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Research papers

Evaluating the sensitivity of precipitation-based drought indices to different lengths of record

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A R T I C L E I N F O

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A B S T R A C T

Nowadays, preparing long-term data is one of the main concerns of researchers in many countries. Many hydro-climatological studies have reported that at least 30-year data are required for such studies. Unfortunately, it is impossible to provide 30-year data in many countries (even developed countries). Even the recording the precipitation data in many of the regions varies from one station to another station. There are also regions which cannot be ignored due to data for less than 30 years. The objective of this research was to evaluate the sensitivity of the seven different precipitation-based drought indices, including the China Z Index (CZI), the Modified China Z Index (MCZI), Percent of Normal Precipitation Index (PNPI), Deciles Index (DI), the Z-score Index (ZSI), Effective Drought Index (EDI), and Standardized Precipitation Index (SPI) to different lengths of record at monthly, seasonal, and annual time scales. In this research, monthly, seasonal, and annual precipitation data of 8 meteorological stations representing eight different climate classes in Iran were used for a 55-year period (1960–2014). For each of the monthly, seasonal, and annual time scales, the lengths of record 55, 50, 45, 40, 35, and 30 years were extracted from the main period (1960–2014), which each of these lengths was lengths ending to 2014. First, the correlation coefficient of the indices was obtained for all lengths of record. Then, match and non-match of the indices obtained from the longer lengths of record with the values obtained from shorter lengths of record were investigated for all three-time scales. Finally, the unique drought and flood years of stations were compared for the time scales. The results revealed that better time stability was seen in the Effective Drought Index (EDI) and Z-score Index (ZSI) compared to other indices in the monthly time scale. It means that the sensitivity of these two indices to different lengths of record was less. Percentage of Normal Precipitation Index (PNPI) in two seasonal and annual scales also shows the lowest sensitivity was seen among the studied indices. However, Deciles Index (DI) and the Modified China Z Index (MCZI) were two indices, which had the highest sensitivity to different lengths of record among other indices. It means that these two indices have more sensitivity to lengths of record studied and they should be used carefully.

1. Introduction

Water-related natural disasters pose major impediments to achieving human security and sustainable socio-economic development (WWAP, 2012). Droughts are one of the most complicated and at the same time the most unknown water-related natural disasters that humans grapple with (Hagman, 1984). This phenomenon has the greatest effect on human activities compared to other natural hazards (Wilhite, 1987; Kogan, 1997; Salami, 2004). The drought's effects are basically non-structural, their spatial extension is wide, and the extent of their damage is much greater compared to other water-related natural disasters. These non-structural effects of droughts have been a major obstacle to the development of timely, reliable and accurate estimates of the severity of droughts so that setting up and preparing any drought preparedness plan in many countries have become difficult (Chopra, 2006).

Nearly all regions of the world with various climates have suffered from drought; however, its effects and frequencies are more vivid in arid and semiarid regimes. Specifying the characteristics of droughts and wetness in these regions can be considered as one of the essential needs of planners for water resources management. The vast country of Iran is located in one of these arid and semi-arid regions of the world, which great changes in the rate of precipitation, its high severity and distribution, and temperature fluctuations are considered as its characteristics. During recent years, precipitation anomalies have been increased in various regions in Iran due to the factors that are

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predominantly related to global climatic change. The increase in precipitation anomalies has caused changes in the temporal-spatial properties of Iran's droughts (Mahmoudi et al., 2019; Daneshmand and Mahmoudi, 2017). The results of these changes have been extravagant damages imposed onto the various economic, social and bioenvironmental sectors in this territory.

Hence, specifying a set of appropriate and accurate indices, which can be used to quantify and evaluate the severity and the breadth of drought in the country, has special importance. Several indices have been defined in various regions of the world to monitor the droughts, which base of all of them is climatic and environmental data, including Palmer Drought Severity Index (PDSI; Palmer, 1965), Deciles Index (DI; Gibbs and Maher, 1967), Crop Moisture Index (CMI; Palmer, 1968), Bhalme –Mooley Drought Index (BMDI; Bhalme and Mooley, 1980), Surface Water Supply Index (SWSI; Shafer and Dezman, 1982), Standardized Precipitation Index (SPI; McKee et al., 1993), Effective Drought Index (EDI; Byun and Wilhite, 1999), and Reclamination Drought Index (RDI; Tsakiris et al., 2007).

During the several past decades, the increase in the number of various indices of drought monitoring has led to an increase in the comparative studies of them, as well. The comparative study of several various indices provides the researchers with the possibility of comparing them thereby to become able to choose the best index for monitoring the study region's droughts to specify the accuracy, relationship, and integration of the relevant indices in respect to a special goal, as well. Amongst the most important studies performed in this regard, the researches by Mahmoudi et al. (2019), Dogan et al. (2012), Morid et al. (2006) and Wu et al. (2001) can be pointed out. In line with selecting the best index for monitoring Iran's droughts, Mahmoudi et al. (2019) compared seven drought precipitation-based indices in comparative research for various climates in Iran and concluded that the effective drought index (EDI) and standardized precipitation index (SPI) have had better performances than the other indices. These results were exactly the same as the findings attained by Morid et al (2006) in the designing of the drought monitoring system in Tehran Province in Iran. Wu et al. (2001), as well, concluded in a comparison of three indices, namely standardized precipitation index (SPI), China Z-Index and Z-score index, in various temporal scales for the arid and humid climates in China that all three indices have had identical results for all of the various temporal scales.

Palmer's Drought Severity Index (PDSI) was developed in 1965 by Palmer. The index has been used for 30 years as an appropriate tool for monitoring the droughts. Amongst the variables used in this index, temperature, precipitation, runoff, evaporation and transpiration as well as soil moisture can be pointed out. As an optimal executive index for monitoring systems, the index is faced with a lot of problems like the complexity of the calculations, doubts in the accuracy of the proposed water balance model, non-clarity of the temporal span and unclearness of its physical and statistical nature due to its need for a lot of information as pointed out by Kao and Govindaraju (2010). However, Colorado State University researchers offered a new probability index called as Standardized Precipitation Index (SPI) for better and accurate monitoring under the conditions of drought and wetness periods (McKee et al., 1993, 1995). The Standardized Precipitation Index (SPI) is calculable for different time intervals and it has high importance for providing early warning and helping to assess the drought severity.

This index is also an appropriate tool in analyzing the precipitation data and has been considered by many researchers and it is widely used for monitoring and zoning regional and local droughts around the world such as Iran (Karimpour et al., 2009; Raziei et al., 2009; Negaresh et al., 2010; Shahabfar and Eitzinger, 2013; Safari Shad et al., 2013; Akbari et al., 2015), the Mediterranean (Paulo and Pereira, 2007; Lana et al., 2001), Turkey (Keskin, 2009; Touchan et al., 2005; Komuscu, 1999), the United States (Guttman, 1999; Hayes et al., 1999; Keyantash et al., 2002), and other parts of the world (Ntale and Gan, 2003; Pandey et al., 2008; Patel et al., 2007; Roudier and Mahe, 2010). Considering the advantages of this index, which some of them were mentioned above, this index has several unique limitations and disadvantages, which they should be considered when using it. One of these limitations is the sensitivity of this index to the probability distributions used in it, since this index analyzes precipitation for monitoring droughts through gamma distribution, and this distribution might not be appropriate for all regions or stations investigated (Blain, 2011a). A few studies have been carried out so far on the selection of the best probability distribution for this index (Blain, 2011b in Brazil, Angelidis et al., 2012 in Portugal, Ntale and Gan, 2003 in East Africa). Another disadvantage of the Standardized Precipitation Index (SPI) is this index sensitivity to the lengths of the record used, which very limited number studies are seen in this regard (Mirabbasi et al., 2013). One of the most important studies conducted in this regard is the study of Wu et al. (2005). In this research, they showed that the percentage related to non-matches when the time scale of the data is longer, the differences would be more significant for some stations. Another result of this research is the match of SPI values for unique drought and flood years in short and long-term scales. Besides, SPI values obtained from longer lengths of record are correlated with SPI values obtained from shorter lengths of record for all time scales in the studied periods.

Now, it has been observed in a review of the subjective literature's resources of the present study that there are many strong and weak points of the various drought indices, especially standardized precipitation index (SPI), taken into account by many of the researches in such fields as hydrology, geography, meteorology, climatology, and agriculture. But, in between, one of the weak points to which less attention has been paid, is the sensitivity of the various drought indices to the length of the various temporal periods. Although Wu et al. (2005) have considered it for standard precipitation index (SPI), there is a need for being that much sensitive to the other indices, as well. Thus, the present study sought to investigate the sensitivity of SPI in addition to the sensitivities of other drought indices like ZSI, PN, DI, MCZI, CZI, and EDI to different lengths of record.

2. Study area and data

Given the specific geographical position and topography characteristics of each region of Iran, different climates govern it, so that based on the classification performed by Masoodian (2012), Iran can be divided into eight climatic regions (Fig. 1). In this research, one station representing that climate region was selected (Fig. 1).

In this research, monthly, seasonal, and annual precipitation data of the studied stations were used for a 55-year period (1960–2014). The names, geographical coordinates, mean annual temperatures, total means of the annual precipitation, establishment years and types of the used station have been presented in Table 1. The lengths of record 55, 50, 45, 40, 35 and 30 years were extracted from the main period (1960–2014) for each of the monthly, seasonal and annual time scales. It should be stated that each of these lengths was the lengths ending in 2014. The reason that the minimum length of the studied lengths was selected to be 30 years was that it is the most appropriate length of the record to calculate the SPI at best state of continuous lengths with minimum 30 years of data (McKee et al., 1993).

3. Methodology

The model and method used in this research were derived from the research carried out by Wu et al. (2005). They examined the impact lengths of record of data on calculation of Standardized Precipitation Index (SPI). In this research, drought indices were calculated for the mentioned time scales for all selected lengths of record. DIP software was used to calculate these indices. This software was offered by Morid et al. in 2007 drought monitoring. The indices used in the research are introduced in brief.

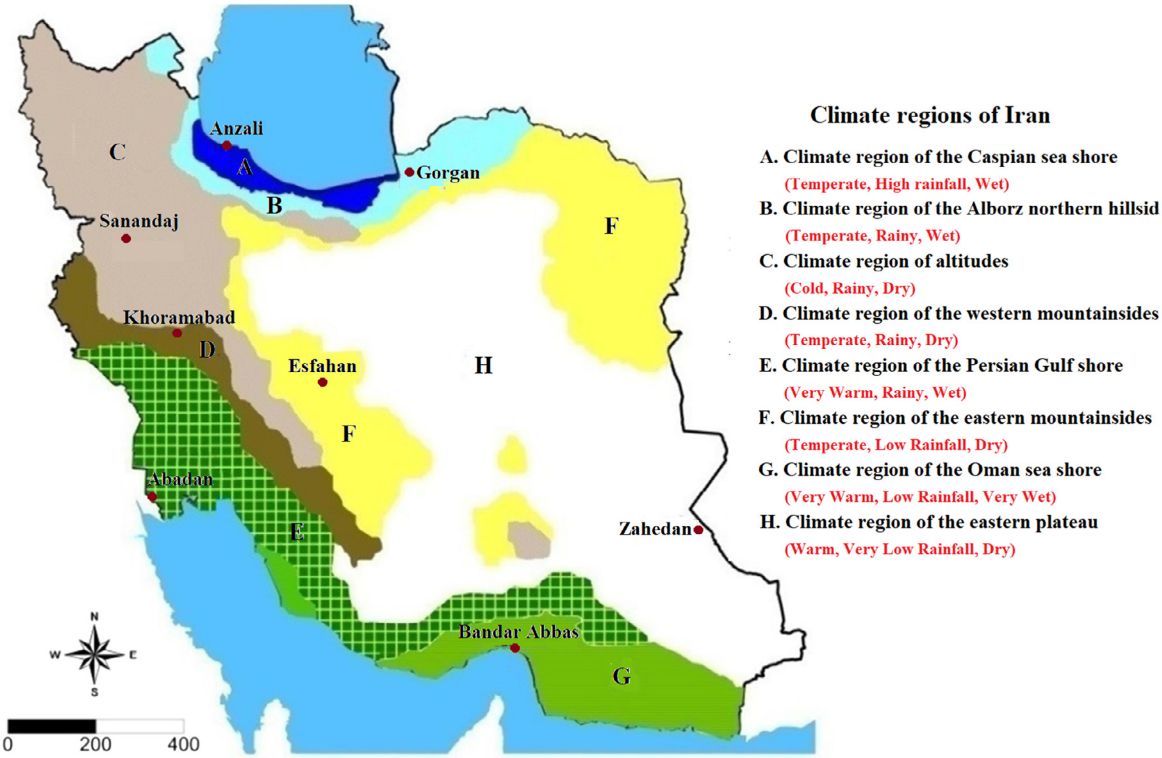

Fig. 1. Climatic classification of Iran and the geographical position of selected stations.

3.1. Standardized precipitation index (SPI)

This index was provided by McKee et al. (1993) and widely used throughout the world.

This index is based only on the precipitation variable and it is an appropriate tool to realize the drought phenomena in different regions. The first step in calculating the SPI index is determining the probability distribution function. Based on the studies conducted by McKee et al. (1995), Guttman (1999), Ntale and Gan (2003), and Wu et al. (2007), the most appropriate probability distribution function for fit to precipitation data is gamma family functions, which are defined as follows.

$$g(x) = \frac{1}{B^{a}\Gamma(a)} x^{a-1} e^{-x/B} \quad (1)$$

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

$$\alpha = \frac{1}{4A}\left[1 + \sqrt{1 + \frac{4A}{3}}\right]$$
$$B = \frac{\bar{x}}{\alpha}$$
$$A = \ln(\bar{x}) - \sum \ln(x)/n \quad (2)$$

where n is the number of precipitation observations. Then, calculated parameters are used to find the precipitation cumulative probability for the considered time scale for each of the stations. Assuming $t = X/\tilde{\beta}$, the cumulative probability is transformed into the incomplete gamma function.

$$G(x) = \int_0^x y(x)dx = \frac{1}{B^{\alpha}\Gamma(\alpha)} \int_0^x x^{\alpha-1} \quad e^{-x/B}dx \quad (3)$$

When the gamma function is not defined for $X = 0$ and precipitation distribution is zero, the cumulative probability is calculated as follows:

$$H(x) = q + (1 - q)G(x) \quad (4)$$

In the equation above, the precipitation probability is zero, while m is the number of zeros in precipitation time series. q is estimated in m/n and $H(x)$ is transformed into the normal variable (Z) with the following approximation

Table 1
The names, geographical coordinates, mean annual temperatures, total means of the annual precipitation, establishment years and types of the used stations for a period of 1985–2014.

Station	Latitude	Longitude	Elevation (m)	Average annual temperature (°C)	Average annual precipitation (mm)	Year of station establishment	Station type
Abadan	30° 22′	48° 15′	6.6	25.4	156	1951	Synoptic
Bandar Abbas	27° 13′	56° 22′	10	27.3	185.5	1957	Synoptic
Babolsar	36° 43′	52° 39′	−21	16.6	894.4	1951	Synoptic
Esfahan	32° 37′	51° 40′	1550.4	16.2	122.8	1951	Synoptic
Gorgan	36° 51′	54° 16′	13.3	17.8	601	1952	Synoptic
Khoramabad	33° 26′	48° 17′	1147.8	17.3	510	1951	Synoptic
Sanandaj	33° 20′	47° 00′	1373.4	14.2	458.4	1959	Synoptic
Zahedan	29° 28′	60° 53′	1370	18.6	90.6	1951	Synoptic

$$z = spi = +\left[t - \frac{c_0 + c_1 + c_2t^2}{1 + d_1t + d_2t^2 + d_3t^3}\right] \quad 0 < H(x)0.5 \tag{5}$$

$$z = spi = +\left[t - \frac{c_0 + c_1 + c_2t^2}{1 + d_1t + d_2t^2 + d_3t^3}\right] \quad 0.5 < \ H(x)1.0 \tag{6}$$

where:

$$t = \sqrt{\ln\left[\frac{1}{(H(x))^2}\right]} \quad 0 < H(x) \le 0.5 \tag{7}$$

$$t = \sqrt{\ln\left[\frac{1}{1.0 - (H(x))^2}\right]} \quad 0.5 < H(x) \le 1.0 \tag{8}$$

And $d_1{\cdot}d_2{\cdot}d_3{\cdot}c_0{\cdot}c_1{\cdot}c_2$ are constant coefficients as follows:

$d_1 = 1.432788 \quad c_0 = 2.515517$
$d_2 = 0.189269 \quad c_1 = 0.802853$
$d_3 = 0.001308 \quad c_2 = 0.010328$

When the equation of probability of current precipitation data was obtained, the spot probability of each of the observed precipitation data is calculated and used to calculate the standard normal probability density function, which has the mean of zero and one unit standard deviation. These values indicate the SPI value for each precipitation data. As SPI values are fitted with same normal distribution, it can be expected that approximately 68% of the times to be placed in values with one unit of standard deviation, 95% of the times to be placed with two deviations, and 99% of the times to be placed with three standard deviations of mean. SPI values are classified in Table 2.

3.2. Percent of normal precipitation index (PNPI)

Percent of Normal Precipitation Index (PNPI) is one of the simplest indices for detecting the droughts. This index was first presented by Wileke et al. (1994). The basic concept of this index is the ratio of actual precipitation to its normal value in a specified time period, expressed as a percentage and can be calculated for different time scales (weekly, monthly, seasonal, and annual). The actual value of this index for the studied length of record and station is calculated using the following formula:

$$PNPI = \frac{P_i}{P}\,100 \tag{9}$$

where PNPI, P_i, and P are the percent of normal precipitation index, precipitation of the considered year, and mean long-term precipitation, respectively. The point which should not be forgotten in using this index is that this index can be used when the mean precipitation is matched with precipitation median or the precipitation distribution is normal. If this condition does not govern precipitation time series, its results might result in false interpretations. However, using this index is simple and has high flexibility for other calculations. Moreover, the results of this index show the deviation from mean well and easily. It is considered one advantage of PNPI index. Table 2 shows the drought classification based on this index.

Table 2
The classification of different degrees of drought in all the indices studied in this research.

Value	Class	SPI	EDI	DI%	PNPI
3	Extremely wet	≥2	2.5≥	≥90	
2	Very wet	1.5 to 1.99	1.5 2.49 to	80 to 90	
1	Moderately wet	1.0 to 1.49	0.7 1.49 to	70 to 80	
0	Normal	−0.99 to 0.99	0.69 to 0.69-	30 to 70	70 to 80%
−1	Moderately dry	−1.0 to −1.49	0.7- to 1.49-	20 to 30	55 to 70%
−2	Severely dry	−1.5 to −1.99	1.5- to 2.49-	10 to 20	40 to 55%
−3	Extremely dry	≤−2	2.5-≤	≤10	< 40%

Table 3
Correlation coefficient of drought indices in monthly, seasonal, and annual time scale.

A	MCZI 55	MCZI 50	MCZI 45	MCZI 40	MCZI 35	MCZI 30
MCZI 55	1	0.37 **	0.52 **	0.45 **	0.52 **	0.41 **
MCZI 50	0.37 **	1	0.69 **	0.58 **	0.23 **	0.28 **
MCZI 45	0.52 **	0.69 **	1	0.53 **	0.31 **	0.38 **
MCZI 40	0.45 **	0.58 **	0.53 **	1	0.26 **	0.33 **
MCZI 35	0.52 **	0.23 **	0.31 **	0.26 **	1	0.44 **
MCZI 30	0.41 **	02 **	0.38 **	0.34 **	0.44 **	1
B						
	EDI 55	EDI 50	EDI 45	EDI 40	EDI 35	EDI 30
EDI 55	1	1**	1**	1**	1**	0.97 **
EDI 50	1**	1	1**	1**	1**	0.97 **
EDI 45	1**	1**	1	1**	1**	0.97 **
EDI 40	1**	1**	1.00	1	1**	0.97 **
EDI 35	1**	1**	1**	1**	1	0.97 **
EDI 30	0.97 **	0.97 **	0.97 **	0.97 **	0.97 **	1
C						
	DI 55	DI 50	DI 45	DI 40	DI 35	DI 30
DI 55	1	0.70 **	0.33 **	0.54 **	0.63 **	0.50 **
DI 50	0.70 **	1	0.31 **	0.74 **	0.78 **	0.55 **
DI 45	0.33 **	0.31 **	1	0.28 **	0.23 **	0.23 **
DI 40	0.54 **	0.74 **	0.28 **	1	0.86 **	0.83 **
DI 35	0.63 **	0.78 **	0.23 **	0.86 **	1	0.76 **
DI 30	0.50 **	0.55 **	0.23 **	0.83 **	0.76 **	1 **
D						
	PNPI 55	PNPI 50	PNPI 45	PNPI 40	PNPI 35	PNPI 30
PNPI 55	1	0.97 **	0.97 **	0.98 **	0.96 **	0.96 **
PNPI 50	0.97 **	1	1 **	0.99 **	0.99 **	0.99 **
PNPI 45	0.97 **	1 **	1	0.99 **	0.99 **	0.99 **
PNPI 40	0.98 **	0.99 **	0.99 **	1	0.98 **	0.99 **
PNPI 35	0.96 **	0.99 **	0.99 **	0.98 **	1	0.99 **
PNPI 30	0.96 **	0.99 **	0.99 **	0.99 **	0.99 **	1
E						
	ZSI 55	ZSI 50	ZSI 45	ZSI 40	ZSI 35	ZSI 30
ZSI 55	1	0.92 **	0.92 **	0.92 **	1 **	1 **
ZSI 50	0.92 **	1	1 **	1 **	0.92 **	0.92 **
ZSI 45	0.92 **	1 **	1	1 **	0.92 **	0.92 **
ZSI 40	0.92 **	1 **	1 **	1	0.92 **	0.92 **
ZSI 35	1	0.92 **	0.92 **	0.92 **	1	1 **
ZSI 30	1	0.92 **	0.92 **	0.92 **	1 **	1
F						
	DI 55	DI 50	DI 45	DI 40	DI 35	DI 30
DI 55	1	0.10	0.36 *	0.04	−0.29	0.10
DI 50	0.10	1	0.20	0.46 **	0.17	−0.06
DI 45	0.36 *	0.20	1	0.28	0.42 *	0.12
DI 40	0.04	0.46 **	0.28	1	0.27	0.6 **
DI 35	−0.29	0.17	0.42 *	0.27	1	0.08
DI 30	0.10	−0.06	0.12	0.6 **	0.08	1

**Correlation is significant at the 0.01 level (2-tailed).
*Correlation is significant at the 0.05 level (2-tailed).

3.3. Deciles index (DI)

This index was for the first time used in 1967 by Gibbs and Maher for the investigation of the historical droughts in Australia. In this index, the long-term monthly, seasonal, or annual precipitation values of the studied stations are arranged in ascending or descending order, so that their cumulative frequency distribution to be formed.

Then, they are divided into groups of normal distribution. Each of these groups is called a decile. The first decile is the amount of precipitation, which is less than 10% of the precipitations. The second decile shows the amount of precipitation, which is less than 20% of the precipitation. The fifth decile or median is the amount of precipitation, which does not exceed 50% of the precipitations. Table 2 shows the classification of this index.

The point which should be remembered in using this index is that if the precipitation data do not follow the normal distribution, the data

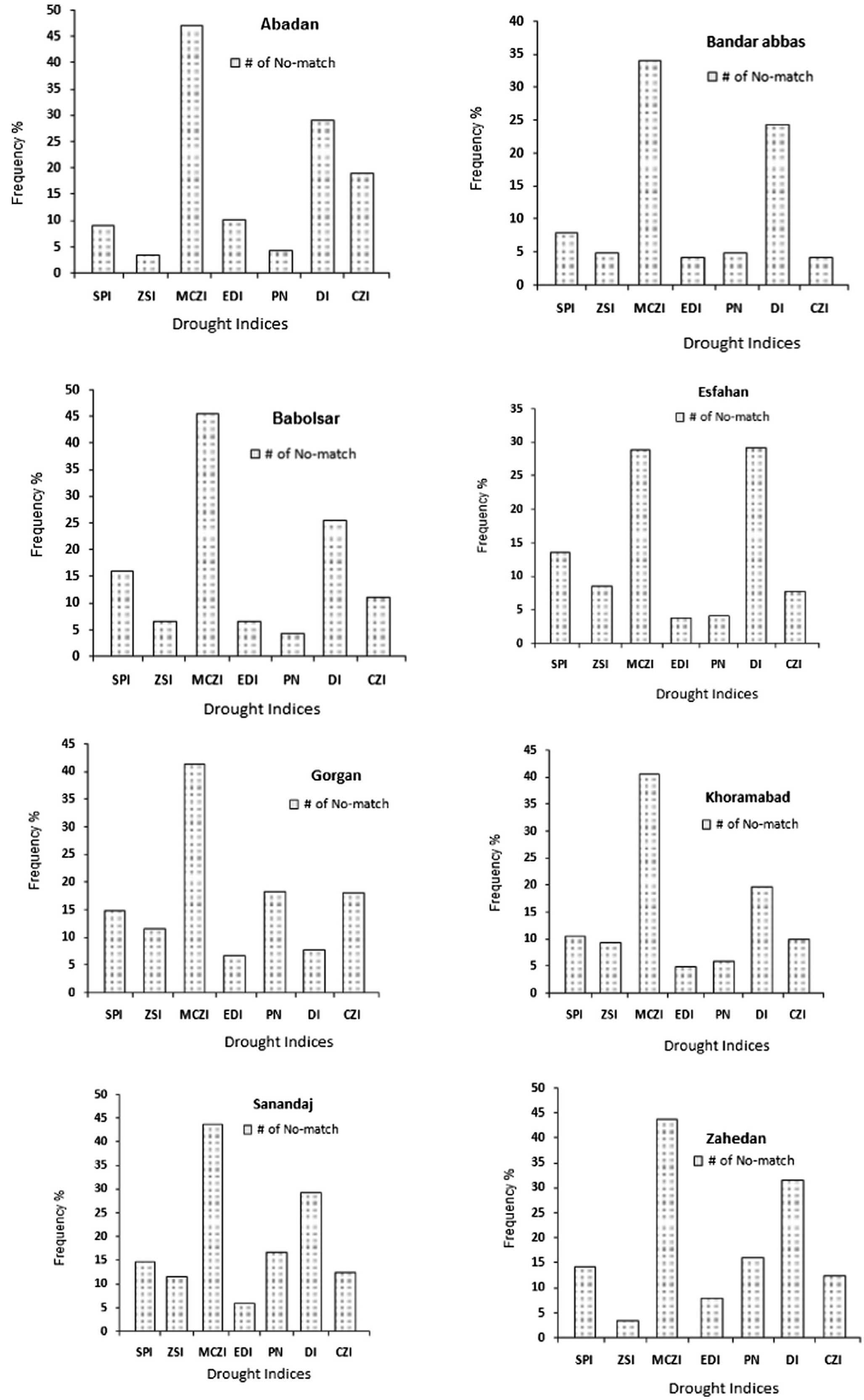

Fig. 2. Total percentage of non-match at monthly time scale at the stations studied.

Table 4
The percentage of non-match between different classes of drought in the monthly time scale in the studied stations

Station	Class	CZI	DI	EDI	MCZI	PNPI	SPI	ZSI
	1	19	19.7	10.3	40	4.4	9.2	3.6
Abadan	2		5.8		6.9			
	3		3.6		0.3			
	1	11.1	15.6	6.7	39.7	4.4	15.3	6.7
Babolsar	2		3.3		5.8		0.8	
	3		6.7					
	1	2.2	14.4	4.2	32.8	4.2	6.9	1.9
Bandarabbas	2	1.7	6.7		1.4	0.6	1.1	1.1
	3	0.3	3.3			0.3		1.9
	1	7.8	12.8	3.9	17.2	4.2	13.6	7.5
Esfahan	2		3.6		1.7			1.1
	3		12.8					
	1	14.7	28.1	5.8	39.2	18.3	14.4	10.6
Gorgan	2	3.3		1.1	1.4		0.6	1.1
	3		9.7		0.8			
	1	10	8.3	5.3	34.7	6.1	10.3	8.3
Khoramabad	2	0.3	5.6		5.8		0.3	1.1
	3		5.8					
	1	10	20	6.1	37.8	16.9	11.7	10.6
Sanandaj	2	2.5			5.6		3.1	1.1
	3		9.4		0.6			
	1	9.7	21.9	8.1	37.8	16.1	11.4	3.1
Zahedan	2	2.8	0.3		5.6		3.1	0.6
	3		9.4		0.6			

should be normalized using one of the normalization methods. One of the methods used in normalizing the data is BOX-COX transformation. In this research, these transformations were used for stations, where their distribution did not follow the normal distribution.

3.4. Z-Score index

ZSI index is calculated very simple. It has been used in many drought studies such as Tsakiris and Vangelis (2004), Patel et al. (2007), Morid et al. (2006). The ZSI index does not require transforming the fit data for distributions such as Gamma or Pearson Type III, as used in SPI and CZI. This index is obtained from the following equation:

$$ZSI = \frac{(X_{ij} - \bar{X})}{\sigma_i} \quad (10)$$

In the equation above, X_{ij} is the precipitation of month j for length i, and σi and $\bar{X}$ are the standard deviation of precipitation and mean in each time scale, respectively. Table 2 shows the classification of this index.

3.5. The China Z index (CZI) and the modified China Z index (MCZI)

The CZI index was widely used in 1995 by the National Climate Center of China. The CZI index is calculated based on the third Wilson-Hilferty third root transformation (Wilson and Hilferty, 1931), assuming that the data follow the Pearson Type III distribution. The CZI index is calculated as follows:

$$\sigma = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2} \quad (11)$$

$$C_s = \frac{\sum_{i=1}^{n}(x_i - \bar{x})^3}{n \times \sigma^3} \quad (12)$$

$$CZI = \frac{6}{C_s}\left(\frac{C_s}{2}Z - Score - 1\right)^{1/3} - \frac{6}{C_s} + \frac{C_s}{6} \quad (13)$$

In the equations above, σ is the standard deviation, n is the number of observations, and C_s is the coefficient of Skewness.

x_i and $\bar{x}$ are calculated exactly as x_i and $\bar{x}$ are calculated in Z-Score Index. The modified CZI index (MCZI) is calculated as CZI is calculated, while the median is used instead of the mean. Table 2 shows the severity of drought- related to this index.

3.6. Effective drought index (EDI)

This index was developed by Byun and Wilhite in 1999 to detect and determine the start time and end time of droughts. Effective Drought Index (EDI) in its original form is calculated based on daily data (Akhtari et al., 2009; Kalamaras et al., 2010; Kim and Byun, 2009; Kim et al., 2009; Morid et al., 2006; Roudier and Mahe, 2010), unlike other drought indices. However, its principles can be generalized to monthly precipitation data, as Morid et al. (2007) developed this index for monthly scale. Thus, the monthly time scale developed by Morid et al. (2007) was used in the current research.

To calculate EDI, there are many steps, which described later in brief. The main concept in this index is effective precipitation (EP). Effective precipitation is the sum of daily precipitation values with a time-dependent reducing function, which is calculated using the following equation

$$EP = \sum_{n=1}^{i}\left[\left(\sum_{m=1}^{n} P_m\right)/n\right] \quad (14)$$

In which, i is the duration of summation, and P_m is precipitation up to $m-1$ days before.

In the next step of calculating this index, the deviation of the EP of MEP is calculated. This deviation is calculated by calculating the DEP, which its equation is presented below. In fact, MEP is the mean of EP for each calendar day, which it is climatic characteristics in one place and time.

$$DEP = EP - MEP$$

Calculation of the precipitation needed for a return to normal daily conditions (PRN) is another step of the calculation, obtained using Eq. (12):

$$PRN = DEP/\sum_{N=1}^{j}\frac{1}{N} \quad (16)$$

Finally, the EDI, which is the standardized form of PRN, is calculated according to the following equation:

$$EDI = PRN/ST(PRN) \quad (17)$$

In the equation above, ST (PRN) represents the standard deviation of PRN.

Table 2 shows the classification of different degrees of drought in all the indices studied in this research.

After calculating the indices, the Pearson correlation coefficient and Spearman Rank Correlation Coefficient (Kendall and Stuart, 1977), measuring the power of the linear relationship between the pair of values of the indexes extracted from different lengths of record, were calculated for all stations in time scales. Ranks of values of indices in a specified time period are an important index for the severity of drought and wetness events. The rank of each single index value is specified based on its row in the list of ranks. Then, Pearson and Spearman correlation coefficients are calculated between the pair of values of indices, which ranks are used for it as the base for measuring the strength of the relationship between the two index values. It should be noted that the numerical correlation coefficients are numbers between zero and one. As the correlation value is close to number one, the correlation between the two variables would be higher, and as it is closer to zero, the correlation would be lower. The correlation equals to one means linear and 100% relationship. Correlation can be positive or negative.

In the second step, match and non-match between the occurrence

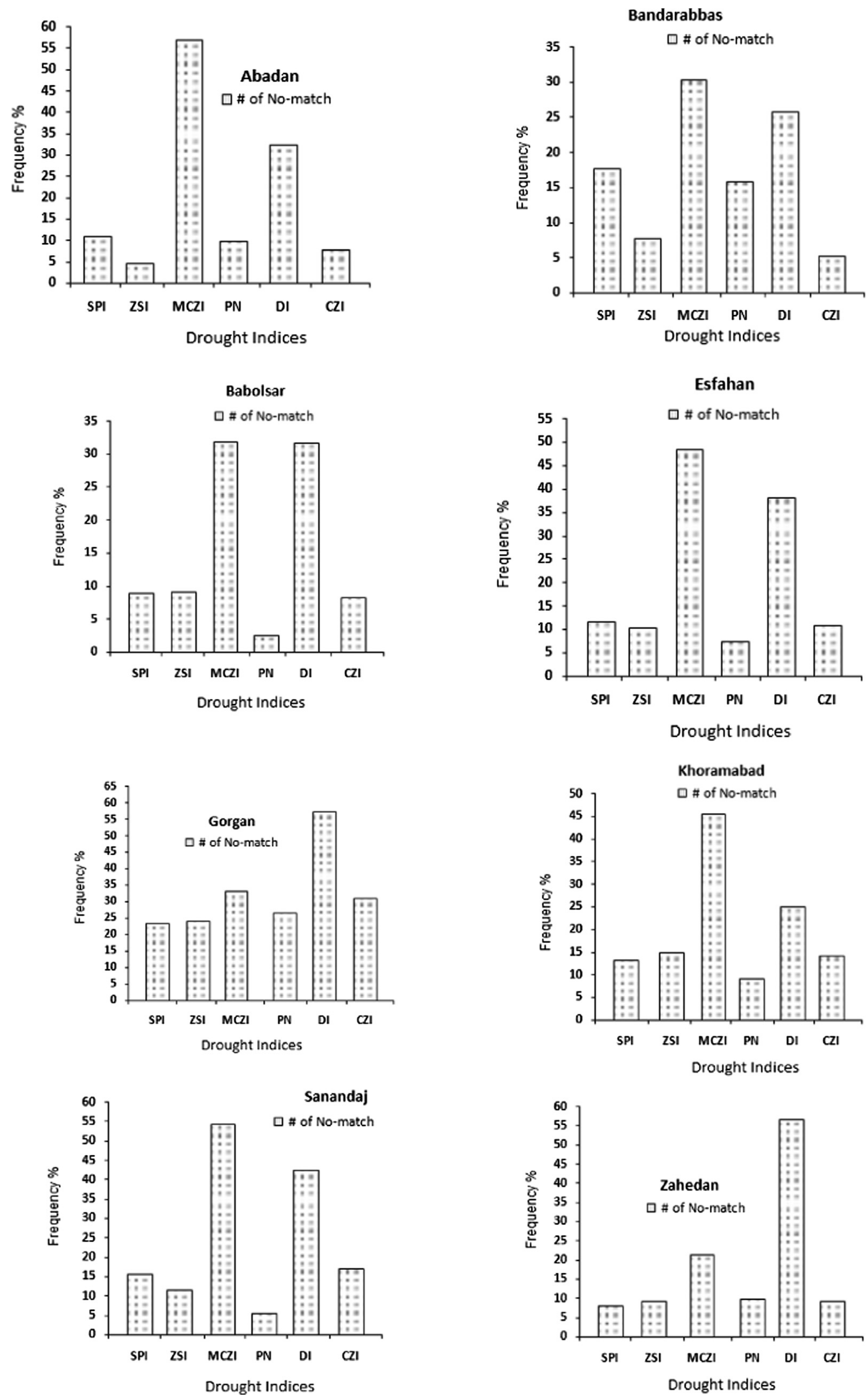

Fig. 3. General percentage of non-match in the seasonal time scale at the studied stations.

Table 5
Percentage of non-match among different classes of drought in seasonal time scale at the studied stations

Station	Class	CZI	DI	MCZI	PNPI	SPI	ZSI
	1	7.8	15	33.1	8.3	11.1	4.4
abadan	2		2.5	9.2			0.3
	3		15	0.8	1.7		
	1	8.3	15	25.3	2.5	8.9	9.2
Babolsar	2		6.7	6.4			
	3		10	0.3			
	1	3.9	15.8	28.3	8.3	17.8	7.2
Bandarabbas	2	1.4	3.3	1.9	7.5		0.6
	3		6.7				
	1	10.8	20.8	43.6	7.5	11.7	10.3
Esfahan	2		5.8	5			
	3		11.7				
	1	24.4	54.2	29.7	26.7	22.5	22.8
Gorgan	2	6.7		3.3		1.1	1.4
	3		3.3				
	1	14.2	12.5	40	8.3	13.3	14.2
Khoramabad	2		4.2	5.3			0.8
	3		8.3	0.3	0.8		
	1	14.2	41.7	47.2	5.6	14.7	10.6
Sanandaj	2	3.1	0.8	6.4		0.8	1.1
	3			0.8			
	1	8.1	55	206	10	7.5	9.4
Zahedan	2	1.4		0.8		0.6	
	3		1.7				

severities obtained from the long and short lengths for each station are investigated in three-5time scales. In the third step, the values of indices obtained from different lengths of record in the unique years of the severe drought and flood in the recorded data were compared.

4. Results and discussion

Seven drought indices of DI, SPI, PNPI, ZSI, MCZI, CZI, and EDI were used in this research. First, the lengths of record of 55, 50, 45, 40, 35, and 30 years were extracted at monthly, seasonal, and annual, time scales. Then, the sensitivity of lengths of record was investigated in several steps. The correlation coefficient of these indices and then the match and non-match of the indices obtained from the longer lengths of record with values obtained from shorter lengths were determined and studied for each of three-time scales. Finally, unique drought and flood years of stations were compared for the mentioned time scales.

4.1. Comparing the correlation coefficients

Pearson correlation coefficient and Spearman correlation coefficient (rank) were obtained for all studied stations for all lengths in monthly, seasonal, and annual time scales, which 2 cases from each time scale were included in the paper. As the results of the two correlation coefficients were very close and similar, the results of the Spearman correlation coefficient were included in the paper.

The results of the correlation coefficient obtained at monthly time scales suggested that EDI index had the highest correlation coefficient among the indices. As the length of record increases in this index, the correlation coefficient between lengths of the record increases (Table 3B). In this scale, the MCZI index and then DI index have the lowest correlation coefficient among the indices so that a weak correlation was found between them in some lengths of record (Table 3A). In other indices, the correlation coefficient between the lengths of record was obtained very strong and high. For example, the relationship between the length of records in the SPI, ZSI and PNPI indices was above 0.90. It should be noted that the results obtained in the SPI index are completely similar to the results of Wu et al. (2001) and confirm the results of their work.

In the seasonal time scale, the EDI index was removed since it can be calculated only on a daily and monthly scale. The results of the correlation coefficient between the indices were similar to the monthly scale, but the results of the correlation coefficient in the DI index were reduced significantly, so that weak relationship was observed between them in some of the lengths of record (Table 3C). In this scale, the highest correlation coefficient among the indices was related to the PNPI index, which correlation coefficient between the lengths of the records was higher than 0.9 in all of the studied stations (Table 3D).

The correlation coefficient was obtained in annual scale at all stations. The correlation coefficient was obtained very strong in all indices except for DI index. In this index, the relationship between lengths of record was reduced and in some lengths, the relationship was not found between the lengths of record (Table 3E). In other indices, such as ZSI index, the correlation coefficient between all lengths of record was obtained higher than 0.9 (Table 3F). The MCZI index was not calculated in this scale.

4.2. Comparison of match and non-match in the studied indices

Investigating the match and non-match of different classes of drought and wetness from the long-term (1960–2014) and short-term (1985–2014) was derived from the main length. This match and non-match are determined as follows. If one class of classes of occurrence of droughts derived from long-term lengths of record matches with short-term lengths of record, it is called match, otherwise, it is called non-match. Hence, percentage of non-match is obtained by dividing the number of “non-matches” into the sum of the number of “matches” and “non-matches”. Moreover, to show level of “non-match”, the number of frequencies, in which difference of match was more than one class, was also counted. For example, this case occurs when the value of the index obtained from the long-term length of record is classified within the “close to normal” class and the value of corresponding index extracted from the short-term length of record was classified into severe drought or very severe drought class.

In first, the percentage of non-match was generally obtained for all indices (Fig. 2). Findings revealed that the lowest non-match in all stations, except for Abadan and Babolsar stations, was related to EDI index, so that this value in Isfahan and Abadan stations was 3.6 and 3.9 percent less than that in other indices. Additionally, the highest non-match in all stations (except Isfahan station) was related to the MCZI index in the range between 34.2% (Bandar Abbas station) and 47.2% (Abadan station). Following this index, DI index had the highest non-match.

In the monthly time scale, non-match in the MCZI and DI indexes had difference more than one class. The highest percentage of non-match occurred in DI index (21.9%) at Zahedan station, and it occurred in the MCZI index (40%) at Abadan station, which this difference between the long term and the short term was one class (Table 4). The important point on the EDI index is that the percentage of non-match in this index in all stations (except Gorgan station) was not more than one class. The highest percentage of non-match between short term and long term length in this index was 10.3% in the Abadan station.

In the seasonal time scale, as with the second stage, EDI index analysis section was removed. In this scale, the indices of ZSI, SPI, MCZI and CZI were calculated as moving mean. The results obtained in this scale showed that the two indices of MCZI and DI had the highest non-match between the two long and short term lengths, so that the non-match for the MCZI index was more than 50% in Sanandaj and Abadan stations. Moreover, this value has been repeated for two stations of Zahedan and Gorgan in the DI index. The lowest non-match among the indices was in two indices of PNPI and SPI at different stations. At the stations of Zahedan, Abadan, and Gorgan, SPI index had the lowest non-match, and at stations of Babolsar, Isfahan, Khorramabad, and Sanandaj, PNPI index had the lowest non-match. The important point observed in this scale was that in all indices, the non-match was more than 23% at the Gorgan station in all indices (Fig. 3). One of its reasons

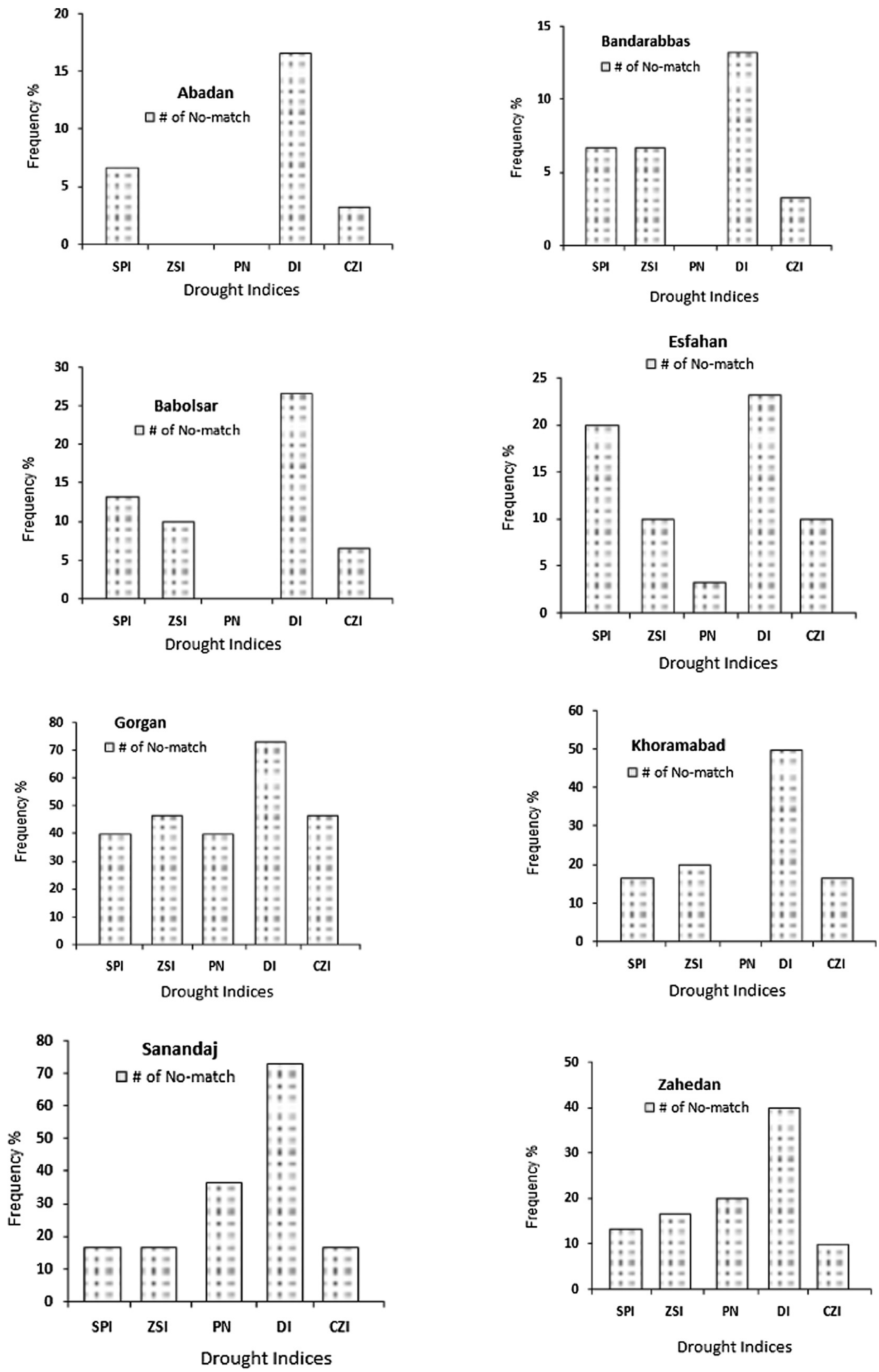

Fig. 4. General percentage of non-match in the annual time scale at the studied stations.

Table 6
Percentage of non-match among different classes of drought at annual time scale at the studied stations

Station	Class	CZI	DI	PNPI	SPI	ZSI
	1	3.3	16.7		6.7	
Abadan	2					
	3					
	1	6.7	13.2		13.3	10
Babolsar	2					
	3		13.3			
	1	3.3	10		6.7	6.7
Bandarabbas	2					
	3		3.3			
	1	10	23.3	3.3	20	10
Esfahan	2					
	3					
Gorgan	2	6.7	3.3			
	3					
	1	16.7	33.3		16.7	20
Khoramabad	2		3.3			
	3		13.3			
	1	13.3	70	36.7	13.3	13.3
Sanandaj	2	3.3			3.3	3.3
	3		3.3			
	1	10	40	20	10	16.7
Zahedan	2				3.3	
	3					

is the precipitation regime of this station, which precipitation fluctuations of the station is not uniform. The geographical position of this city is so that it is placed in the wet and dry region border.

In the seasonal time scale, the difference of classes between the two MCZI and DI indices between long-term and short-term lengths was seen more than one class. For example, at Abadan station, non-match in both indices of the three classes was different, while this difference was up to two classes for other indices. This difference of classes in SPI index at all stations was one class, except for Sanandaj, Gorgan, and Zahedan stations. As the distance of classes increases from one class to another class, the distance between classes is reduced (Table 5).

Fig. 4 shows total percentage of non-match at the annual time scale at the studied stations. In this scale, the MCZI index was removed from the sum of indices. The highest percentage of non-match among the indices belonged to DI index. At Khoramabad Station, the percentage of non-match in this index reached to more than 50%. At stations of Abadan, Bandar Abbas, and Khoramabad, the percentage of non-match for the PNPI index was obtained zero. At Gorgan Station, as with other two scales, the percentage of non-match was increased for all studied indices, which its value for all indices was more than 30%.

Table 6 shows the difference of drought and wetness classes at the annual scale. As seen, the difference of classes in the PNPI index was not observed for many of stations such as Abadan, Babolsar, Bandar Abbas, and Khoramabad. The highest difference of classes, as with seasonal time scales, is in the DI index. After the PNPI index, the ZSI index has the lowest difference in its classes. No difference was seen in classes of this index even in Abadan stations. Other indices, like the SPI index at all stations (except for Sanandaj Station), have one difference class. The non-match in the CZI index is evident both in one and two difference classes in the studied stations.

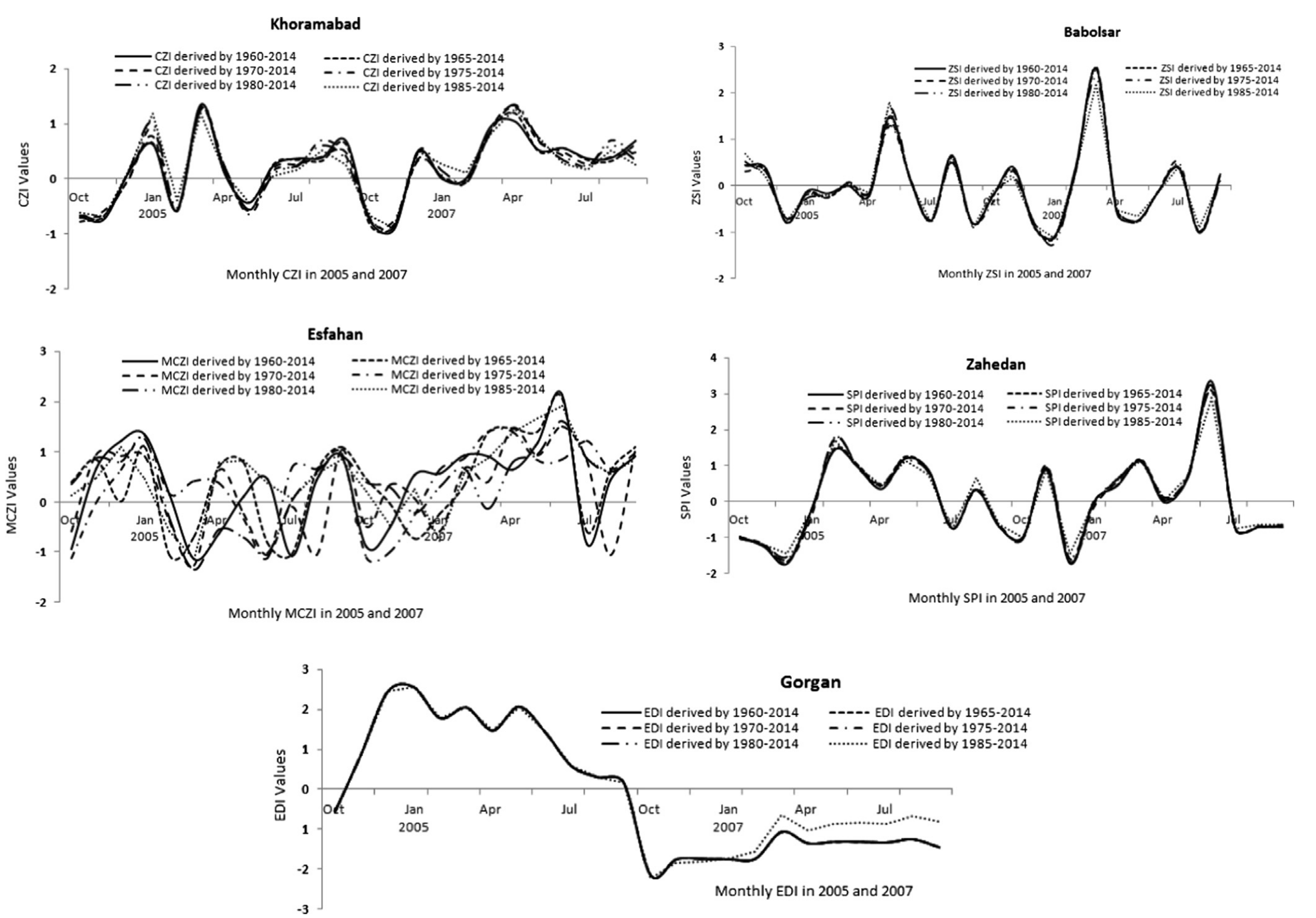

Fig. 5. The variations of time series related to the values of various drought indices and their match and non-match with the driest year (2007) and wettest year (2005).

4.3. Comparing values of different indices in unique years

In order to examine the match and non-match of the studied indices, one very wet year and one very dry year were selected among the studied years in order to examine the length of record match and find the strength of the droughts and witnesses. For this purpose, the year 2005 was determined as the wet year and the year 2007 was selected as the drought year. These years were recognized before by Nooshirvani (2014). As shown in Fig. 5, the EDI index has the best match among all lengths. This index could easily identify the drought year of 2007 and the severe wet year of 2005. The indices of SPI, ZSI, and CZI had relatively similar performance. These indices, as with EDI index, could not show drought and wetness of the considered years. The performance MCZI index is very different with that of other indices, so that none of the lengths of record match with each other.

5. Conclusion

Nowadays, preparing the long-term data is one of the main concerns of researchers in many countries. Many studies have reported that at least 30-year data are required for a scientific research. Unfortunately, it is impossible to provide 30-year data in many countries (even developed countries). Even the recording the precipitation data in many of the regions varies from one station to another station.

There are also regions which cannot be ignored due to data less than 30 years. This research tried to evaluate the sensitivity of precipitation lengths of record in different indices to introduce an index so that the lengths of record to have the lowest impact on its values and can cover this weakness of data shortage weakness. It should be noted that this research has been conducted regardless of other shortcomings of the indices. It means that only one aspect has been considered in the paper. At a monthly scale, the EDI index showed better time stability compared to other indices. In this index, the values derived from the lengths of record did not differ significantly. As the lengths of record increases, the accuracy of index increases and the effect on the classes is reduced. This index is very appropriate at these time scale for places and regions, where they have no longer lengths of record. The PNPI index at annual and seasonal scale at most of the stations had the lowest non-match among the studied indices. Even at several stations, no non-match was seen among lengths of record in this index.

The ZSI index is one of the indices, which non-match in this index is less compared to other indices. This index has the lowest non-match after the EDI index at monthly time scale and after the PNPI index in the seasonal time scale. This index at the annual scale, both after the PNPI index and along with the CZI index is among the indices showed the better match. The CZI index has shown better match compared to SPI index. The SPI index showed appropriate performance, but the results are not reliable. Non-match at studied time scales was not equal for different stations. At stations of Gorgan, Khorramabad, and Sanandaj non-match increases are from monthly time scale to seasonal time scale and from seasonal time scale to annual time scale. However, non-match at stations such as Zahedan, Babolsar, Isfahan, reduces from monthly time scale to seasonal time scale and increases from seasonal time scale to annual time scale. One of the most important non-match at different stations is the probability distribution (gamma) used in SPI index, which is equal for all studied stations. To solve this problem, probability distribution should be obtained for each station and examine the length of record. The highest non-match among the studied indices was seen in two MCZI and DI indices. Very low time stability was seen in these indices at studied time scale. These indices were severely sensitive to lengths of record and they should be used with caution in the studies.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jhydrol.2019.124181. These data include Google maps of the most important areas described in this article.

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