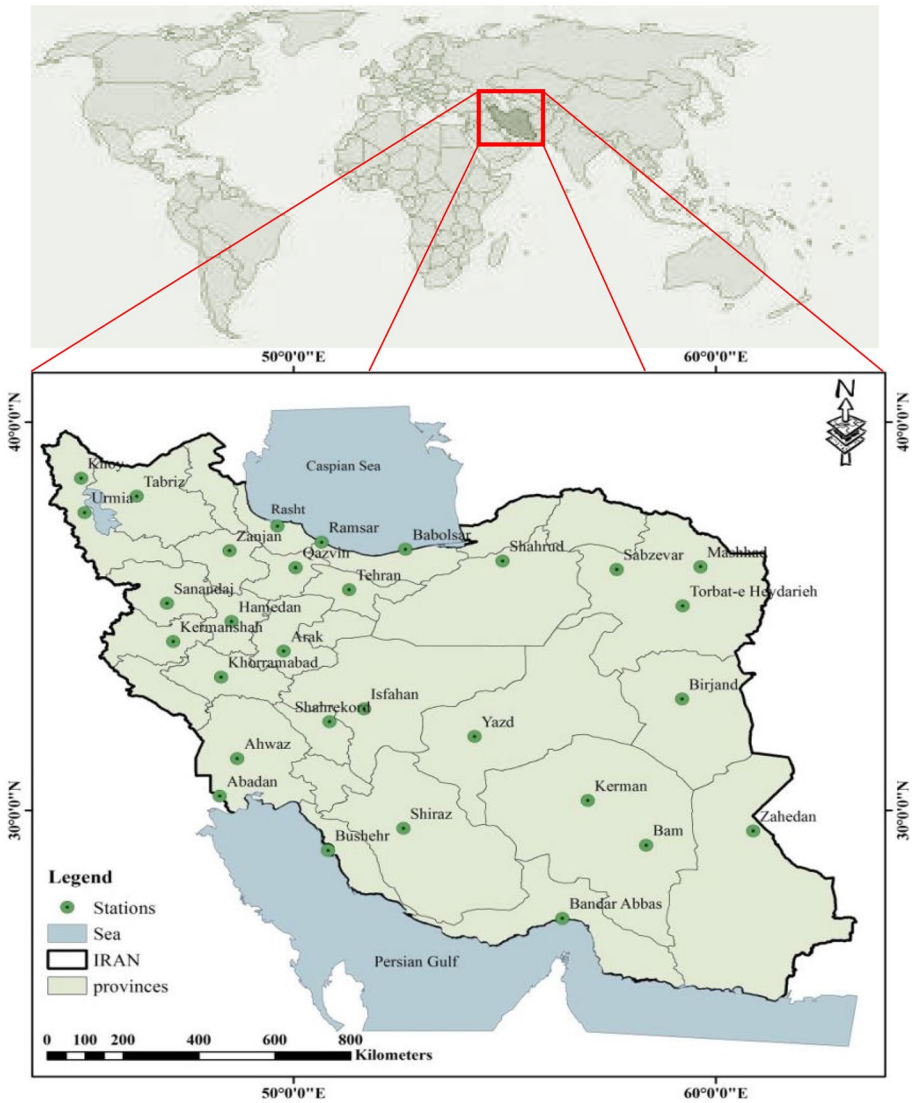


Fig. 1 Geographical position of 30 studied stations in Iran

$$g(x) = \frac{1}{\beta^\alpha \Gamma(\alpha)} x^{\alpha-1} e^{-x/\beta} \quad \text{for } x > 0 \tag{1}$$

Using the maximum likelihood method, the optimal values of the α (shape parameter) and β (scale parameter) can be calculated as:

$$\alpha = \frac{1}{4A} \left(1 + \sqrt{1 + \frac{4A}{3}} \right) \quad \text{and} \quad \beta = \frac{\bar{x}}{\alpha} \tag{2}$$

Table 1 Geographical information and mean annual precipitation of 30 synoptic stations in Iran with initial analysis results

No	Station	Lat	Lon	Mean (mm)	Run test	Mass curve
1	Yazd	31° 54'	54° 18'	56.3	-1.7675	0.999
2	Bam	29° 06'	58° 24'	58.1	-0.9506	0.9991
3	Zahedan	29° 30'	60° 54'	80.7	-0.6783	0.9989
4	Esfahan	32° 30'	51° 42'	123.6	0.6832	0.9972
5	Kerman	30° 18'	57° 00'	139.4	-0.9506	0.9997
6	Abadan	30° 24'	48° 12'	151.7	-0.9506	0.9992
7	Shahrud	36° 24'	54° 54'	155.6	-0.6783	0.9998
8	Birjand	32° 54'	59° 18'	162.3	-0.9506	0.9997
9	Bandarabbas	27° 12'	49° 36'	167.6	-1.7675	0.9966
10	Sabzevar	36° 12'	57° 42'	187.8	0.6832	0.9996
11	Ahvaz	31° 18'	48° 42'	224	0.6832	0.9997
12	Tehran	35° 42'	51° 18'	232.3	0.9555	0.9993
13	Bushehr	29° 00'	50° 48'	240.7	0.4109	0.9971
14	Mashhad	36° 12'	59° 36'	249	-0.406	0.9996
15	Torbate-heydarieh	35° 18'	59° 12'	259.6	0.1386	0.9996
16	Tabriz	38° 06'	46° 12'	281.6	-0.6783	0.9981
17	Khoy	38° 36'	45° 00'	290.3	0.6832	0.9986
18	Zanjan	36° 42'	48° 30'	305.6	0.6832	0.9995
19	Shiraz	29° 36'	52° 36'	314.6	-1.7675	0.999
20	Qazvin	36° 18'	50° 06'	315.6	-1.7628	0.9996
21	Hamedan	35° 12'	48° 42'	317.7	-1.4952	0.9997
22	Shahrekord	32° 18'	50° 48'	328.5	0.6832	0.9996
23	Arak	34° 06'	49° 48'	330.2	1.2278	0.9995
24	Urmia	37° 42'	45° 06'	332.1	0.6832	0.9994
25	Sanandaj	35° 18'	47° 00'	442.3	1.8448	0.999
26	Kermanshah	34° 24'	47° 12'	443.5	-1.4952	0.9994
27	Khorramabad	33° 24'	48° 18'	491.6	-0.9506	0.9999
28	Babolsar	36° 42'	52° 42'	898.7	0.6832	0.9992
29	Ramsar	36° 54'	50° 42'	1218.4	-0.9506	0.9995
30	Rasht	37° 18'	49° 36'	1334.3	-0.9506	0.9998

$$A = \ln(\bar{x}) - \frac{\sum \ln(x)}{n} \quad (3)$$

where, \bar{x} is the average value of time series, precipitation in this study, and n is the number of observations., The cumulative probability of Gamma distribution is given by using calculated parameters:

$$G(x) = \int_0^x g(x)dx = \frac{1}{\beta^\alpha \Gamma(\alpha)} \int_0^x x^{\alpha-1} e^{-x/\beta} dx \quad (4)$$

Since the values of precipitation may be zero and the Gamma distribution cannot be defined for zero values; therefore, the cumulative probability becomes:

$$H(x) = q + (1 - q)G(x) \tag{5}$$

where q is the probability of precipitation = zero. Then, the cumulative probability, $H(x)$, is transformed to the standard normal variable (with variance of unity and mean zero), which is the value of the SPI index.

2.2.2 Deciles Index (DI)

Deciles Index (DI) was developed by Gibbs and Maher (1967), and it is widely used in drought analysis in Australia (Simmonds and Hope 1997; Mpelasoka et al. 2008). In order to calculate this index, actual precipitation values are ranked from lowest to highest ones, and then a cumulative frequency distribution is constructed. Then the distribution is divided into ten sub-sections, and each sub-section is named a decile. The first decile, including the high precipitation values, indicates the wettest periods, while the last decile, including the low precipitation values, indicates the driest periods in the studied time series. The other values of precipitation fall into one of the other declines (2 to 9).

2.2.3 The Other Studied Drought Indices

The integral equations for the calculation of other drought indices are presented in Table 2. In this table, P_i is the value of precipitation, \bar{P} is the average value of precipitation, δ is the standard deviation of precipitation value, P_m is the median of precipitation value, \bar{E} is the mean of 10 lowest (for negative anomalies) and mean of 10 highest (for positive anomalies) values of precipitation in the studied time series and C_s is the skewness coefficient. It should be mentioned that the calculation process of SPI2 and Z-score is similar. The difference between these two indices is the different classifications of them for the determination of wet and dry periods (Table 2).

Table 2 Seven studied drought indices

Index	equation	Reference(s)
SPI2	$SPI2_i = \frac{P_i - \bar{P}}{\delta}$	-
SPI3	$SPI3_i = \frac{P_i - P_m}{\delta}$	-
RAI ^a	$RAI_i = \pm 3 \left[\frac{P_i - \bar{P}}{\bar{E} - \bar{P}} \right]$	Van Rooy (1965)
PNPI ^b	$PNPI_i = \frac{P_i}{\bar{P}} \times 100$	Willeke et al. (1994)
Z-score	$Z - score_i = \frac{P_i - \bar{P}}{\delta}$	Kutiel et al. (1996)
CZI	$CZI_i = \frac{6}{C_s} \left(\frac{C_s}{2} (Z - score_i) + 1 \right)^{1/3} - \frac{6}{C_s} + \frac{C_s}{6}$ $C_s = \frac{\sum_{i=1}^n (P_i - \bar{P})^3}{n \times \delta^3}$	Kendall and Stuart (1977); Dogan et al. (2012)
MCZIC	$CZI_i = \frac{6}{C_s} \left(\frac{C_s}{2} (SPI3_i) + 1 \right)^{1/3} - \frac{6}{C_s} + \frac{C_s}{6}$ $C_s = \frac{\sum_{i=1}^n (P_i - P_m)^3}{n \times \delta^3}$	Wu et al. (2001); Morid et al. (2006)

^aRainfall Anomaly Index (RAI)

^bPercent of Normal Precipitation Index (PNPI)

^cModified CZI (MCZI)

The SPI3 index, which is presented in Table 2, was first used in this study. Its calculation process is similar to the SPI2. In the calculation of the mentioned indices, the transformation of studied data from their probability distribution to the Normal distribution (identical to the SPI index) is not required. But, contrary to the SPI2 index, in the calculation of SPI3, the median value is used instead of the mean value of precipitation. It should be mentioned that the median and average values of precipitation time series were different due to not having the Normal distribution.

Table 3 provides a classification based on nine used drought indices. Common Quantitative Grouping (CQG), including seven categories, has been defined to better compare studied drought indices.

2.3 Trend Study

2.3.1 Mann–Kendall Approach

The Mann–Kendall is a well-known and standard test to detect a trend in time series data. This test includes all advantages of non-parametric methods and is less sensitive to extreme values (Xu et al. 2003). It should be mentioned that the common Mann–Kendall test was first introduced by Mann (1945) and then was developed by Kendall (1975). The steps of trend analysis for N data using the mentioned test are presented by Eqs. (6) to (9):

$$S = \sum_{i=1}^{N-1} \sum_{j=i+1}^N \text{sgn}(x_j - x_i) \tag{6}$$

$$\text{sgn}(x_j - x_i) = \begin{cases} +1 & \text{if}(x_j - x_i) > 0 \\ 0 & \text{if}(x_j - x_i) = 0 \\ -1 & \text{if}(x_j - x_i) < 0 \end{cases} \tag{7}$$

$$\text{Var}(S) = \frac{1}{18} [N(N - 1)(2N + 5) - \sum_{i=1}^m t_i(t_i - 1)(2t_i + 5)] \tag{8}$$

Table 3 Specified common quantitative grouping of the studied drought indices for wet and dry periods

CQG values	Class	SPI, SPI2, SPI3, CZI, MCZI	RAI	DI (%)	PNPI	Z-score
+3	Extremely Wet (EW)	> 2	> 3	> 90	> 160	> 1.5
+2	Severe Wet (SW)	1.5 to 1.99	2.1 to 3	80 to 90	145 to 160	1.0 to 1.5
+1	Moderately Wet (MW)	1 to 1.49	1.2 to 2.1	70 to 80	130 to 145	0.5 to 1.0
0	Near normal (N)	-0.99 to 0.99	-1.2 to 1.2	30 to 70	70 to 130	-0.5 to 0.5
-1	Moderately Drought (MD)	-1 to -1.49	-2.1 to -1.2	20 to 30	55 to 70	-0.1 to -0.5
-2	Severe Drought (SD)	-1.5 to -1.99	-3 to -2.1	10 to 20	40 to 55	-1.5 to -1.0
-3	Extremely Drought (ED)	< -2	< -3	< 10	< 40	< -1.5

$$Z = \begin{cases} \frac{S-1}{\sqrt{Var(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S+1}{\sqrt{Var(S)}} & \text{if } S < 0 \end{cases} \tag{9}$$

where x_j and x_i are the consecutive values of the series in the j and i years, respectively, n is the duration of time series, $sgn(x_j - x_i)$ is the sign function, $Var(S)$ is the variance of S , which for $n \geq 8$ normally distributed and has a zero mean, m is the number of tied values, t_i is the number of ties for the i^{th} value and Z is the Mann–Kendall test statistic. More details can be obtained by Yue et al. (2002a) and Khanmohammadi et al. (2017c). This method is used when there is no significant autocorrelation coefficient in time series of data. Otherwise, the modified version of the Mann–Kendall which has been introduced by Hamed and Rao (1998), should be used. The calculation phases of the modified version are almost similar to the initial version of the Mann–Kendall test, but it uses modified variance [$Var(S)^*$] instead of $Var(S)$. $Var(S)^*$ can be calculated as:

$$Var(S)^* = Var(S) \frac{n}{n^*} \tag{10}$$

$$\frac{n}{n^*} = 1 + \frac{2}{n(n-1)(n-2)} \sum (n-k)(n-k-1)(n-k-2) r_k^R \tag{11}$$

$$r_k^R = \frac{\frac{1}{n-k} \sum_{i=1}^{n-k} [(RX_i - E(RX_i))(RX_{i+k} - E(RX_{i+k}))]}{\frac{1}{n} \sum_{i=1}^n (RX_i - E(RX_i))^2} \tag{12}$$

where $\frac{n}{n^*}$ represents the correction factor, r_k^R represents the lag- k serial correlation coefficient of the ranks RX_i of the studied data, and n represents the number of data (Hamed and Rao 1998; Yue et al. 2002b; Dinpashoh et al. 2013). Equation (13) represents the existant significance (95% confidence level) in k^{th} autocorrelation coefficient of data. In other words, if obtained r_k^R places in this bound, the used data will be independent (95% confidence level). Otherwise, the used data are dependent, and for their analysis, the effect of the autocorrelation coefficient should be considered. Using these phases the obtained Z value will be modified Z (Hamed and Rao 1998; Kumar et al. 2009).

$$\frac{-1 - 1.96\sqrt{n-k-1}}{n-k} \leq r_k^R(95\%) \leq \frac{-1 + 1.96\sqrt{n-k-1}}{n-k} \tag{13}$$

It is necessary to state that IMK and MMK in this study illustrate initial and modified Mann–Kendall tests, respectively.

2.3.2 Theil–Sen’s Estimator

The trend line slope (β) for n data was calculated by Theil–Sen’s Approach (TSA) (Theil 1950; Sen 1968):

$$\beta = \text{Median}\left(\frac{x_j - x_i}{j - i}\right) \quad \forall i < j \quad (14)$$

In Eq. (14), $1 < i < j < n$ and x_i and x_j are the observed i^{th} and j^{th} data, respectively. The positive value β represents an increasing trend and vice versa; the negative value of this parameter represents a decreasing trend for data series (Kumar et al. 2009).

In the present study, the time series of nine drought indices were obtained for each station. First, the capability of the mentioned indices was compared. Then the superior drought index was selected, and it was used for trend analysis of wet and dry periods. For trend analysis, the initial and modified versions of the Mann–Kendall test were applied. Also, the trend magnitude in the studied time series was determined by the Theil–Sen’s slope approach.

3 Results and Discussion

3.1 Selection of Superior Drought Index

Due to defining CQG for studied drought indices, it is able to investigate the relationship between studied indices. Therefore, to assess the performance of studied indices and compare them, the determination coefficient between the SPI index and the other eight indices are reported in Table 4. Although the SPI, SPI2, and SPI3 indices have similar classification limits, their different results in this table can be explained regarding their different calculations. In fact, in the SPI index, the precipitation data were transformed to Normal distribution. In other words, the distribution of precipitation data was considered. According to this table, the linear relationship between the mentioned indices with SPI has been increased, and consequently, the value of the determination coefficient (R^2) has been improved (from 0.966 to 0.973) by using the average value (for calculation of SPI2 index) instead of median value (for calculation of SPI3 index). Moreover, it is necessary to note that the difference between SPI and Z-score indices is based on the different classification limits. Besides this study, in Wu et al.’s (2001) study, $R^2 > 0.9$ resulted between annual SPI and CZI in studied stations. However, the value of R^2 can not only describe the linear relationship between studied indices. The values of $R^2 > 0.9$ in Table 4 shows the good linear relationship between studied indices with the SPI but give no detail and complete information. Therefore, in addition to the

Table 4 Determination coefficient between SPI index and eight other indices

SPI vs Index	R^2
SPI vs SPI2	0.973
SPI vs SPI3	0.966
SPI vs RAI	0.970
SPI vs DI	0.950
SPI vs PNPI	0.924
SPI vs Z-score	0.960
SPI vs CZI	0.980
SPI vs MCZI	0.957
SPI vs SPI2	0.973

R^2 values, a graphical relationship between indices in three different classes (drought, normal and wet) is needed. The values of the SPI index (as the base index) against the values of other studied indices for all selected stations are shown in Fig. 2. In other words, Fig. 2 shows the scatter diagrams between the classified values of the SPI index and classified values of eight indices. As seen in Fig. 2, opposite of Table 4, except CZI and MCZI indices, there was no linear relationship between the time series of studied indices and the SPI time series, and each index showed a unique behavior. Similar to Table 4, Fig. 2 shows that the linear deviation of SPI3 from SPI was more than SPI2. This deviation is based on the use of the median value in the calculation of SPI3 instead of the mean value. According to this figure, the value of R^2 is the highest in the Normal period compared to wet and dry periods. The results of Fig. 2 show the insufficiency of Table 4 results and also show that the relationship between indices in different periods was different.

Moreover, to select the suitable index, the probability density function (PDF) of dry and wet periods was considered based on the CQG drought events classification (Table 3) for all nine drought indices and studied stations. Figure 3 shows the PDF of dry and wet periods for nine drought indices in all studied stations. Based on Fig. 3, the PDF of dry and wet periods in SPI, SPI2, SPI3, PNPI, CZI, and MCZI indices was similar to the PDF of the Normal distribution. In fact, 68% of mentioned indices have been placed in the Normal class, and the sum of other values probability in wet or dry classes was equal (16%). The PDF of wet and dry periods based on RAI, Z-score, and DI indices had approximately symmetric form and a few ranges of variation. The probability of normal state ($CQG=0$) in the three mentioned indices was approximately 40%, and the sum of the probability of both of the different wet or dry states was approximately 30% (about two times of six mentioned indices). In other words, the more severe wet and dry periods were reported on the basis of these indices. Overall, the indices with a PDF similar to PDF of Normal distribution are more acceptable to analyze the drought as a natural phenomenon. Therefore, RAI, Z-score, and DI indices cannot correctly determine the class of drought. However, these mentioned indices cannot be a good candidate for the appropriate index because of non-following from Normal distribution. Therefore, these mentioned indices were not considered in the following steps, and the residual indices were compared to each other.

In order to select the best index among residual five indices, their sensitivities to drought analysis of minimum precipitation were examined. The calculated values based on mentioned indices for minimum recorded precipitation data in all studied stations are presented as a box plot diagram (minimum, 25%, 50%, 75%, and maximum) in Fig. 4. Based on the results of this figure, in the majority of stations and the process of drought analysis based on minimum precipitation, the SPI index was more sensitive than others. The minimum calculated values for CZI and MCZI indices correspond to Bushehr station. In drought analysis based on minimum precipitation, MCZI and SPI2 indices had considerable efficiency, and they were more sensitive than CZI and SPI3 indices. Therefore, the use of SPI2 instead of SPI3 (using the average value instead of the median value) and MCZI instead of CZI (using the median value instead of the average value) are recommended.

The results of the correlation coefficient (R) between the SPI index and precipitation data are presented in Table 5 to ensure the correct selection of the SPI index in the studied area. The values of the correlation coefficient, more than 0.920, confirm the capability of the selected index (SPI) for the drought analysis. Therefore, the trend of the selected index can express the trend of wet and dry periods in Iran. Similar to this study, the SPI was chosen as a suitable drought index for drought analysis in Pakistan (Adnan et al. 2018).

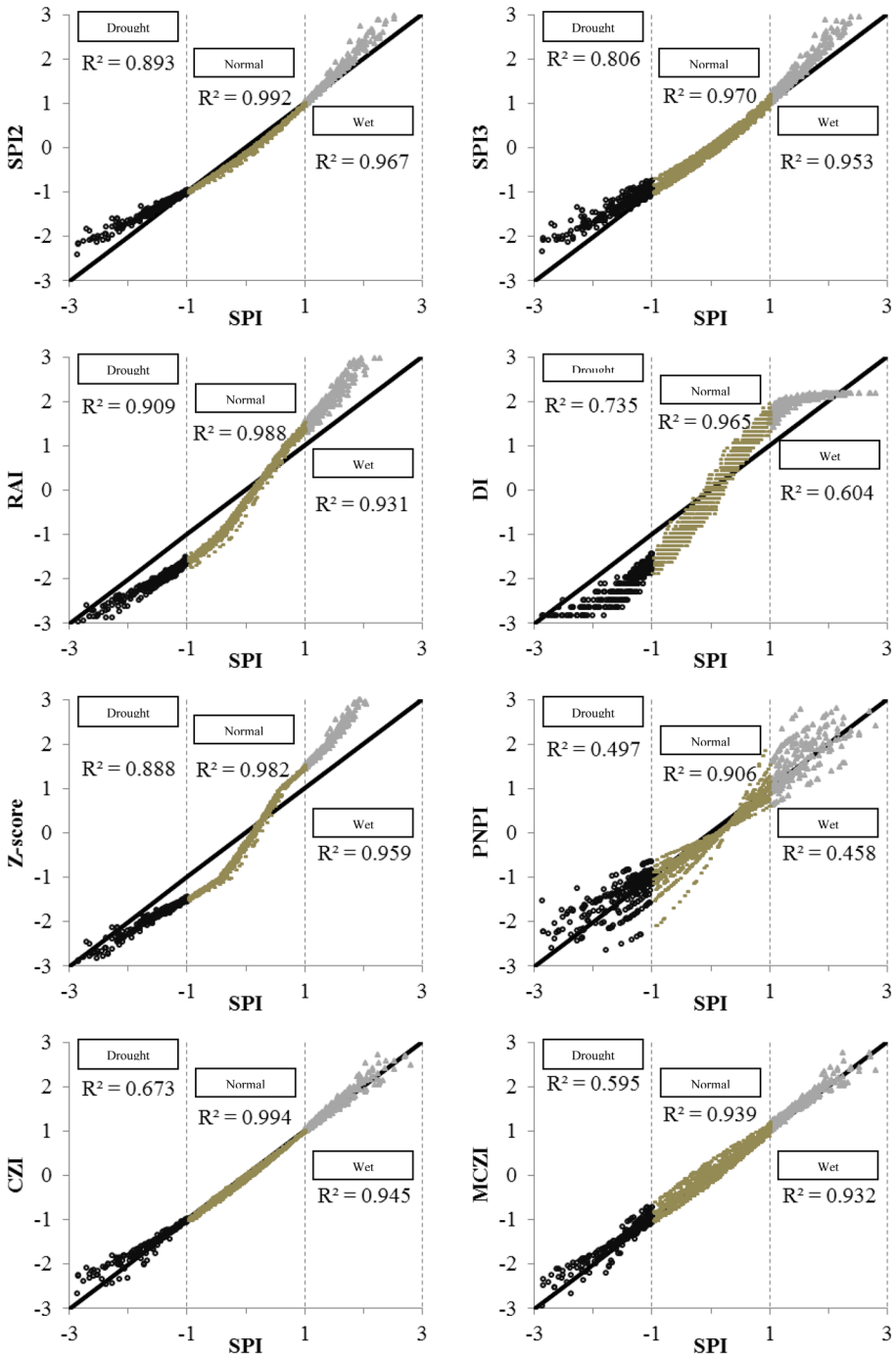


Fig. 2 Values of SPI index against the values of other eight studied indices for all selected stations

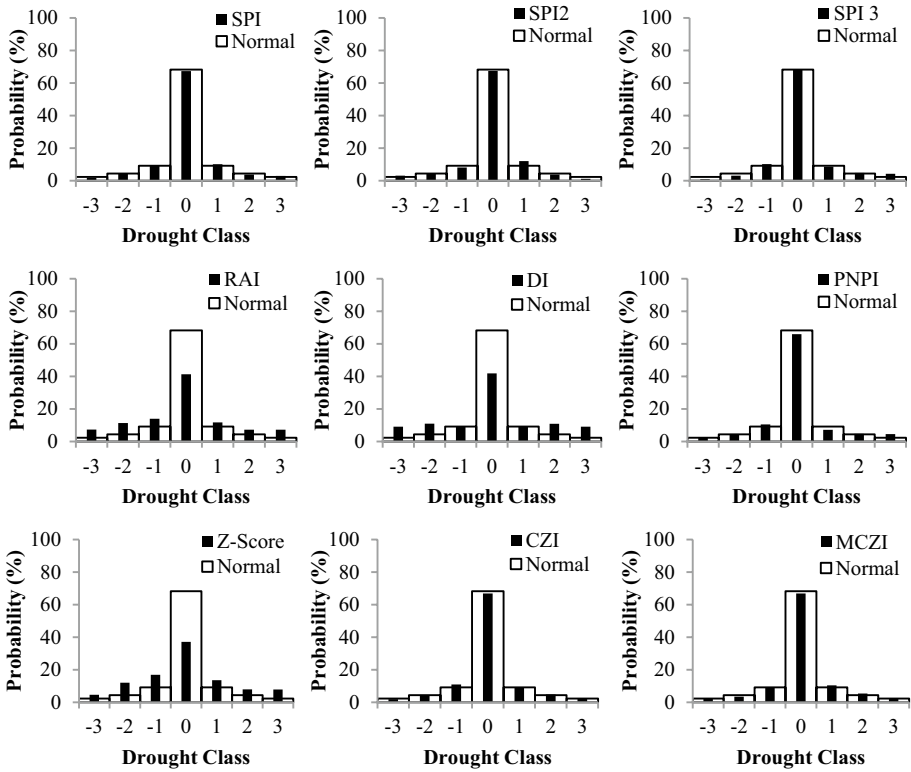


Fig. 3 Probability density function (PDF) of dry and wet periods based on nine studied indices in comparison with the PDF of normal distribution

It should be noted that the obtained results will be correct for precipitation-based indices. In other words, the conclusion does not include other indices such as RDI or SPEI, which need evapotranspiration and precipitation data.

Fig. 4 Calculated values based on the SPI, SPI2, SPI3, PNPI, CZI and MCZI indices for minimum recorded precipitation data in all studied stations

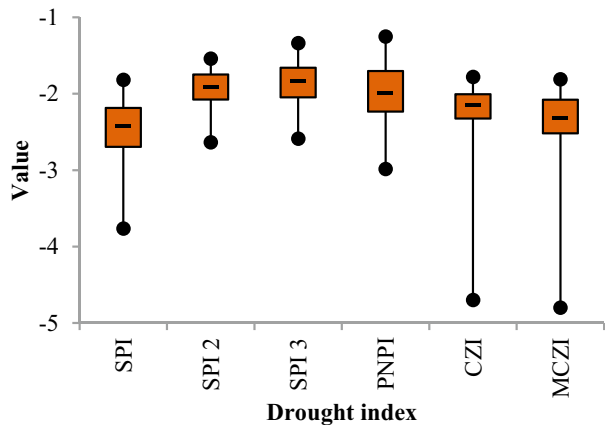


Table 5 Correlation coefficient (R) between SPI and precipitation values in all studied stations

Station	R	Station	R	Station	R
Abadan	0.983	Tehran	0.993	Qazvin	0.994
Ahvaz	0.983	Yazd	0.976	Sanandaj	0.991
Bam	0.979	Zahedan	0.987	Shahrekord	0.994
Bandarabbas	0.921	Arak	0.992	Shiraz	0.985
Birjand	0.990	Hamedan	0.989	Tabriz	0.993
Bushehr	0.954	Kermanshah	0.993	Torbate-heydarieh	0.991
Esfahan	0.985	Khorrarnabad	0.994	Zanjan	0.992
Kerman	0.982	Khoy	0.993	Babolsar	0.996
Sabzevar	0.990	Mashhad	0.994	Ramsar	0.997
Shahrud	0.986	Urmia	0.993	Rasht	0.997

3.2 Drought Monitoring

Figure 5 illustrates the wet or dry conditions of studied stations each year. This figure shows the number of stations that are located in one of the defined classes (Table 3) on the basis of the SPI index results. As seen, in 10 years of the studied period (~ 18%), including 1968, 1969, 1972, 1976, 1977, 1982, 1984, 1986, 1992, and 2004, no drought (moderate, severe, and extreme) happened in the studied stations, but in other years, minimum one drought was reported in each station. At some years, for example, in 1960, 1973, 1990, 2001, 2008, and 2010, drought occurrences were monitored in 15, 18, 15, 18 and 17 stations, respectively (at minimum 50% of stations (15 cases)). The SPI values also showed that there was an extreme drought in 1960–1962, 1964, 1966–1967, 1970, 1973, 1985, 1987, 1989–1990, 1995, 2001, 2005, 2008, and 2010 in some of the stations. Generally, on the basis of the values of the SPI index in Fig. 5, there was a minimum of one drought in the majority of studied years (~82%), which confirms that the drought condition had governed the studied area, especially in 2008 and 2010.

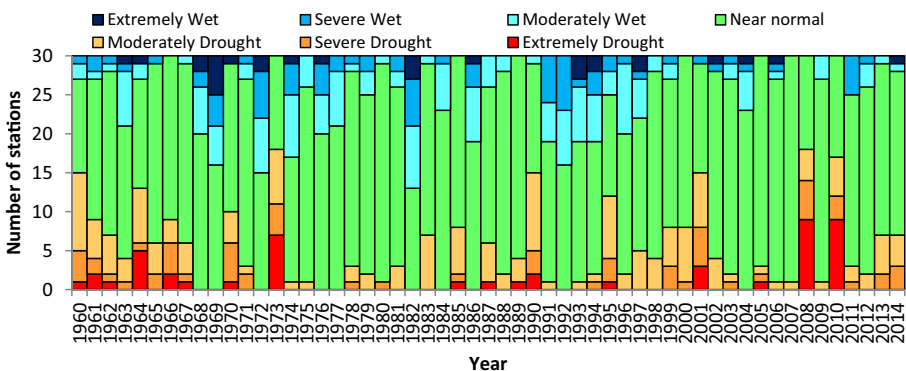


Fig. 5 Wet or dry condition of studied stations at each year

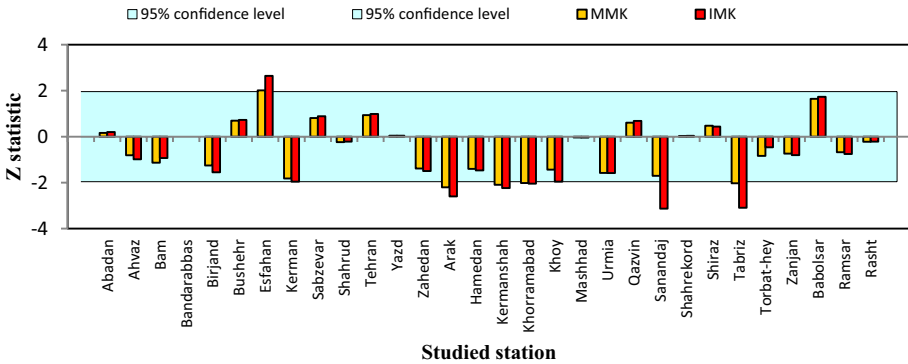


Fig. 6 Values of initial (IMK) and modified (MMK) Mann–Kendall tests for the SPI index

3.3 Trend Analysis

The results of trend analysis of wet and dry periods, which were calculated using the initial (IMK) or modified Mann–Kendall (MMK) tests in the studied area, are presented in Fig. 6. As shown in this figure, on the basis of both the initial and modified Mann–Kendall tests, the trend of SPI index was negative (decreasing trend) in 19 stations and was positive (increasing trend) in 10 stations. The trend value of this index in Bandarabbas station was zero ($Z=0$). The results of two methods showed that the positive trend of SPI was significant (at 95% confidence level) only in Esfahan station. On the basis of the results of initial and modified Mann–Kendall tests, the negative trend of SPI was significant (at 95% confidence level) in seven and four stations, respectively. Therefore, not only the trend value but also the number of stations that had a significant trend was changed by using the modified Mann–Kendall test (with removing all significant autocorrelation coefficients). Figures 7 and 8 show the effect of significant autocorrelation coefficients on the results of trend values which were obtained using the modified Mann–Kendall test in comparison with the results, which were calculated using the initial Mann–Kendall test. As shown in these

Fig. 7 Box plot of initial (IMK) and modified (MMK) Mann–Kendall tests values for the SPI index

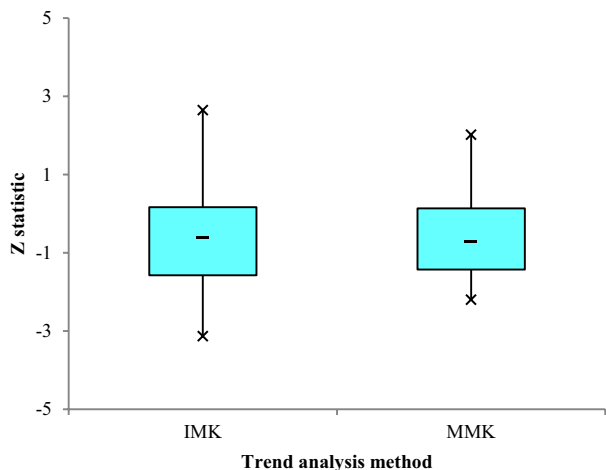


Fig. 8 Linear relationship between the values of initial (IMK) and modified (MMK) Mann–Kendall tests for the SPI index

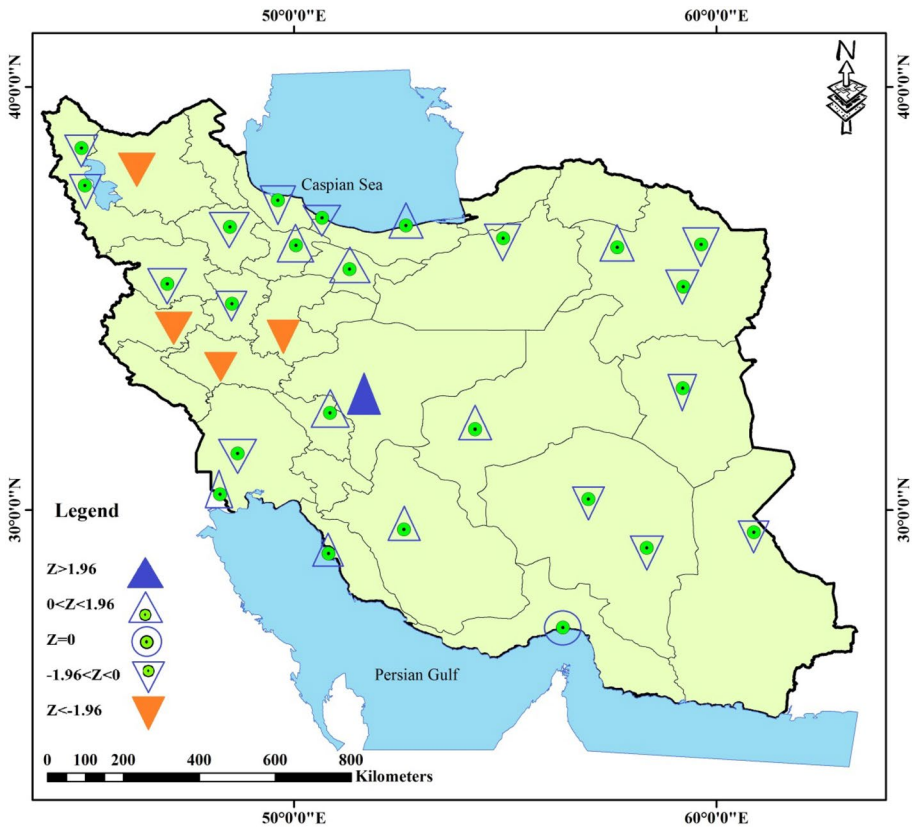
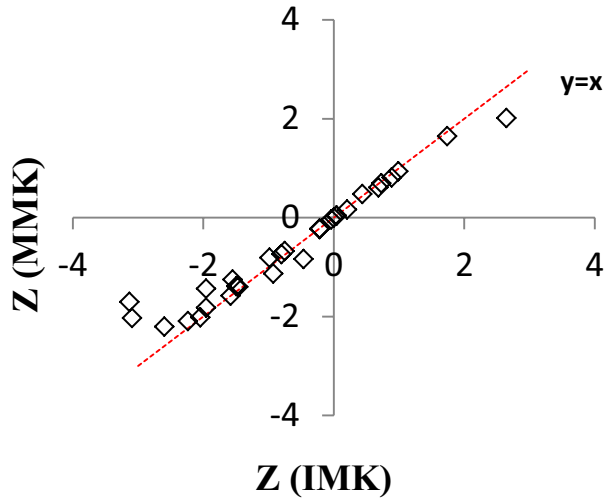


Fig. 9 Spatial distribution of wet and dry periods trend on the basis of SPI index (the values of modified Mann–Kendall test)

Table 6 Values of trend line slope for SPI index

Station	β (mm/year)	Station	β (mm/year)	Station	β (mm/year)
Abadan	0.002	Tehran	0.010	Qazvin	0.007
Ahvaz	-0.008	Yazd	0.001	Sanandaj	-0.024
Bam	-0.009	Zahedan	-0.014	Shahrekord	0.000
Bandarabbas	0.000	Arak	-0.023	Shiraz	0.004
Birjand	-0.015	Hamedan	-0.014	Tabriz	-0.027
Bushehr	0.006	Kermanshah	-0.020	Torbat-heydarieh	-0.004
Esfahan	0.025	Khorramabad	-0.020	Zanjan	-0.007
Kerman	-0.015	Khoy	-0.017	Babolsar	0.016
Sabzevar	0.009	Mashhad	-0.001	Ramsar	-0.007
Shahrud	-0.002	Urmia	-0.013	Rasht	-0.002

figures, there was a linear relationship between the positive values of Z statistic, which were calculated using both the initial and modified Mann–Kendall tests. But there was not this relationship between negative values of Z. Therefore, for correct analysis of the trend which exists in hydrological time series, all significant autocorrelation coefficients should be attended.

Figure 9 shows the spatial distribution of dry and wet periods trend based on the SPI drought index calculated by the modified Mann–Kendall test (the trend of wet and dry periods). This figure shows that the SPI trend was negative in the west, east, southeast, northeast, and northwest of Iran, but the SPI trend was positive in the south, some northern and central parts of Iran. Besides this study, the results of Tabari et al. (2012) also showed that, during 1966–2005, the annual trend of SPI in the majority of stations located in the east of Iran, was negative. The results of this figure also show that in studied stations located in Urmia Lake Basin, the trend of dry and wet periods was negative. Based on the results of the SPI trend, the reduction of water in Urmia Lake is reasonable.

The values of trend line slope for the SPI index are presented in Table 6. The values of this slope for SPI index were negative in the majority of stations. The maximum negative and positive values of this index correspond to Tabriz and Esfahan stations, respectively.

Similar to the obtained results, Tabari et al. (2012) and Nikbakht et al. (2013) reported the reduction for the SPI and PNI indices at most of the studied stations of Iran, respectively.

4 Conclusions

In this study, using annual precipitation data in 30 stations in Iran, nine precipitation-based drought indices including SPI, SPI2, SPI3 (introduced in this study), RAI, DI, PNPI, Z-score, CZI, and MCZI were compared. The SPI index was determined as the best index. On the basis of the results of the SPI index, drought monitoring of the studied area was assessed, and the obtained results showed that the studied area was faced with drought conditions, especially in 2008 and 2010.

Then, on the basis of the results of the SPI index, the annual trend analysis was conducted using the initial and modified Mann–Kendall tests. The trend analysis results showed the decreasing trend of the SPI index in the majority of studied stations. In the west

and northwest of Iran, this decreasing trend was significant at a 95% confidence level. But the SPI index had an increasing trend in south and some parts of north and central of Iran. The positive trend of this index in Esfahan station was significant (95% confidence level). The values of the trend slope of the SPI index in most of the studied stations were negative. The maximum positive and negative values of trend line slope were observed in Esfahan and Tabriz stations, respectively. On the basis of the obtained results, for acceptable trend analysis of the SPI drought index, all significant autocorrelation coefficients must be removed.

Finally, results indicated that to correctly assess the drought, the existence indices should be compared and the best index should be selected.

For future studies, it is recommended that other indices, especially agricultural drought indices, are compared with each other, and the best index is selected for arid or semiarid regions such as Iran. Also, the comparison of meteorological and agricultural drought indices can be an interesting issue. In addition, the effect of climate change on drought conditions can be a pertinent issue that helps programmers to have a view of future conditions to make the right decisions and consequently reduce the possible damages.

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Declarations

Ethical Approval The authors certify that the submission is not under review at any other publication.

Consent to Publish The authors would like to publish their article in the Water Resources Management journal.

Consent to Participate This paper should be of interest to a broad readership, including those interested in water resources engineering.

Conflicts of Interest/Competing Interests The authors declare that there are no conflicts of interest/Competing interests in the manuscript.

References

- Adeloye AJ, Montaseri M (2002) Preliminary streamflow data analyses prior to water resources planning study. *J Hydrol Sci* 47:679–692. <https://doi.org/10.1080/02626660209492973>
- Adnan S, Ullah K, Shuanglin L, Gao S, Hayat Khan A, Mahmood R (2018) Comparison of various drought indices to monitor drought status in Pakistan. *Clim Dyn* 51:1885–1899. <https://doi.org/10.1007/s00382-017-3987-0>
- Achite M, Krakauer NY, Wałęga A, Caloiero T (2021) Spatial and Temporal Analysis of Dry and Wet Spells in the Wadi Cheliff Basin, Algeria. *Atmos* 12:1–16. <https://doi.org/10.3390/atmos12060798>
- Al-Faraj FAM, Tigkas D (2016) Impacts of multi-year droughts and upstream human-induced activities on the development of a semiarid transboundary basin. *Water Resour Manage* 30:5131–5143. <https://doi.org/10.1007/s11269-016-1473-9>
- Asadi-Zarch MA, Malekinezhad H, Mobin MH, Dastorani MT, Kousari MR (2011) Drought monitoring by Reconnaissance Drought Index (RDI) in Iran. *J Water Resour Manage* 25:3485–3504. <https://doi.org/10.1007/s11269-011-9867-1>

- Asadi-Zarch MA, Sivakumar B, Sharma A (2015) Droughts in a warming climate: A global assessment of Standardized Precipitation Index (SPI) and Reconnaissance Drought Index (RDI). *J Hydrol* 526:183–195. <https://doi.org/10.1016/j.jhydrol.2014.09.071>
- Bars RL (1990) *Hydrology: an introduction to hydrologic science*. Addison-Wesley, New York
- Byakatonda J, Parida BP, Moalafhi DB, Kenabatho PK (2018) Analysis of long term drought severity characteristics and trends across semi-arid Botswana using two drought indices. *Atmos Res* 213:492–508. <https://doi.org/10.1016/j.atmosres.2018.07.002>
- Belayneh A, Adamowski J, Khalil B (2016) Short-term SPI drought forecasting in the Awash River Basin in Ethiopia using wavelet transforms and machine learning methods. *J Sustain Water Resour Manage* 2:87–101. <https://doi.org/10.1007/s40899-015-0040-5>
- Bonaccorso B, Bordi I, Cancelliere A, Rossi G, Sutera A (2003) Spatial variability of drought: an analysis of the SPI in Sicily. *J Water Resour Manage* 17:273–296. <https://doi.org/10.1023/A:1024716530289>
- Dinpashoh Y, Mirabbasi R, Jhajharia D, Abianeh HZ, Mostafaeipour A (2013) Effect of short-term and long-term persistence on identification of temporal trends. *J Hydrol Eng* 19(3):617–625. [https://doi.org/10.1061/\(ASCE\)HE.1943-5584.0000819](https://doi.org/10.1061/(ASCE)HE.1943-5584.0000819)
- Dogan S, Berktaş A, Singh VP (2012) Comparison of multi-monthly rainfall-based drought severity indices, with application to semi-arid Konya closed basin, Turkey. *J Hydrol* 470–471:255–268. <https://doi.org/10.1016/j.jhydrol.2012.09.003>
- Edwards DC, Mckee TB (1997) Characteristics of 20th century drought in the United State at multiple time scales. *J Atmos Sci* 634:1–30
- Gibbs WJ, Maher JV (1967) Rainfall deciles as drought indicators. Bureau of Meteorology, Bulletin No. 48, Commonwealth of Australia, Melbourne, Australia
- Hamed KH, Rao AR (1998) A modified Mann-Kendall trend test for autocorrelated data. *J Hydrol* 204:182–196. [https://doi.org/10.1016/S0022-1694\(97\)00125-X](https://doi.org/10.1016/S0022-1694(97)00125-X)
- Jain VK, Pandey RP, Jain MK, Byun HR (2015) Comparison of drought indices for appraisal of drought characteristics in the Ken River Basin. *J Weather Clim Extrem* 8:1–11. <https://doi.org/10.1016/j.wace.2015.05.002>
- Ju XS, Yang XW, Chen LJ, Wang YM (1997) Research on determination of station indexes and division of regional flood/drought grades in China. *Q J Appl Meteorol* 8(1):26–33. (in Chinese)
- Keetch JJ, Byram GM (1968) A drought index for forest fire control. United States Department of Agriculture Forest Service Research Paper SE-38, Southeastern Forest Experiment Station, Asheville, NC
- Kendall MG (1975) Rank correlation measures. Charles Griffin Inc., London
- Kendall MG, Stuart A (1977) *The Advanced Theory of Statistics*. Charles Griffin Company, London, High Wycombe 400–401
- Khalili D, Farnoud T, Jamshidi H, Kamgar-Haghighi AA, Zand-Parsa S (2011) Comparability analyses of the SPI and RDI meteorological drought indices in different climatic zones. *J Water Resour Manage* 25:1737–1757. <https://doi.org/10.1007/s11269-010-9772-z>
- Khanmohammadi N, Rezaie H, Montaseri M, Behmanesh J (2017a) The effect of temperature adjustment on reference evapotranspiration and Reconnaissance Drought Index (RDI) in Iran. *J Water Resour Manage* 31:5001–5017. <https://doi.org/10.1007/s11269-017-1793-4>
- Khanmohammadi N, Rezaie H, Behmanesh J (2017b) The spatial-temporal variation of dry and wet periods in Iran based on comparing SPI and RDI indices. *J Stoch Environ Res Risk Assess* 32:2771–2785. <https://doi.org/10.1007/s00477-018-1594-1>
- Khanmohammadi N, Rezaie H, Montaseri M, Behmanesh J (2017c) The effect of reference-condition-based temperature modification on the trend of reference evapotranspiration in arid and semi-arid regions. *J Agric Water Manage* 194:204–213. <https://doi.org/10.1016/j.agwat.2017.09.010>
- Khezri F, Irandoost M, Jalalkamali N, Yazdanpanah N (2021) Modelling of bivariate meteorological drought analysis in Lake Urmia Basin using Archimedean copula functions. *Meteorol Appl* 28:1–13. <https://doi.org/10.1002/met.2040>
- Kumar S, Merwade V, Kam J, Thurner K (2009) Streamflow trends in Indiana: effects of long term persistence, precipitation and subsurface drains. *J Hydrol* 374:171–183. <https://doi.org/10.1016/j.jhydrol.2009.06.012>
- Kutiel H, Maheras P, Guika S (1996) Circulation and extreme rainfall conditions in the eastern Mediterranean during the last century. *Int J Climatol* 16(1):73–92
- Mann HB (1945) Non-parametric test against trend. *J Econom* 13:245–259
- Mathbout S, Lopez-Bustins JA, Martin-Vide J, Bech J, Rodrigo FS (2018) Spatial and temporal analysis of drought variability at several time scales in Syria during 1961–2012. *Atmos Res* 200:153–168. <https://doi.org/10.1016/j.atmosres.2017.09.016>
- McGuire JK, Palmer WC (1957) The 1957 drought in the eastern United States. *Mon Weather Rev* 85(9):305–314. [https://doi.org/10.1175/1520-0493\(1957\)085%3c0305:TDITEU%3e2.0.CO;2](https://doi.org/10.1175/1520-0493(1957)085%3c0305:TDITEU%3e2.0.CO;2)

- McKee TB, Doesken NY, Kleist Y (1993) The relationship of drought frequency and duration to time scales. 8th Conference on Applied Climatology, Anaheim, CA, 179–184
- Mohammed Y, Yimam A (2021) Analysis of meteorological droughts in the Lake's Region of Ethiopian Rift Valley using reconnaissance drought index (RDI). *Geoenviron Dis* 8:1–16. <https://doi.org/10.1186/s40677-021-00183-1>
- Moreira EE, Paulo AA, Pereira LS, Mexia JT (2006) Analysis of SPI drought class transitions using log-linear models. *J Hydrol* 331:349–359. <https://doi.org/10.1016/j.jhydrol.2006.05.022>
- Morid S, Smakhtin V, Moghaddasi M (2006) Comparison of seven meteorological indices for drought monitoring in Iran. *Int J Climatol* 26:971–985. <https://doi.org/10.1002/joc.1264>
- Mpelasoka F, Hennessy K, Jones R, Bates B (2008) Comparison of suitable drought indices for climate change impacts assessment over Australia towards resource management. *Int J Climatol* 28:1283–1292. <https://doi.org/10.1002/joc.1649>
- Nikbakht J, Tabari H, Hosseinzadeh Talaei P (2013) Streamflow drought severity analysis by percent of normal index (PNI) in northwest Iran. *J Theor Appl Climatol* 112:565–573. <https://doi.org/10.1007/s00704-012-0750-7>
- Nitzche MH, Silva BB, Martinez AS (1985) Indicativo De Ano Seco E Chuvoso. Sociedade Brasileira de Agrometeorologia: Londrina, Brazil 307–314
- Palmer WC (1965) Meteorological drought. Weather Bureau Research Paper No. 45, US Department of Commerce, Washington, DC, 58 pp
- Palmer WC (1968) Keeping track of crop moisture conditions, nationwide: the new crop moisture index. *Weatherwise* 21:156–161. <https://doi.org/10.1080/00431672.1968.9932814>
- Paulo AA, Rosa RD, Pereira LS (2012) Climate trends and behaviour of drought indices based on precipitation and evapotranspiration in Portugal. *Nat Hazards Earth Syst Sci* 12:1481–1491. <https://doi.org/10.5194/nhess-12-1481-2012>
- Pham QB, Yang TC, Kuo CM, Tseng HW, Yu PS (2021) Coupling Singular Spectrum Analysis with Least Square Support Vector Machine to Improve Accuracy of SPI Drought Forecasting. *J Water Resour Manage* 35:847–868. <https://doi.org/10.1007/s11269-020-02746-7>
- Quiring SM, Papakryiakou TN (2003) An evaluation of agricultural drought indices for the Canadian prairies. *J Agricul Forest Meteorol* 118:49–62. [https://doi.org/10.1016/S0168-1923\(03\)00072-8](https://doi.org/10.1016/S0168-1923(03)00072-8)
- Rawat KS, Tripathi VK (2016) Standardized precipitation index based approach for development of regional drought monitoring system. *J Remote Sens Technol* 4:48–57. <https://doi.org/10.18005/JRST0401004>
- Sen PK (1968) Estimates of the regression coefficient based on Kendall's tau. *J Am Stat Assoc* 63:1379–1389. <https://doi.org/10.2307/2285891>
- Shiau JT (2020) Effects of Gamma-Distribution Variations on SPI-Based Stationary and Nonstationary Drought Analyses. *J Water Resour Manage*. <https://doi.org/10.1007/s11269-020-02548-x>
- Silva Y, Takahashi K, Chávez R (2008) Dry and wet rainy seasons in the Mantaro River basin (central Peruvian Andes). *Adv Geosci* 14:261–264
- Simmonds I, Hope P (1997) Persistence characteristics of Australian rainfall anomalies. *Int J Climatol* 17:597–613
- Tabari H, Abghari H, Hosseinzadeh Talaei P (2012) Temporal trends and spatial characteristics of drought and rainfall in arid and semiarid regions of Iran. *J Hydrol Process* 26:3351–3361. <https://doi.org/10.1002/hyp.8460>
- Theil H (1950) A rank-invariant method of linear and polynomial analysis. part 3. *Nederlandse Akademie Van Wetenschappen, Proceedings* 53:1397–1412
- Tigkas D, Vangelis H, Tsakiris G (2019) Drought characterisation based on an agriculture-oriented standardised precipitation index. *Theor Appl Climatol* 135:1435–1447. <https://doi.org/10.1007/s00704-018-2451-3>
- Tsakiris G, Pangalou D, Vangelis H (2007) Regional drought assessment based on the reconnaissance drought index (RDI). *J Water Resour Manage* 21:821–833. <https://doi.org/10.1007/s11269-006-9105-4>
- Van Rooy MP (1965) A rainfall anomaly index independent of time and space. *Notes* 14:43–48
- Vicente-Serrano SM, Cuadrat-Prats JM (2007) Trends in drought intensity and variability in the middle Ebro valley (NE of the Iberian peninsula) during the second half of the twentieth century. *Theor Appl Climatol* 88:247–258. <https://doi.org/10.1007/s00704-006-0236-6>
- Vicente-Serrano SM, González-Hidalgo JC, de Luis M, Raventós J (2004) Drought patterns in the Mediterranean area: the Valencia region (eastern Spain). *Climate Res* 26:5–15. <https://doi.org/10.3354/cr026005>
- Vicente-Serrano SM, Beguería S, López-Moreno JI (2010) A multiscalar drought index sensitive to global warming: the standardized precipitation evapotranspiration index. *J Climate* 23:1696–1718. <https://doi.org/10.1175/2009JCLI2909.1>
- Wable PS, Jha MK, Shekhar A (2019) Comparison of drought indices in a semiarid river basin of India. *J Water Resour Manage* 33:75–102. <https://doi.org/10.1007/s11269-018-2089-z>
- Willeke G, Hosking JRM, Wallis JR, Guttman NB (1994) The National Drought Atlas. Institute for Water Resources Report 94-NDS-4, U.S. Army Corps of Engineers

- Wu H, Hayes MJ, Welss A, Hu Q (2001) An evaluation the standardized precipitation index, the china-z index and the statistical z-score. *Int J Climatol* 21:745–758. <https://doi.org/10.1002/joc.658>
- Xu ZX, Takeuchim K, Ishidaira H (2003) Monotonic trend and step changes in Japanese precipitation. *J Hydrol* 279:144–150. [https://doi.org/10.1016/S0022-1694\(03\)00178-1](https://doi.org/10.1016/S0022-1694(03)00178-1)
- Yerdelen C, Abdelkader M, Eris E (2021) Assessment of drought in SPI series using continuous wavelet analysis for Gediz Basin, Turkey. *J Atmos Res* 260:1–11. <https://doi.org/10.1016/j.atmosres.2021.105687>
- Yue S, Pilon P, Cavadias G (2002a) Power of the Mann-Kendall and Spearman's tests for detecting monotonic trends in hydrological series. *J Hydrol* 259:254–271. [https://doi.org/10.1016/S0022-1694\(01\)00594-7](https://doi.org/10.1016/S0022-1694(01)00594-7)
- Yue S, Pilon P, Phinney B, Cavadias G (2002b) The influence of autocorrelation on the ability to detect trend in hydrological series. *Hydrol Process* 16:1807–1829. <https://doi.org/10.1002/hyp.1095>
- Zhang Q, Xu CY, Zhang Z (2009) Observed changes of drought/wetness episodes in the Pearl River basin, China, using the standardized precipitation index and aridity index. *Theor Appl Climatol* 98:89–99. <https://doi.org/10.1007/s00704-008-0095-4>

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