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Meteorological drought monitoring using several drought indices (case study: Salt Lake Basin in Iran)

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Abstract

Drought detecting is a necessary aspect of drought risk management. It is generally performed using different drought indices that are effectively continuous functions of rainfall and other hydro- meteorological variables. A number of drought indices have been introduced and used in various countries to date. In the current research, four meteorological drought indices including the standardized precipitation index (SPI), China-Z index (CZI), modified CZI (MCZI) and Z-Score (Z) are compared and evaluated for monitoring droughts in Salt Lake Basin in Iran. The comparison of indices was carried out based on drought classes that were monitored in the study area using 40 years of data. The results indicated that SPI, CZI and Z-Score performed similarly with regard to drought identification and responded slowly to drought onset. DI appeared to be very sensitive to precipitation rates, but had unsteady spatial and temporal variation. Additionally, by considering the advantages and disadvantages of the mentioned drought predictors in Iran, the CZI and Z-Score could be used as good meteorological drought predictors.

Keywords: Drought monitoring; Drought index; Semi-arid region; Iran

1. Introduction

Drought is a complex natural phenomenon and a recurring meteorological event that affects environmental factors and agriculture, vegetation, humans and wildlife, as well as local economies (Azarakhshi *et al*., 2011; Dastorani and Afkhami, 2011; Jeyaseelan, 1999; Morid *et al*., 2006; Nohegar *et al*., 2013; Zarei *et al*., 2013). It originates from a shortage of precipitation, high evapotranspiration and overexploitation of water resources, or a combination of all these factors (Bhuiyan, 2004), over a prolonged period of time. Drought develops slowly, is difficult to detect and can present a range of diverse aspects in different regions (Jeyaseelan, 2005; Morid, 2007).

According to Wilhite and Glantz' (1985) classification, four categories of droughts can be identified: 1. meteorological drought, which is the negative departure of precipitation from the normal precipitation over a period of time; 2. hydrological drought, which is a shortage in surface and subsurface water supplies; 3. agricultural drought, which is a lack of soil moisture required for the development of a special crop at a particular period; 4. socio-economic drought, which refers to the failure of water

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resources to maintain water demands. The first three categories can be defined as environmental droughts, whereas the final one can be considered a water resources drought (Azarakhshi *et al*., 2011).

The prediction of drought can play an important role in mitigation its effects. In other words, fundamental to mitigating the detrimental effects of droughts is the ability to forecast drought conditions in advance by either a few months or a number of seasons (Dastourani *et al*., 2011).

Many different drought indices have been introduced and used as drought monitoring tools in different parts of the world. The most popular indices include the Palmer drought severity index (PDSI) (Palmer, 1965), which has been widely used by the US Department of Agriculture, the decile index (Gibbs and Maher, 1967), which is operational in Australia, the China-Z index (CZI), which is used by the National Metrological Center of China (Wu *et al*., 2001) and the standardized precipitation index (SPI), which has gained popularity worldwide, and was first introduced by McKee *et al*. (1993) at Colorado State University. Another drought indicator is the reconnaissance drought index (RDI), first introduced at a coordinating meeting of MEDROPLAN2 (Tsakiris, 2004). Most of these indices are calculated using climate data (rainfall or temperature).

Kirono et al.'s (2011) study is an example of RDI application for the characterization of Australian droughts under enhanced greenhouse conditions. In their study, RDI was applied to simulate climate variables from 14 GCMs performed for the IPCC's fourth assessment report. The results showed a general increase in drought areal extent and frequency for most regions of the country. The review of drought indices can be found in several manuscripts (including Bazrafshan and Khalili, 2013, Shahabifar and Eitzinger, 2013, and Zehtabian *et al*., 2013). Morid *et al*. (2006) studied drought conditions by comparing seven drought indices (decile index, percentage of normal index, standardized precipitation index (SPI), China-Z index (CZI), modified CZI, Z-score and effective drought index (EDI)) in Tehran Province, Iran. Their study showed that SPI, CZI and Z-Score performed similarly for drought identification, while SPI and EDI could detect the commencement of a drought condition. Bazrafshan (2002) analysed seven meteorological drought indices for diverse climates in Iran (arid to very humid regions) and recommended SIAP, SPI and EDI for drought monitoring on annual, monthly, and daily timescales, respectively.

For countries located in arid and semi-arid regions, such as Iran, drought monitoring has become increasingly important as a tool for natural resources management. In this regard, the purpose of this article was to compare the performance and assess the capability of several rainfall-based drought indices for Salt Lake Basin in Iran.

2. Material and methods

2.1. Study area

Salt Lake Basin is located in the northwestern part of the Iranian Central Plateau (Fig.1). This basin is situated at 48° to 53° longitude and 32° to 37° latitude. The basin has a total area of 89650 km^2. Precipitation varies from 700 mm in the northern parts to 130 mm in the southern parts. It is limited in the north to the Alborz Mountains, from the west to the Zagros heights, from the south to the Zaianderoud basin and in the east to the basin of the Kavir plain. The area has an arid to semi-arid climate. In this study, the precipitation records from 60 rain gage stations in the basin were used. The recorded length at these stations ranged from 1969 to 2009. Missing data gaps were patched using regression equations from data of the nearest suitable station.

2.2. Methodology

In order to contribute to improved drought monitoring in Salt Lake Basin in Iran, in this study, seven drought indices were selected including a decile index (DI), standardized precipitation index (SPI), China-Z index (CZI), modified CZI (MCZI) and Z-Score (Z) for use in multiple time scales in six climate regions. A common aspect of the selected indices is that they are all estimated using precipitation data only. These indices are briefly described in the following section.

2.2.1. Standardized Precipitation Index (SPI)

The SPI may be computed using different time periods (e.g., one month, three months and 24 months) (McKee *et al*., 1993). It was observed that application of SPI at longer time periods was not advisable, as the sample size was reduced as a result, even with originally long-term data sets. Application of various timescales allowed for the effects of a precipitation shortage on different water resource components (groundwater, reservoir storage, soil moisture, stream flow) to be evaluated. Positive SPI values demonstrated that greater than mean precipitation and negative values indicated less than mean precipitation. The SPI can be applied for monitoring both dry and wet situations. The “drought” part of the SPI range is arbitrarily divided into “near normal” (0.99>SPI>−0.99), “moderately dry” (−1.0>SPI> −1.49), “severely dry” (−1.5>SPI>−1.99) and “extremely dry” (SPI<−2.0) situations. A drought event begins when index becomes negative and ends when SPI becomes positive once again. Estimation of the SPI requires that no data is missing in the time series. It is recommended that the data record length not to be less than at least 30 years (Wu *et al*., 2001), because the drought index classes are fitted to this period and are also intercomparable with other regions with different climates. This index has been used widely in various recent drought related studies for evaluating climate change effects on agriculture, hydrology, water resources and ecosystems (Capra *et al*., 2013).

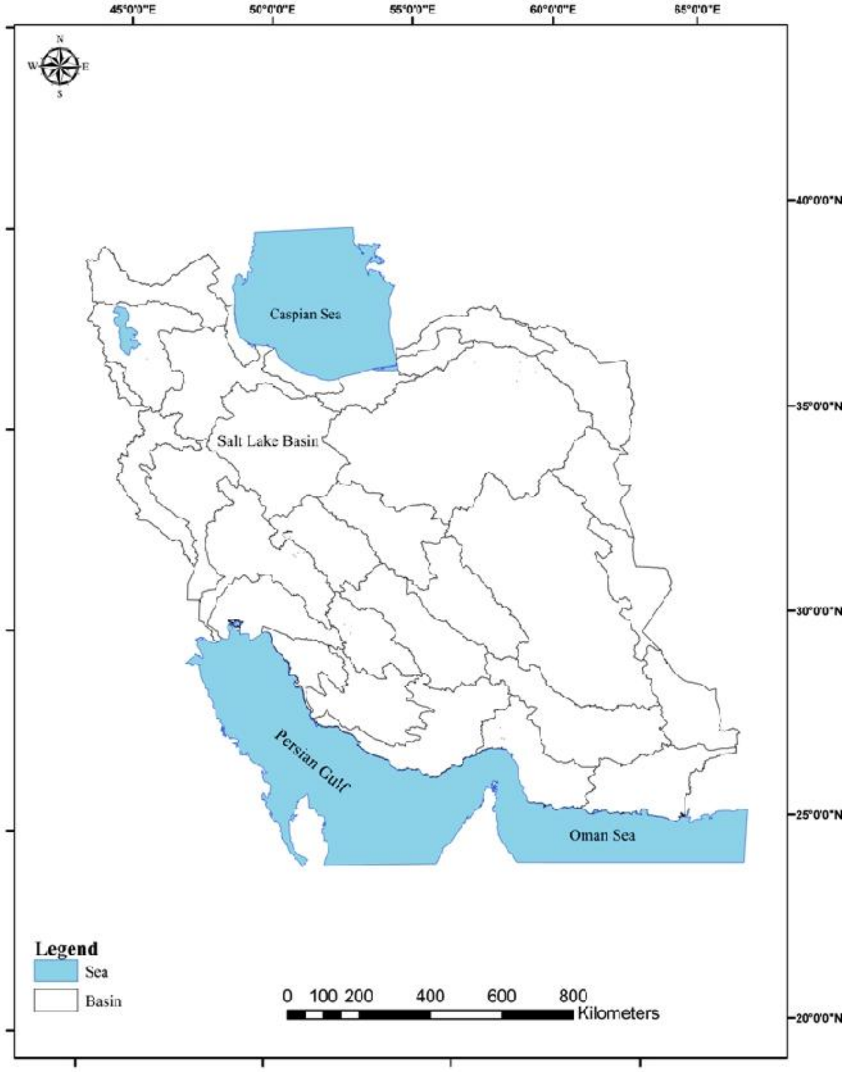

Fig. 1. Location of Salt Lake Basin in Iran

2.2.2. China-Z index (CZI), modified CZI (MCZI) and Z-Score

The CZI is based on the Wilson-Hilferty cube-root transformation (Kendall and Stuart, 1977). Assuming that precipitation data follow the Pearson Type III distribution, the index is computed as:

$$CZI_j = \frac{6}{C_s}\quad \frac{C_s}{Z}\,\varphi_j + 1 \quad {}^{1}\,{}^{3} - \frac{6}{C_s} + \frac{C_s}{6} \tag{1}$$

$$C_s = \frac{\sum_{j=1}^{n} \ x_j - \bar{x} \ ^{3}}{n \times \sigma^3} \tag{2}$$

$$\varphi_j = \frac{x_j - \bar{x}}{\sigma} \tag{3}$$

Where j is the current month, Cs is the coefficient of skewness, n is the total number of months in the record, φ_j is standard variation (also called the Z-Score) and x_j is precipitation in month j. To calculate the MCZI, the median of precipitation (Med) is applied instead of the average precipitation in the computation of the CZI (i.e., Med is substituted for x in equations 2 and 3) (Wu *et al*., 2001).

2.2.3. The decile index (DI)

The decile index was developed by Gibbs and Maher (1967). For this index, monthly precipitation totals from a long-term record are first ranked from highest to lowest to construct a cumulative frequency distribution. The distribution is then divided into 10 parts (tenths of deciles). The first decile is the precipitation value not exceeded by the lowest 10% of all precipitation values in a record. The second decile is between the lowest 10% and 20%, etc. Comparing the rate of precipitation in a month (or during a period of several months) with the long-term cumulative distribution of precipitation rates in that period, the severity of drought can be evaluated. The deciles are classified into five groups with two deciles per group. If precipitation falls into the lowest 20% (deciles 1 and 2), it is determined as considerably below normal. Deciles 3 to 4 (20% to 40%) demonstrate below normal precipitation, deciles 5 to 6 (40% to 60%) demonstrate near normal precipitation, 7 and 8 (60% to 80%) demonstrate above normal precipitation and 9 and 10 (80% to 100%) demonstrate significantly above normal precipitation.

3. Results and discussion

Due to the similar range of numerical values of the CZI, the MCZI, the Z-Score and the SPI (Table 1), they can be applied as comparable. However, as explained, the ranges of the DI are not similar to that of the SPI. To solve this issue and render them comparable with the SPI classes, the DI values have been categorized into similar classes (Table 1). Original DI classes of 30% to 40% (slightly below normal), 50% to 60% (normal) and 60% to 70% (slightly above normal) were increased to form a broader 'normal' DI class of 30% to 70% (corresponding to the 'normal' SPI range).

Table 1. Classification of SPI and DI ranges into groups (Morid et al., 2006)

Rates	Class	SPI	DI (%)
3	Extremely wet	≥ 2	≥ 90
2	Very wet	1.5 to 1.99	80 to 90
1	Moderately wet	1.0 to 1.49	80 to 70
0	Normal	-0.99 to 0.99	30 to 70
-1	Moderately dry	-1.0 to -1.49	20 to 30
-2	Very dry	-1.5 to -1.99	10 to 20
-3	Extremely dry	≤ 2	≤ 10

Linear regressions and the Pearson correlation coefficient (R^2) between the monthly values of the SPI versus the CZI, MCZI and Z-Score were estimated for eight chosen stations. The results showed that the SPI and CZI, Z-Score, MCZI and DI, respectively, generally showed a good relationship in terms of the time scale for one month. The linear regression between the values of the SPI and CZI from 1969 to 2009 is indicated in Figure 2, which shows that the CZI index generally had the strongest relationship with SPI, especially during normal months. As indicated, differences between indices increased during drier months, as the CZI tended to have higher negative values than the SPI. Morid *et al*. (2006) reported that SPI showed larger negative values compared to CZI. The R^2 values for all eight stations varied from 0.8 to 0.96.

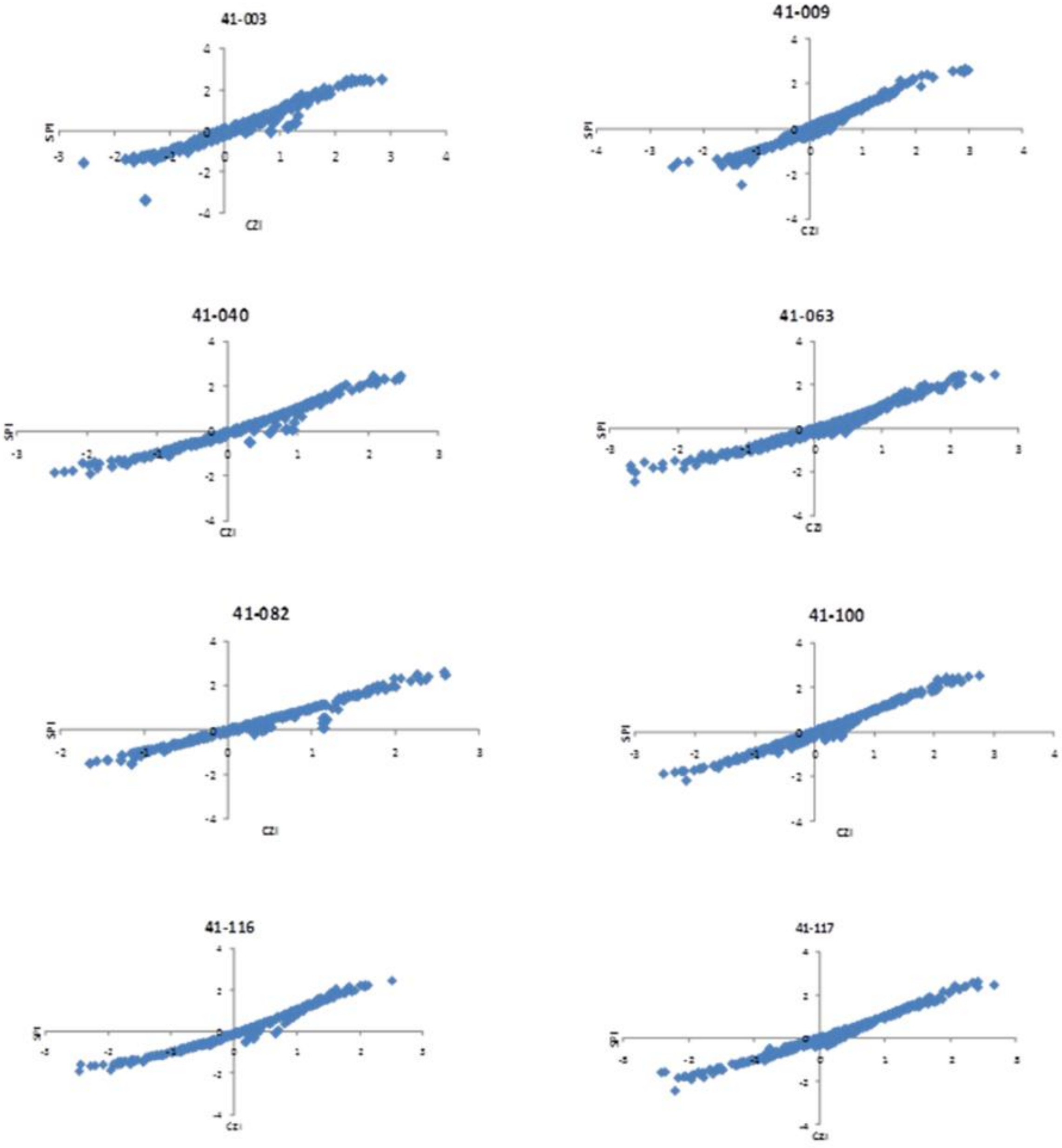

Fig. 2. Scatter diagram showing the SPI and CZI for the selected stations from 1969 to 2009

The MCZI indicated the weakest correlation among all indices (Fig. 3). The Z-Score indicated a good relationship with SPI for five stations and acceptable relationships for the other stations (Fig. 4). Similar to the CZI, the Z-Score tended to have lower values compared to the SPI during drier periods. However, for very wet periods, the index provided values higher than those of the SPI. The R^2 between SPI and the Z-Score differed from 0.55 to 0.86.

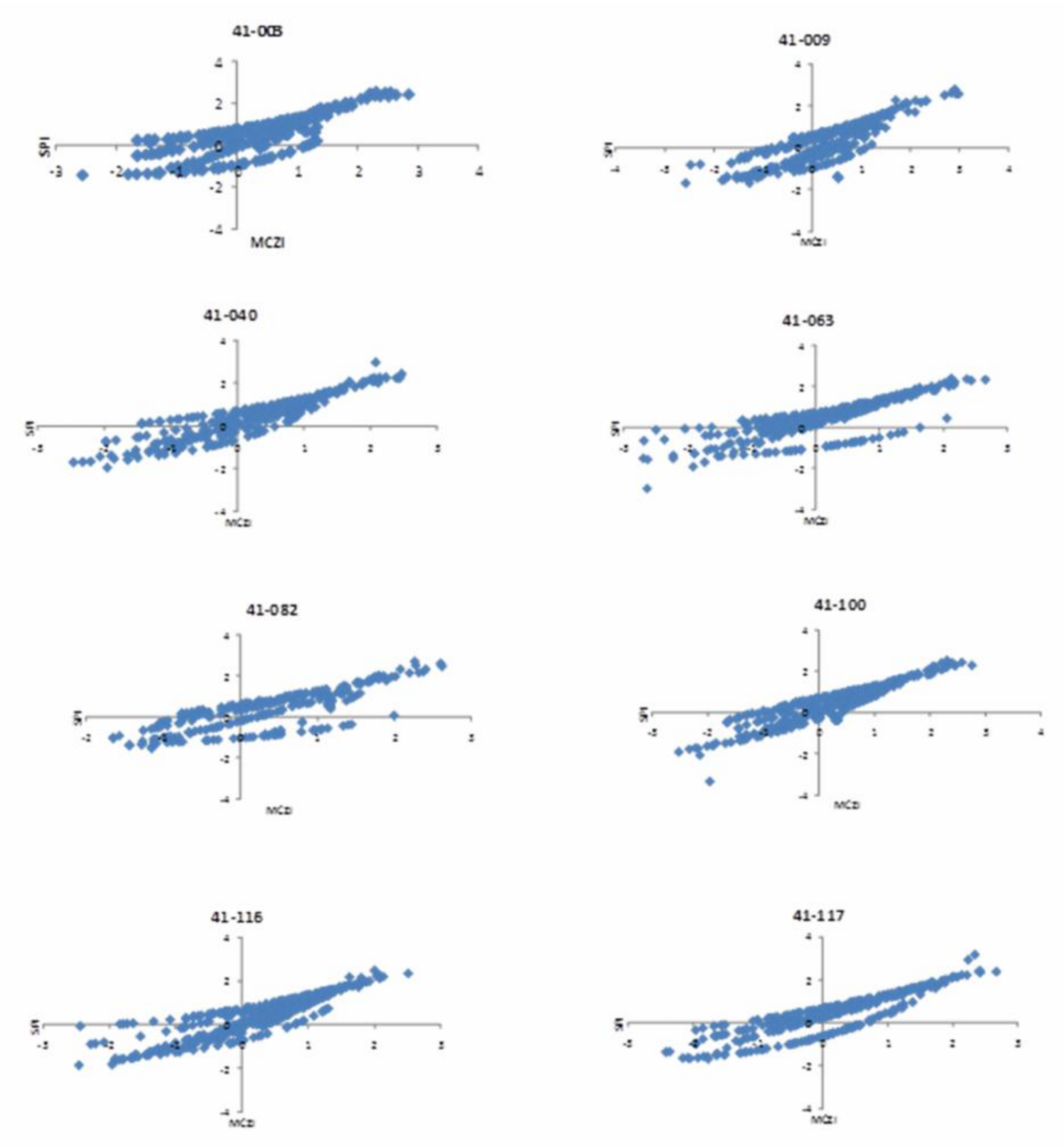

Fig. 3. Scatter diagram showing the SPI and MCZI for the selected stations from 1969 to 2009

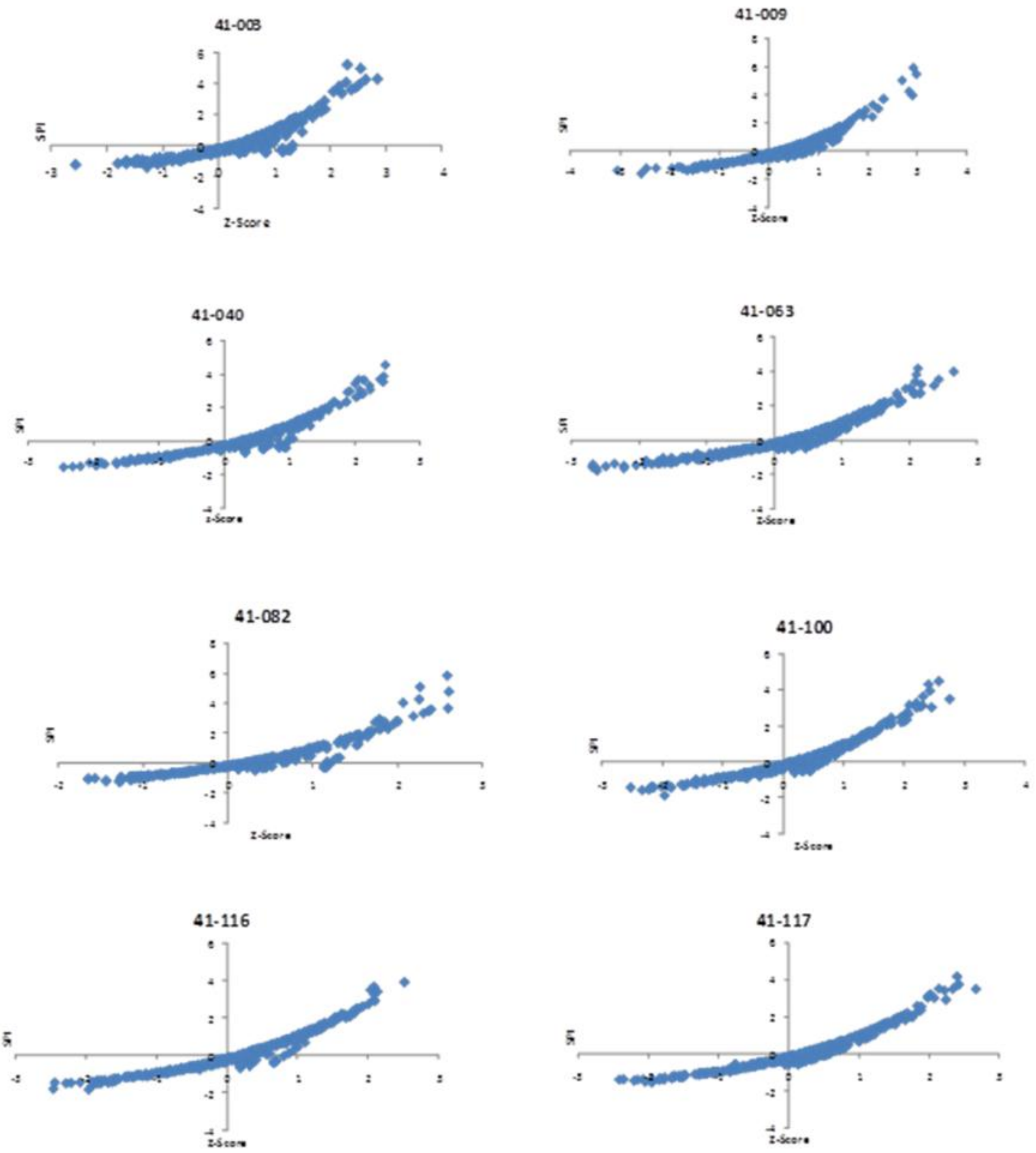

Fig. 4. Scatter diagram showing the SPI and Z-Score for the selected stations from 1969 to 2009

To compare SPI and DI, a histogram of the dry and wet classes were classified in seven classes as follows: ED – extremely dry; SD – severely dry; MD – moderately dry; N – normal; MW – moderately wet; SW – severely wet; EW – extremely wet (Fig. 5). The results showed that the frequency of dry and wet classes differed from the SPI, particularly in the ‘normal class’. The SPI index in Figure 6 shows a bell-shaped histogram and the ‘normal class’ of the SPI is much larger than in other classes. In the DI, other classes are higher than those in the SPI. This indicates a higher sensitivity on the part of DI to rates of precipitation when compared to the SPI.

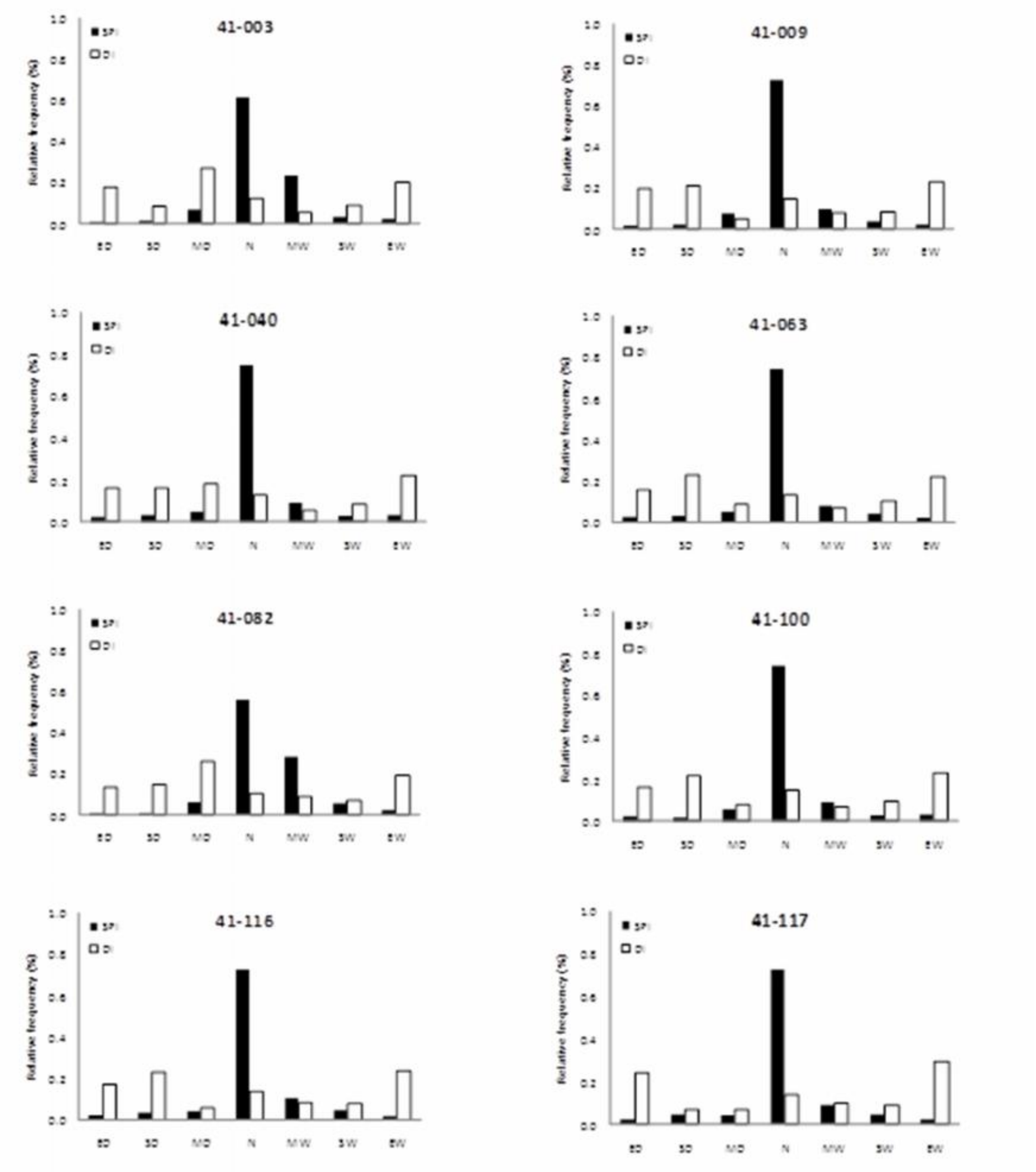

Fig. 5. Histograms for the drought frequency classes of the SPI and DI for the selected stations from 1969 to 2009

3.1. Spatial Analysis of Droughts Index

Based on other research (e.g., Morid *et al*., 2006 and Shahabfar and Eitzinger, 2013), the Iranian Emergency Agency reported 1999 to have been one of the driest years in Iran. Thus, SPI index was estimated using the October 1997 to September 2000 hydrological years and was evaluated for determining the patterns of regional droughts. The spatial distribution pattern of the annual analysis is shown in Figure 6 (a-d). As indicated here, the driest months were located in the northwestern and southwestern regions of study area.

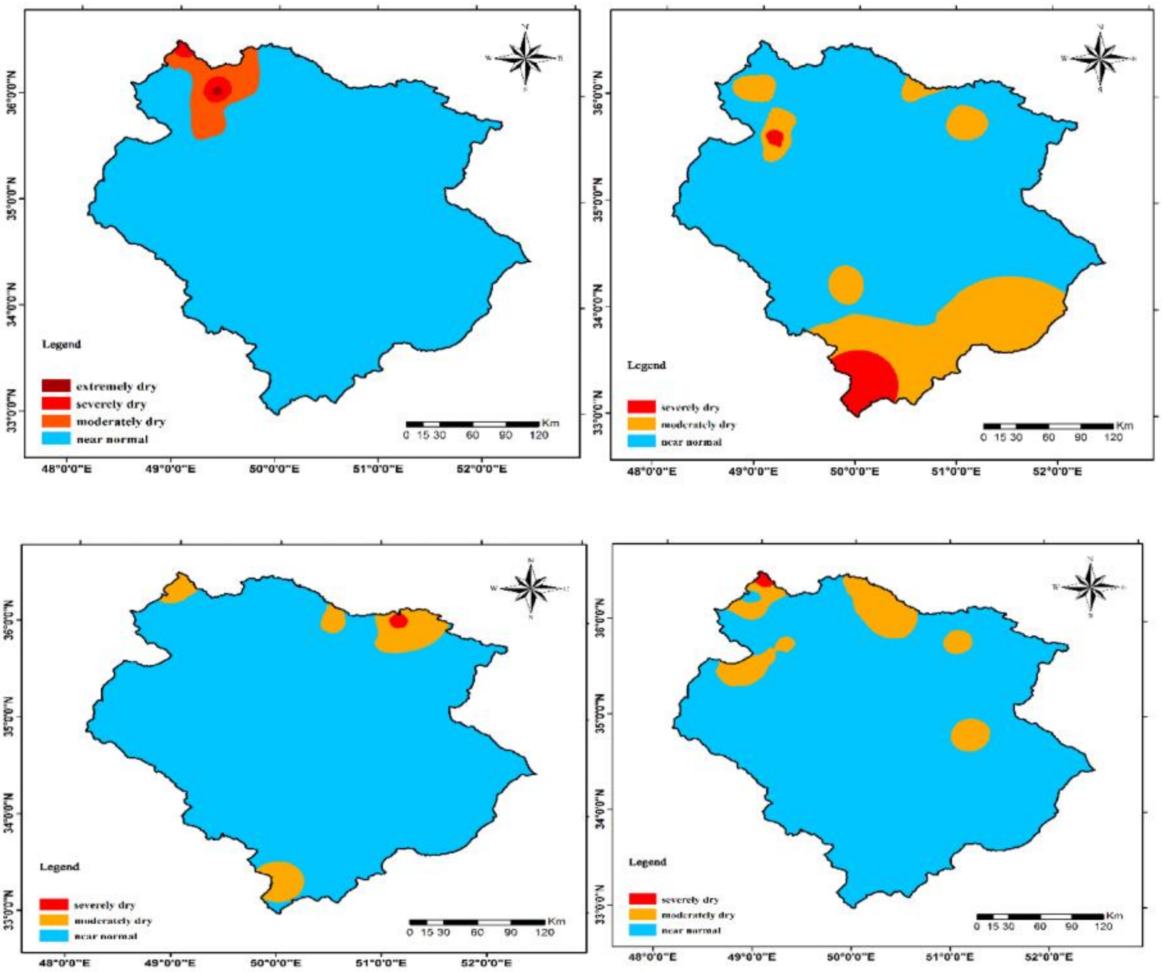

Fig. 6 (a-d). Spatial distribution of annual drought indices based on SPI index

4. Conclusion

This study focused on the application of four known drought indices (CZI, MCZI, Z-score, SPI and DI) for drought detection and monitoring in Salt Lake Basin in Iran.

The authors have concluded that the SPI, CZI and Z-Score drought indices show high performance in detecting and monitoring drought intensity compared to other drought indices. Given the similarities in performance among several indices, their selection can partially be related to such criteria as input information requirements, the simplicity of computations and their present level of acceptance in operational practice worldwide. For this study, linear regressions between the monthly values of the SPI and Z-Score, CZI, MCZI and DI from 1969 to 2009 in the study area showed that the SPI, CZI, Z-Score, MCZI and DI all had very different correlations. The strongest correlations were estimated between SPI and CZI, particularly during rainy months. The MCZI and the DI is not suggested for drought detection in the study area, since they have been found to declare ‘extreme drought’ conditions unreasonably frequently. Surprisingly, Naserzadeh and Ahmadi (2012) found the SPI and DI as the best indices for drought monitoring in Qazvin Province. Additionally, Ensafi Moghaddam (2007) reported SPI and DI as first and second index choices for drought monitoring in Salt Lake Basin.

Regarding the number of rain gage stations that were used in this study and the total area of Salt Lake Basin, the same suggestion for these two indices are applicable to the entire country of Iran. Compared to the other indices, the DI was found to be very sensitive to precipitation rate, which leads to unrealistically high spatial and temporal fluctuations in wet conditions, and variations being more pronounced during summer.

The varying responses of different indices point to the need for applying several indices for drought detection in the study area. According to the results of this research and similar studies conducted in Iran, by considering the advantages and disadvantages of the examined drought indices in Iran (e.g., less limitations from available input data for the computation of the CZI and Z-Score drought indices), the mentioned indices may be used as good drought predictors depending on the season, the length of the drought and climatic conditions (see Morid *et al*., 2006 and Shahabifar and Eitzinger, 2013). Instead of the SPI, these indices can be applied for operational use that is limited by the availability of long-term climatic data and low sensitivity to agro-meteorological drought conditions (Shahabifar and Eitzinger, 2013).

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