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COMPARISON OF SEVEN METEOROLOGICAL INDICES FOR DROUGHT MONITORING IN IRAN

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ABSTRACT

Drought monitoring is an essential component of drought risk management. It is normally performed using various drought indices that are effectively continuous functions of rainfall and other hydrometeorological variables. A number of drought indices have been introduced and applied in different countries to date. This paper compares the performance of seven indices for drought monitoring in the Tehran province of Iran. The indices used include deciles index (DI), percent of normal (PN), standard precipitation index (SPI), China-Z index (CZI), modified CZI (MCZI), Z-Score and effective drought index (EDI). The comparison of indices is based on drought cases and classes that were detected in the province over the 32 years of data, as well as over the latest 1998–2001 drought spell. The results show that SPI, CZI and Z-Score perform similarly with regard to drought identification and respond slowly to drought onset. DI appears to be very responsive to rainfall events of a particular year, but it has inconsistent spatial and temporal variation. The SPI and EDI were found to be able to detect the onset of drought, its spatial and temporal variation consistently, and it may be recommended for operational drought monitoring in the Province. However, the EDI was found to be more responsive to the emerging drought and performed better. Copyright © 2006 Royal Meteorological Society.

KEY WORDS: drought monitoring; drought indices; Tehran province; Iran

1. INTRODUCTION

Drought is perhaps the most complex natural hazard. It is often generally defined as a temporary meteorological event that stems from the lack of precipitation over an extended period of time compared with some long-term average condition (e.g. precipitation). But droughts develop slowly, are difficult to detect and have many facets in any single region. The success of drought preparedness and mitigation depends, to a large extent, upon timely information on drought onset, progress and areal extent. These types of information may be obtained through drought monitoring. Monitoring is normally performed using drought *indices*. Drought indices provide decision makers with information on drought severity and can be used to trigger drought contingency plans, if they are available.

Many drought indices have been developed to date. These include the Palmer Drought Severity Index (PDSI – Palmer, 1965), which is widely used in the United States, 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), the Surface Water Supply Index (SWSI – Shafer and Dezman, 1982) adopted by several states in the United States, and standardized precipitation index (SPI – McKee *et al*., 1993), which has gained world popularity, etc. Most of these indices are calculated using climate data (rainfall and, in some cases (PDSI), temperature). The review of drought indices can be found in several sources including

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http://www.drought.unl.edu/whatis/indices.htm, Alley (1984), Wu *et al*. (2001), Smakhtin and Hughes (2004). No index is ideal and/or universally suitable. The choice of indices for drought monitoring in a specific area should eventually be based on the quantity of climate data available and on the ability of the index to consistently detect spatial and temporal variations during a drought event.

This paper aims to compare the performance and evaluate the applicability of several rainfall-based drought indices in the Tehran province of Iran. Rainfall-dependent indices can point to both – abnormally dry and abnormally wet – conditions. The comparison of indices in this paper is, therefore, based on their ability to predict both cycles.

2. DROUGHTS IN IRAN AND THE STUDY AREA

Iran is frequently hit by recurring droughts. The most recent drought of 1998–2001 was the worst in the last 30 years with rainfall deficits consistently exceeding 60% of the mean annual rainfall in most of the country. The severity of this drought placed an extreme strain on water resources, livestock and agriculture. The Iranian Emergency Agency reported that 278 cities and 1050 villages had been affected. Also, the crops from a rain-fed area of 4 million ha as well as those from an irrigated area of 2.7 million ha were completely destroyed. The total agricultural and livestock losses by the year 2001 were estimated to be US$2.6 billion. Eighteen out of the 28 provinces of the country were affected, but the impact of the drought differed throughout the country and some of the provinces were more hit than others. Tehran province was one of the most severely hit with its average temperature increased by 4 C and storages of its main dams (i.e. Karadj, Latian and Lar) reduced to 50% of its long-term average (Fahmi, 2001; Mir Abolghasemi *et al*., 2001).

Tehran province is located in the northern part of Iran (Figure 1). The province has a total area of 17 250 km^2 and includes 55 cities. The total population in the province is 14 million. Precipitation varies from 700 mm in the northern parts to 120 mm in the southern parts. Six meteorological stations (Deh Someh, Siera, Mehrabad, Abali, Ammameh and Firouzkoh), which are located in different climatic regions in the province, were selected to examine the sensitivity of drought indices at specific points (Figure 1). For studies of areal drought extent, the precipitation records from 43 stations in the province were utilized. The record length at these stations is from January 1970 to December 2001. The missing data gaps were patched using regression equations with the nearest suitable station. A special focus was placed on the most recent drought spell of 1998–2001.

3. DROUGHT INDICES

Seven drought indices have been selected for this study. They include the percent of normal (PN), the standard precipitation index (SPI), the deciles index (DI), the CZI, the modified CZI (MCZI), the Z-Score and the

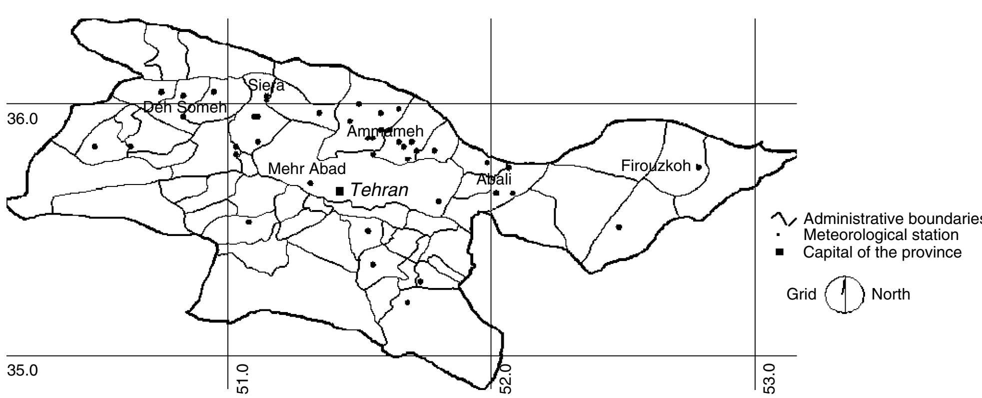

Figure 1. A schematic map of the Tehran province showing the location of the selected stations

effective drought index (EDI). A common feature of the indices selected is that they all are calculated using precipitation data only. All indices considered have been applied to rainfall time series with a time step of 1 month in this study. A brief description of these indices is given in the following text.

3.1. The percent of normal

The PN is one of the most straightforward measures of rainfall deviation from its long-term mean. 'Normal' may be and is usually set to a long-term mean precipitation value at a location. The value of 'normal' may be calculated for a month, a season or a year and is considered to be 100%. The same PN may have different specific impacts at different locations and, therefore, it is a bit of a simplistic measure of precipitation deficit. Also, what is normal may be perceived differently in different regions.

3.2. The decile index

In this approach suggested by Gibbs and Maher (1967) and widely used in Australia (Coughlan, 1987), 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 split into 10 parts (tenths of distribution or 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 amount of precipitation in a month (or during a period of several months) with the long-term cumulative distribution of precipitation amounts in that period, the severity of drought can be assessed. The deciles are grouped into five classes, two deciles per class. If precipitation falls into the lowest 20% (deciles 1 and 2), it is classified as *much below normal*. Deciles 3 to 4 (20 to 40%) indicate *below normal* precipitation, deciles 5 to 6 (40 to 60%) indicate *near normal* precipitation, 7 and 8 (60 to 80%) indicate *above normal* precipitation and 9 and 10 (80 to 100%) indicate *much above normal* precipitation. In the current study, monthly rainfall time series are normalized using the Box–Cox transformation (McMahon, 1986).

3.3. The standardized precipitation index (SPI)

To calculate the SPI, a long-term precipitation record at the desired station is first fitted to a probability distribution (e.g. gamma distribution), which is then transformed into a normal distribution so that the mean SPI is zero (McKee *et al*., 1993, 1995; Edwards and McKee, 1997). The SPI may be computed with different time steps (e.g. 1 month, 3 months, 24 months). Guttman (1998) showed that the use of SPI at longer time steps was not advisable as the sample size reduces even with originally long-term data sets. The use of different timescales allows the effects of a precipitation deficit on different water resource components (groundwater, reservoir storage, soil moisture, streamflow) to be assessed. Positive SPI values indicate greater than mean precipitation and negative values indicate less than mean precipitation. The SPI may be used for monitoring both dry and wet conditions. The 'drought' part of the SPI range is arbitrarily split into 'near normal' ($0.99 > \mathrm{SPI} > -0.99$), 'moderately dry' ($-1.0 > \mathrm{SPI} > -1.49$), 'severely dry' ($-1.5 > \mathrm{SPI} > -1.99$) and 'extremely dry' ($\mathrm{SPI} < -2.0$) conditions. A drought event starts when SPI value reaches -1.0 and ends when SPI becomes positive again. The positive sum of the SPI for all the months within a drought event is referred to as 'drought magnitude'. This index is presently used as one of the indices for drought monitoring in the entire United States (http://www.drought.unl.edu/monitor/spi.htm). Also, a number of studies evaluated the performance of this index (e.g. Wu *et al*. (2001) – in China, Ansari (2003) – in Iran, etc.).

3.4. 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 calculated as:

$$CZI_j = \frac{6}{C_s}\left(\frac{C_s}{2}\varphi_j + 1\right)^{1/3} - \frac{6}{C_s} + \frac{C_s}{6} \tag{1}$$

$$C_s = \frac{\sum_{j=1}^{n} (x_j - \overline{x})^3}{n \times \sigma^3} \quad (2)$$

$$\varphi_j = \frac{x_j - \overline{x}}{\sigma} \quad (3)$$

where j is the current month, C_s is coefficient of skewness, n is the total number of months in the record, ϕ_j is standard variate, also called the Z-Score and x_j is precipitation of j month. To compute the MCZI, the median of precipitation *(Med)* is used instead of the mean of precipitation in the calculation of the CZI (i.e. *Med* is substituted for $\overline{x}$ in equations 2 and 3). This was done by Wu *et al.* (2001) in an attempt to reduce the differences between the SPI and the MCZI. They, however, concluded that the differences between these two indices did not reduce as significantly as they did between the SPI and the CZI.

3.5. The effective drought index (EDI)

Byun and Wilhite (1996) suggested that many indices used have limitations in indicating the exact start and end of the drought period and drought duration. They proposed another rainfall-related measure, named EDI, to rectify some of these disadvantages. Unlike many other drought indices, the EDI in its original form is calculated with a daily time step.

The EDI is a function of the PRN – 'precipitation needed for a return to normal', or in other words, for the recovery from the accumulated deficit since the beginning of a drought.

$$EDI_j = \frac{PRN_j}{ST(PRN_j)} \quad (4)$$

$$PRN_j = \frac{DEP_j}{\sum_{N=1}^{j} (1/N)} \quad (5)$$

$$DEP = EP - MEP \quad (6)$$

where j is actual duration, *ST(PRN)* is the standard deviation of each day's *PRN, EP* is 'effective precipitation' and *MEP* is the mean of each day's *EP*. The *EP* is the main new concept in the calculation procedure. The *EP* refers to the summation of all daily precipitation with a time reduction function. The *EP* for any day is a function of precipitation of the current day, as well as of previous days but with lower weights. The calculation procedure of the EDI starts by applying a dummy water deficit period as a requirement for determining the real period. The dummy duration can vary, e.g. it could be 365 days, a representative value of the total water resources available or stored for a longer period, or it could be as short as 15 days, a representative of a short period. In this study, a dummy value of 365 days is chosen as it represents a dominant precipitation cycle globally. Once the duration is set, the *daily effective precipitation* is calculated with the following equation:

$$EP_i = \sum_{n=1}^{i} \left[\left(\sum_{m=1}^{n} P_m \right) \Big/ n \right] \quad (7)$$

where i is the duration of summation and P_m is the precipitation of $m - 1$ days before. More details on a rather complex calculation procedure of the EDI are available from Byun and Wilhite (1999).

Similar to the SPI, the EDI values are standardized, which allows drought severity at two or more locations to be compared with each other regardless of climatic differences between them. The EDI varies from −2.5 to 2.5. Similar to the SPI, it has thresholds indicating the range of wetness – from extreme drought conditions to extremely wet conditions. The 'drought range' of the EDI indicates extreme drought conditions at EDI < −2.5, severe drought at −1.5 > EDI > 2.49 and moderate drought at −0.7 > EDI > −1.49. Near normal conditions are indicated by −0.69 < EDI < 0.69.

The EDI as the measure of drought has been suggested recently and has not yet received much attention. It however, in principle, is applicable for drought monitoring over large regions. The major problem associated with the EDI in its original form is that it is based on daily precipitation data. Smakhtin and Hughes (2004) modified the algorithm to allow for the EDI application with monthly data. However, this modification is yet to be tested. Therefore, the original 'daily' EDI algorithm is used in the current study.

4. RESULTS AND DISCUSSION

The CZI, the MCZI, the Z-Score, the SPI and the EDI have an almost similar range of numerical values (Table I). Therefore, they are comparable. However, as described above, the ranges of the DI and the PN differ from that of the SPI. To make them comparable with the SPI classes, the DI and PN values have been categorized into similar classes (Table I). Original DI classes of 30–40% (slightly below normal), 50–60% (normal) and 60–70% (slightly above normal) have been added up to form a broader 'normal' DI class of 30–70% (corresponding to the 'normal' SPI range). The high PN values have not been categorized for the purpose of this study and all values in excess of 110% have been considered as 'wet' conditions (Table I).

4.1. Comparison of the CZI, MCZI and Z-Score with the SPI

For this part of the analyses, the Pearson correlation coefficient (R^2) for the SPI *versus* the CZI, MCZI and Z-Score were computed for six selected stations (see preceding text). Figure 2(a)–(f) shows the linear regression between the values of the SPI and CZI from 1969 to 2000. The figure indicates that the two indices generally have a good relationship, particularly during normal and wet months (Figure 2(b), (d), (f)). Discrepancies increase during drier months, as the SPI tends to have larger negative values than the CZI. This fact is more evident at Mehrabad (Figure 2(c)) and Abali (Figure 2(d)). The R^2 values for all six stations vary from 0.84 to 0.96. Surprisingly, Wu *et al*. (2001) reported larger negative values for CZI than for SPI, which contradicts the finding in this study. This mismatch needs to be investigated further.

The MCZI has shown poor results in drought detection (Figure 3). The substitution of the precipitation median with the precipitation mean caused significant changes compared to the original CZI values (Figure 2). The Z-Score has shown a good correlation with SPI (Figure 4). Similar to the CZI, the Z-Score tends to have lower values compared to the SPI during drier periods. But, for very wet periods, the index gives values higher than SPI. The R^2 between SPI and the Z-Score varies from 0.74 to 0.89.

4.2. Comparison of the EDI and SPI

The EDI is effectively a non-parametric index, with a daily timescale. It was, therefore, necessary to average daily values for computing the monthly EDIs. Figure 5 shows the scatter plot of the index *versus* the SPI. It is evident that the correlation is very poor and R^2 is almost zero. For more accurate

Table I. Categorization of SPI, EDI, DI and PN values into classes

Values	Class	SPI	EDI	DI (%)	PN (%)
3	Extremely wet	≥2	≥2.5	≥90	
2	Very wet	1.5 to 1.99	1.5 to 2.49	80 to 90	
1	Moderately wet	1.0 to 1.49	0.7 to 1.49	70 to 80	≥110[a]
0	Normal	−0.99 to 0.99	−0.69 to 0.69	30 to 70	80 to 110
−1	Moderately dry	−1.0 to −1.49	−0.7 to −1.49	20 to 30	55 to 80
−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

[a] All high values of PN (representing wet conditions) are categorized as one 'wet' class.

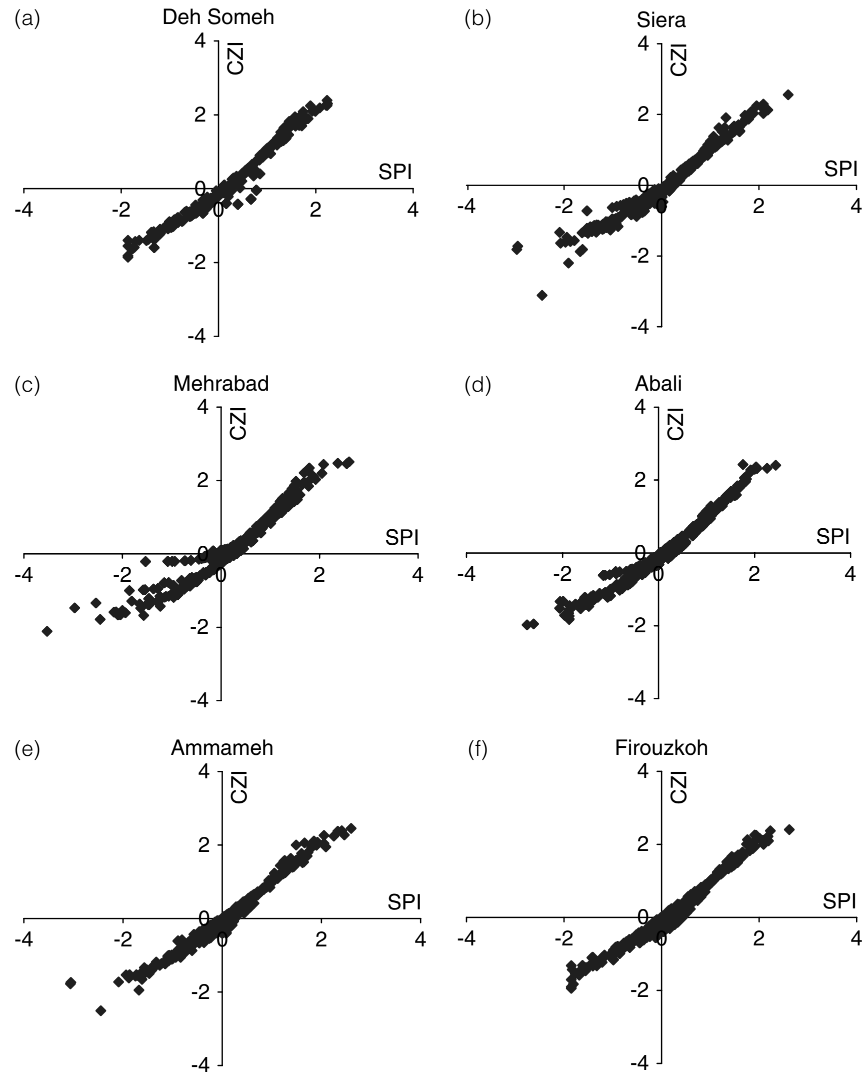

Figure 2. Scatter diagram for the SPI and CZI for the selected stations from 1970 to 2001

evaluation, relative frequencies of the dry classes identified by the two indices were compared for the 32-year-long period. The histogram of the dry and wet classes is shown in Figure 6 (categories on the *X* axis in Figures 6–10 are as follows: ED – 'extremely dry', SD – 'severely dry', MD – 'moderately dry', N – 'normal', MW – 'moderately wet', SW – 'severely wet' and EW – 'extremely wet'). Both indices in Figure 6 have a bell-shaped histogram, but the 'normal class' of the SPI is much larger than that of the EDI. Conversely, other classes in the EDI are higher than those in the SPI. This fact points to a larger sensitivity of the EDI to changes in precipitation, compared to the SPI.

4.3. Comparison of the DI and SPI

The same evaluation has been used for the DI (Figure 7). Similar to the EDI, the frequency of dry and wet cases differs from that of the SPI, especially in the 'normal class'. The magnitude of this class in the SPI is from 2.5 (Deh Someh station) to 3.6 (Abali station) times higher than in the DI. But, the DI declares lower normal status compared to the EDI.

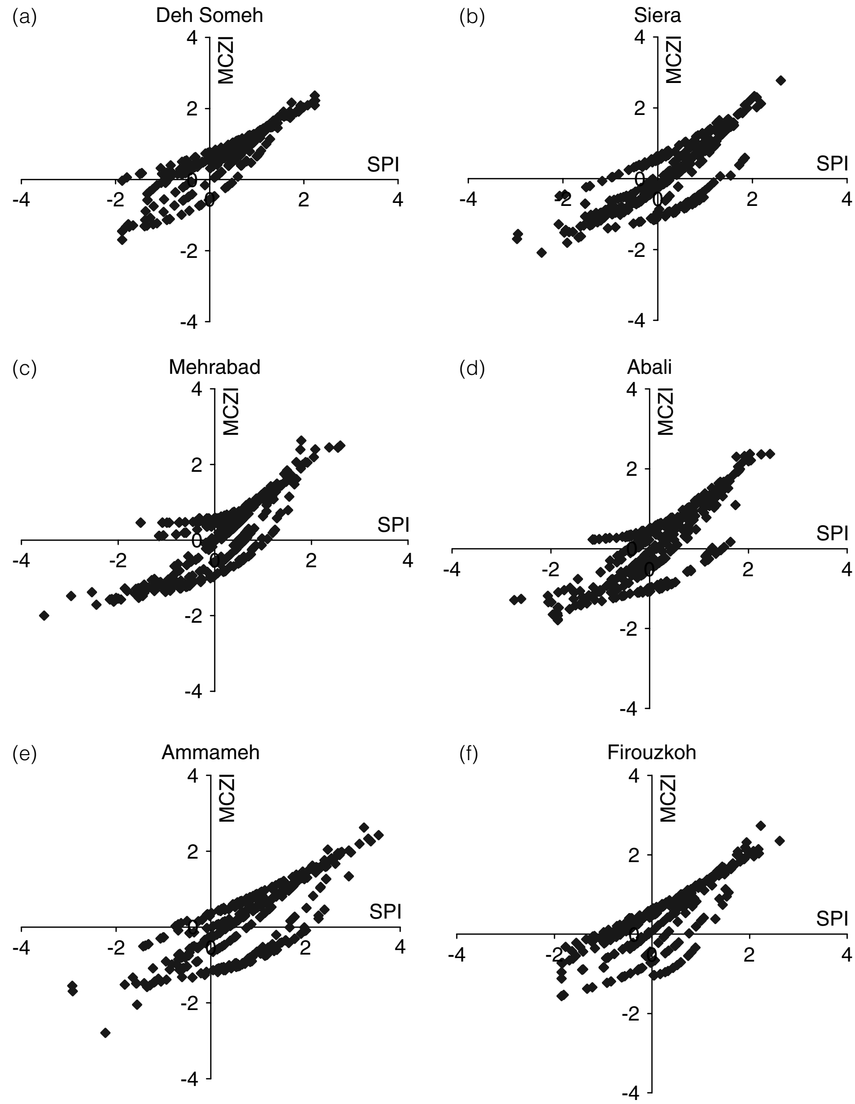

Figure 3. Scatter diagram for the SPI and MCZI for the selected stations from 1970 to 2001

4.4. Comparison of the PN and SPI

To compare the PN and the SPI, all wet SPI classes have been added up and then compared with the PN. Figure 8 shows the histogram of the relative frequency of the dry and wet classes according to the PN and SPI. Conversely, with the other indices (and what is also expected from the statistical point of view), 'extreme drought' is much higher than the 'normal' class in the PN.

4.5. Evaluation of indices during the 1998–2001 drought spell

The previous evaluation showed similar behaviour of the CZI and Z-Score with the SPI and improper response of the MCZI and PN. Therefore, the latter two have been discarded for further analysis. In this section, the performance of the DI, EDI and SPI have been assessed for the 1998–2001 period, during which the Tehran province experienced an extreme and long-lasting drought event. Table II shows relative frequency of the indices during this period. The SPI has detected 63.8 (Tehran station) to 77.7% (Firouzkoh

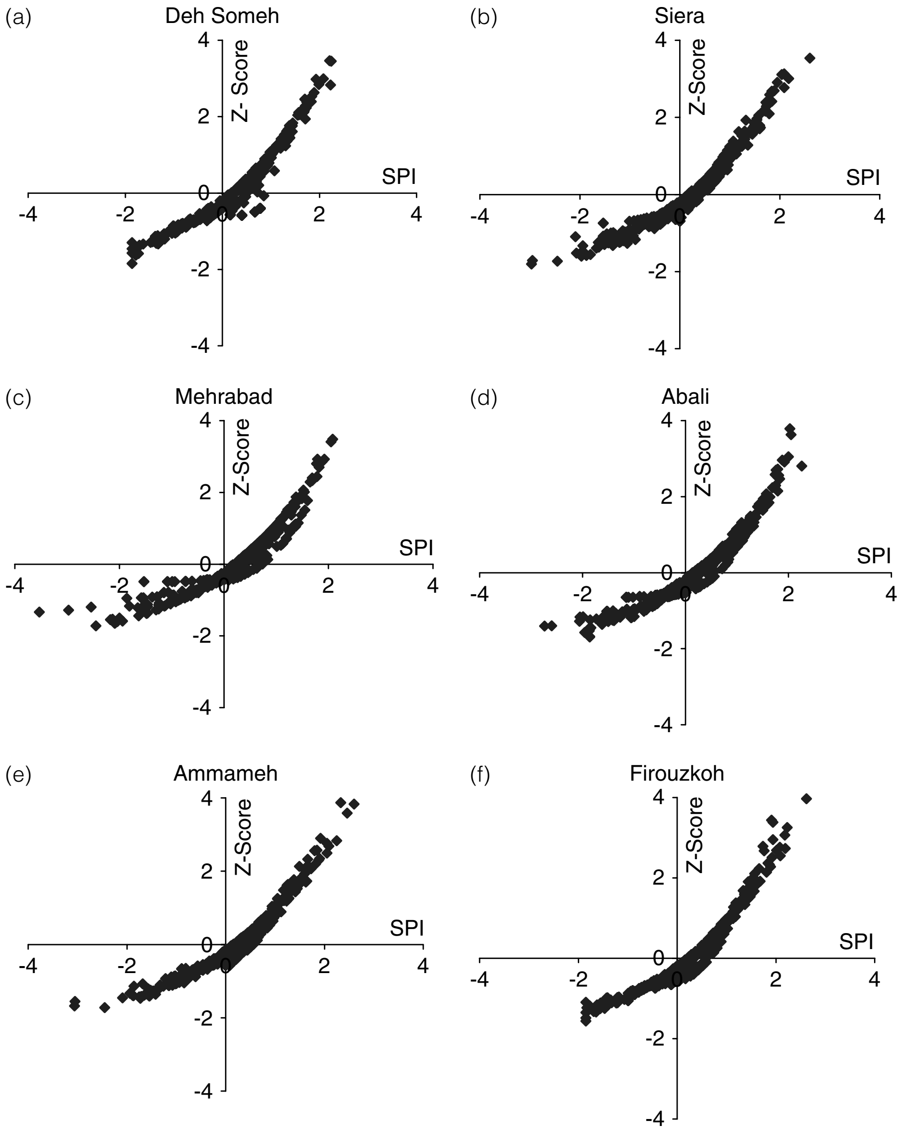

Figure 4. Scatter diagram for the SPI and Z-Score for the selected stations from 1970 to 2001

station) of the months in the 'normal' situation and only 2.7–29.3% of the period in dry classes. But, the DI and EDI have been more responsive to the dry situation. The DI detected only 13.8 (Tehran station) to 38.8% (Firouzkoh station) of the period in the 'normal' class and it is 19.4–41.6% according to the EDI, for the same stations. However, the main difference between the two is the relative frequency of the wet classes. The wet classes' frequency identified by the DI varies from 30.4 to 55.4%. For the severe drought of 1998–2001, such magnitude of wet classes could not be anticipated. As it is shown in Table II, wet classes detected by the EDI are not significant (except Firouzkoh station), which is more realistic.

4.6. Mapping the spatial extent of the 1998–2001 drought

More insights into the performance of different indices can be obtained from examining how they reflect changing drought conditions spatially. Maps of drought conditions for a period of 1998–2001 have

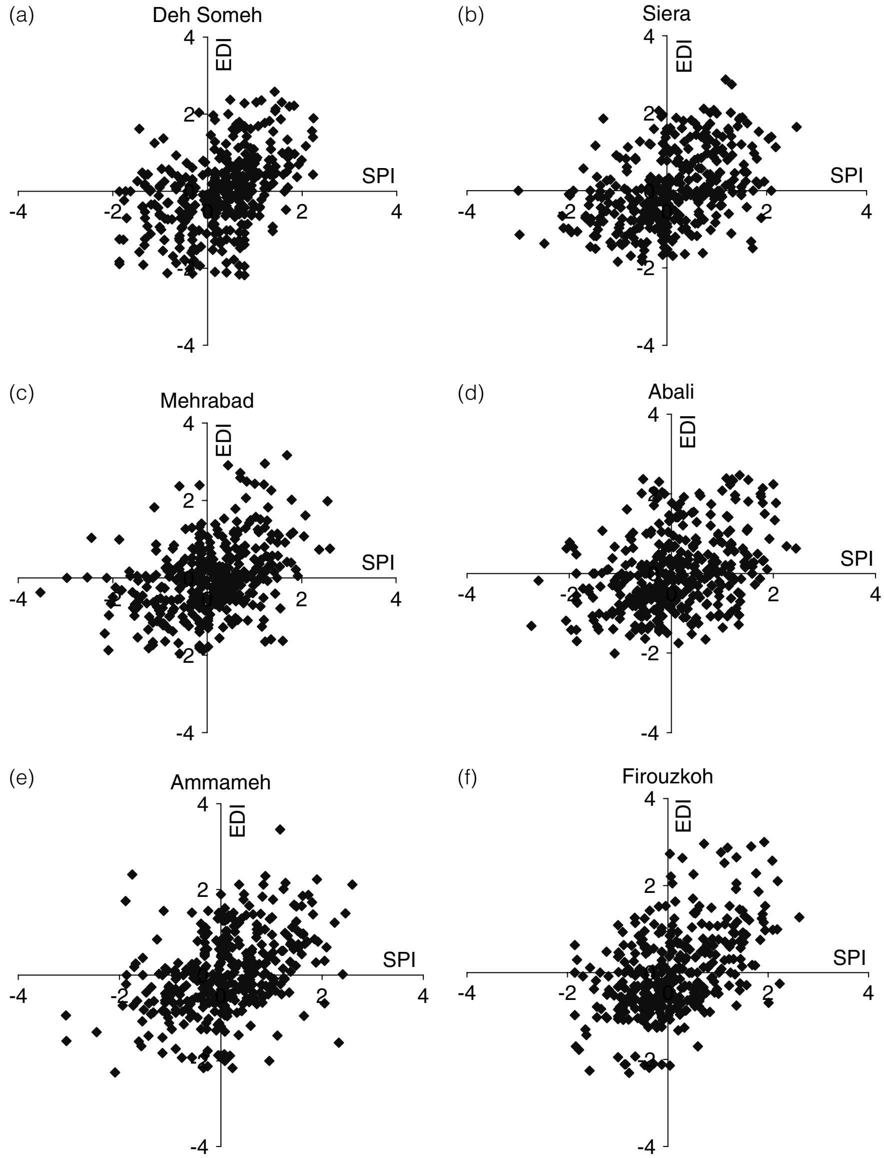

Figure 5. Scatter diagram for the SPI and CZI for the selected stations from 1970 to 2001

been drawn using GIS facilities (IDRISI-32). Analysis of these maps revealed an inconsistent spatial and temporal behaviour of the DI in response to drought. Figure 9(a) and (b) shows drought pattern in the Tehran province for October and November 1998. It is evident that a very wet condition in October 1998 suddenly turned into a very dry condition in November. At the same time, Figure 9(c)–(f), displaying the drought conditions in the province in terms of the SPI and EDI for the same months does not reveal these sudden changes. Another problem with the DI can be seen in Figure 10(a), which shows a drought map of the province for October 1999. The inconsistent spatial change within the province is obvious. While most of the province is in the 'below normal' to 'very much below normal' condition, in the eastern parts, a 'much above normal' condition is detected by this index. At the same time, the drought maps of the SPI and EDI for this month (Figure 10(b) and (c)) do not indicate such high spatial variability in wetness.

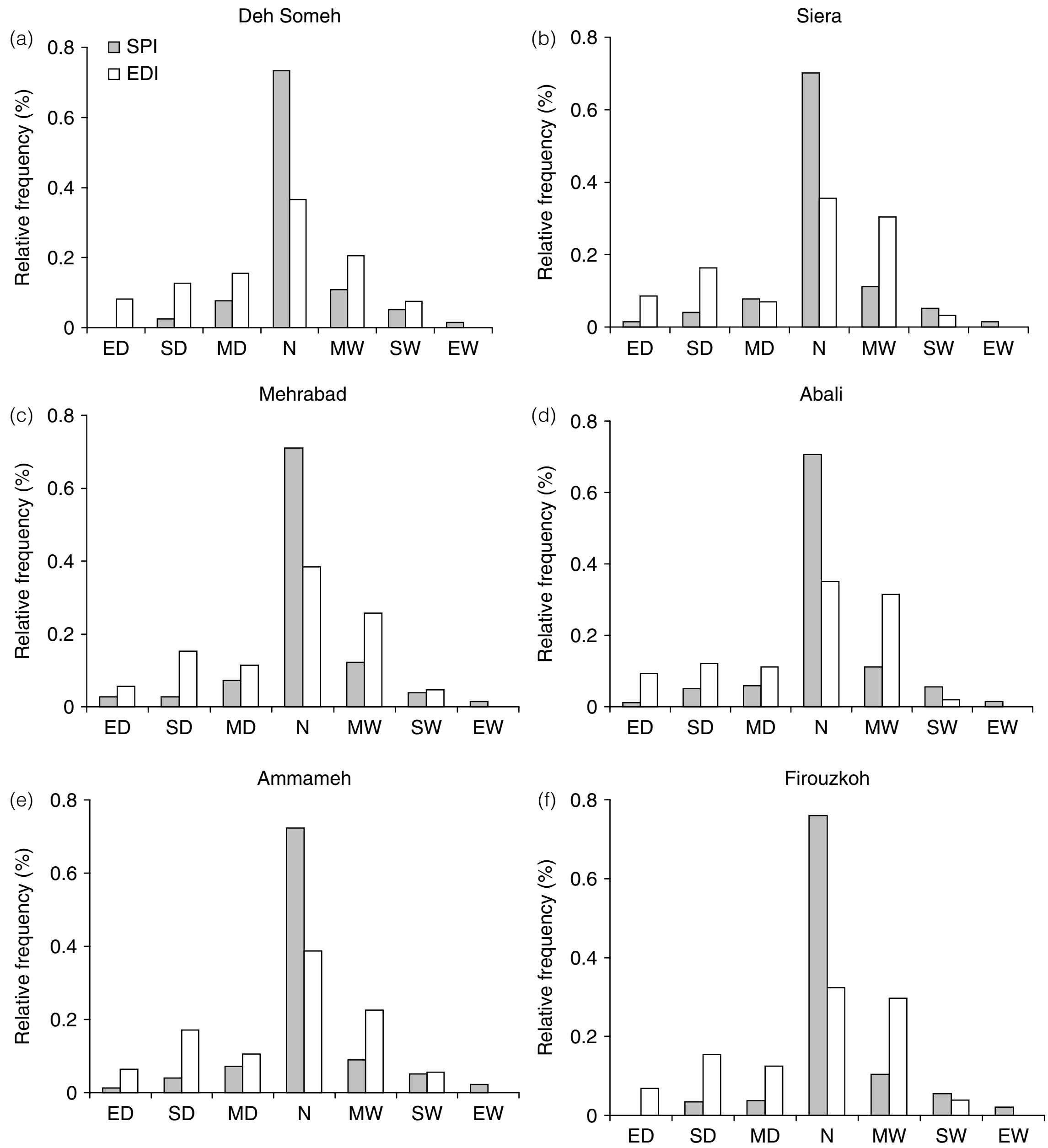

Figure 6. Histograms of the drought frequency classes of the SPI and EDI for the selected stations in 1970–2001

5. CONCLUSIONS

The study examined the performances of seven known drought indices (the CZI, the MCZI, the Z-score, the SPI, the DI, the PN and the EDI) for drought detection and monitoring in the Tehran province of Iran. The following conclusions can be drawn from this research.

- Despite different underlying statistical distributions, the SPI, CZI and Z-Score have performed in a similar manner. This similarity may point to the importance of utilizing long-term precipitation records for drought analyses (which can remove marginal differences between the indices). Given the similarity in

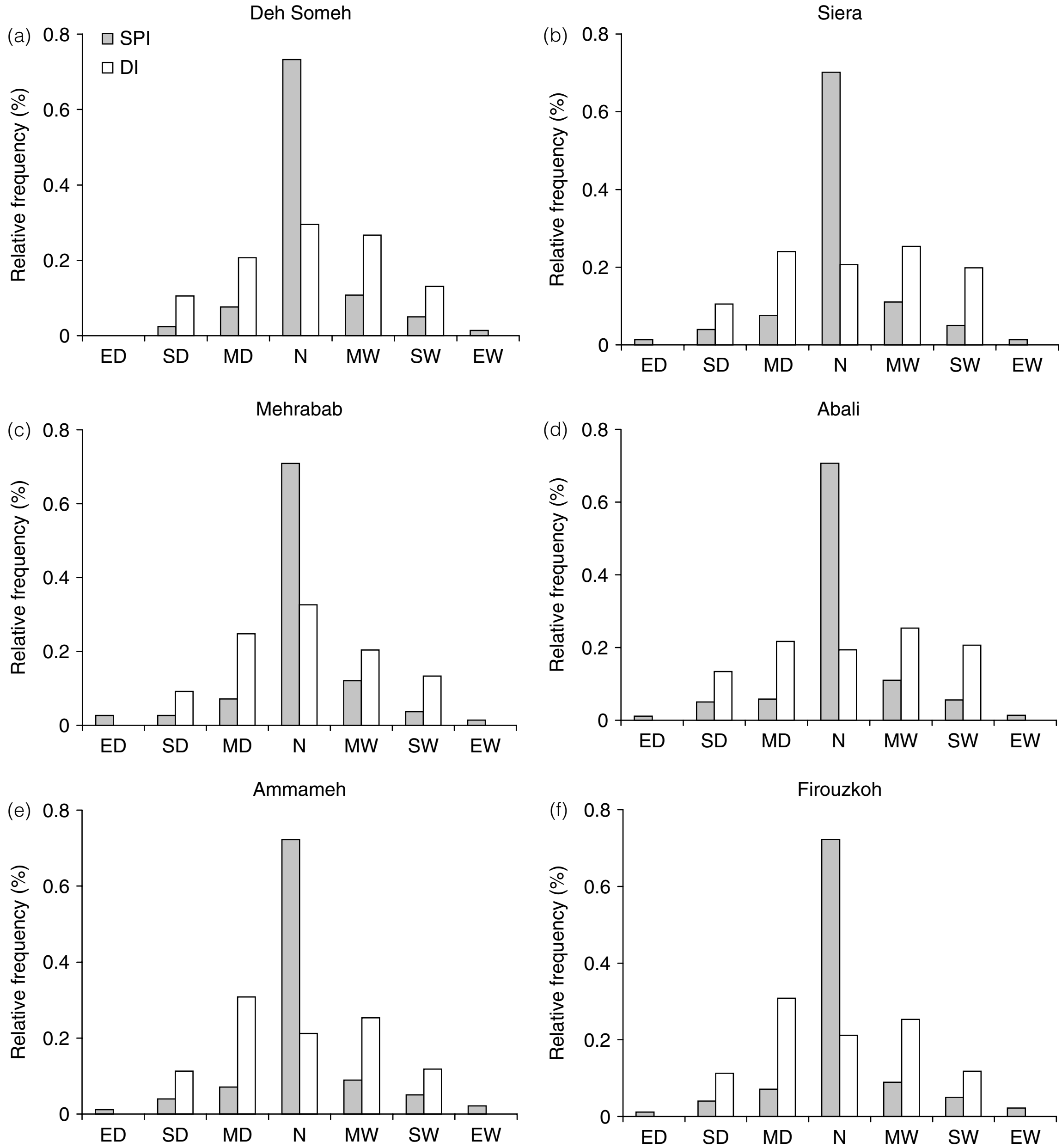

Figure 7. Histograms of the drought frequency classes of the SPI and DI for the selected stations in 1970–2001

the performance of several indices, the choice of an index may partially be based on such criteria as input information requirements, simplicity of calculations and current level of acceptance in operational practice in the world.

- The MCSI and the PN should not be recommended for drought monitoring in the province since they have been found to declare 'extreme drought' conditions unreasonably frequently (about three to four times more often than 'normal'). Given the large range of precipitation between the stations used in this study, the same recommendation for these two indices may be applicable to the entire country.
- The DI appeared to be very sensitive, which leads to unrealistically high temporal and spatial variations in wet conditions and the variations being more pronounced during summer. It is possible that the DI

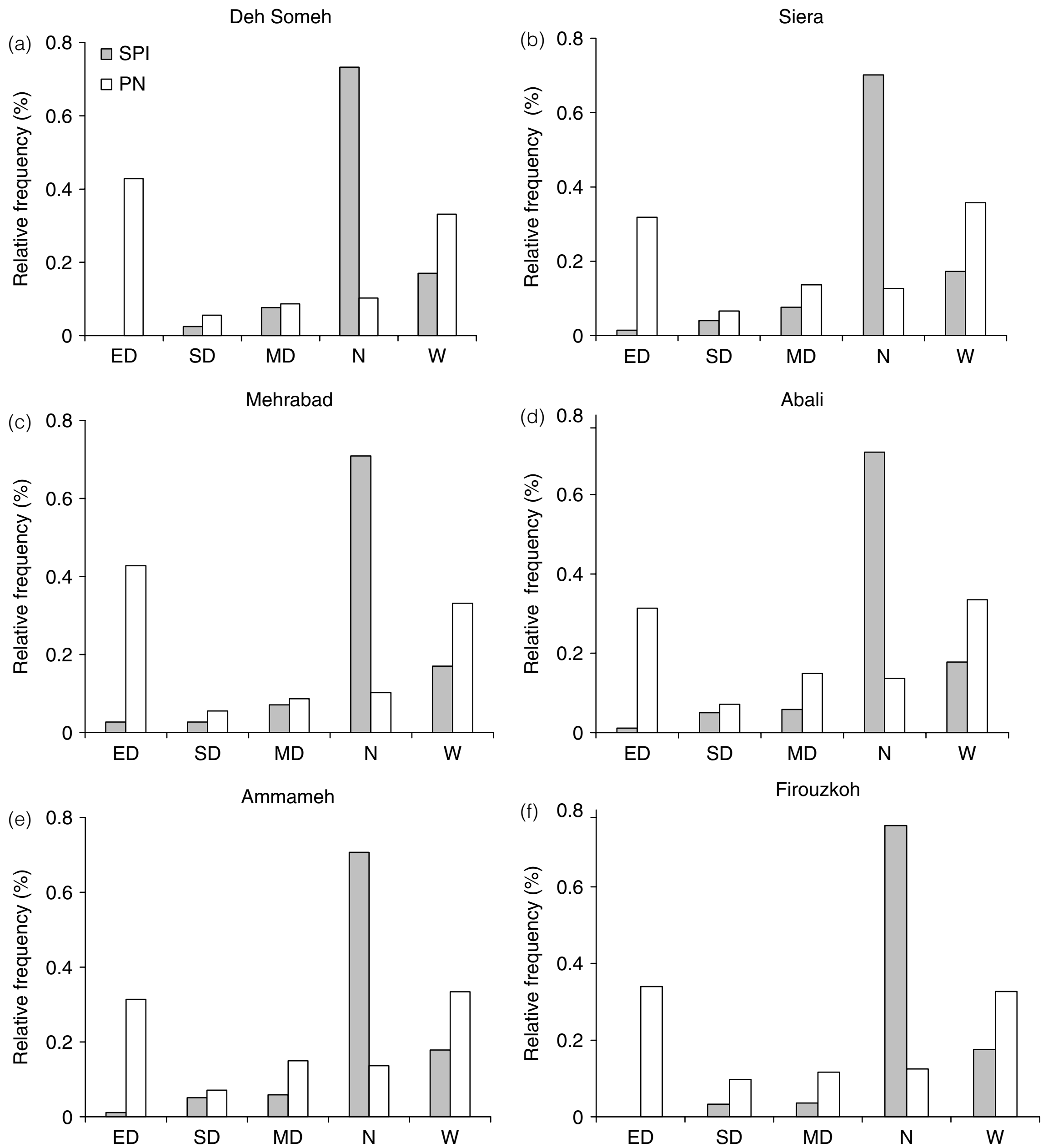

Figure 8. Histograms of the drought frequency classes of the SPI and PN for the selected stations in 1970–2001

sensitivity could be reduced if it is used with temporal scales larger than 1 month. However, in this case, its use for actual drought monitoring (at least in the case of Tehran province) becomes problematic.

- The EDI was found to be more responsive to the emerging drought conditions compared with the DI and the SPI, particularly during the 1998–2001 drought spell. Also, compared to other indices, the EDI was found to be able to describe developing drought conditions well – spatially and temporally. The EDI efficiency can be related to the concept of effective precipitation (EP) that the index uses. However, the requirement of a continuous daily precipitation record can be a serious limitation for the wider use of the EDI.

Table II. Relative frequencies (%) of different wetness categories detected by three indices during 1998–2001 drought

Siera	SPI	EDI	DI	Deh Someh	SPI	EDI	DI
Extremely dry	0	0	0	Extremely dry	0	0	2.7
Very dry	2.7	16.6	11.1	Very dry	0	0	22.2
Moderately dry	16.6	55.5	22.2	Moderately dry	13.8	58.3	30.5
Normal	66.6	25	25	Normal	69.4	33.3	13.8
Moderately wet	5.5	0	25	Moderately wet	13.8	5.5	2.7
Severely wet	8.3	2.7	16.6	Severely wet	2.7	2.7	19.4
Extremely wet	0	0	0	Extremely wet	0	0	8.3
Abali	**SPI**	**EDI**	**DI**	**Mehrabad**	**SPI**	**EDI**	**DI**
Extremely dry	2.7	0	0	Extremely dry	5.5	0	0
Very dry	5.5	2.7	19.4	Very dry	0	22.2	19.4
Moderately dry	11.1	63.8	25	Moderately dry	13.8	52.7	33.3
Normal	63.8	27.7	25	Normal	63.8	19.4	13.8
Moderately wet	16.6	5.5	13.8	Moderately wet	8.3	5.5	16.6
Severely wet	0	0	16.6	Severely wet	8.3	0	16.6
Extremely wet	0	0	0	Extremely wet	0	0	0
Firouzkoh	**SPI**	**EDI**	**DI**	**Ammameh**	**SPI**	**EDI**	**DI**
Extremely dry	0	0	0	Extremely dry	8.3	0	0
Very dry	0	0	8.3	Very dry	2.7	33.3	19.4
Moderately dry	2.7	2.7	8.3	Moderately dry	16.6	36.1	30.5
Normal	77.7	41.6	38.8	Normal	63.8	27.7	19.4
Moderately wet	11.1	27.7	27.7	Moderately wet	2.7	0	27.7
Severely wet	8.3	27.7	16.6	Severely wet	2.7	2.7	27.7
Extremely wet	0	0	0	Extremely wet	2.7	0	0

- Varying responses of different indices point to the need of using several indices for drought monitoring in the study area as well as in the entire country. For the study area in question, it is recommended that at least EDI and SPI are included into an emerging provincial drought monitoring system. A combination of rainfall-based indices with remote sensing–related indices could provide an additional advantage for drought identification and monitoring that needs to be explored.

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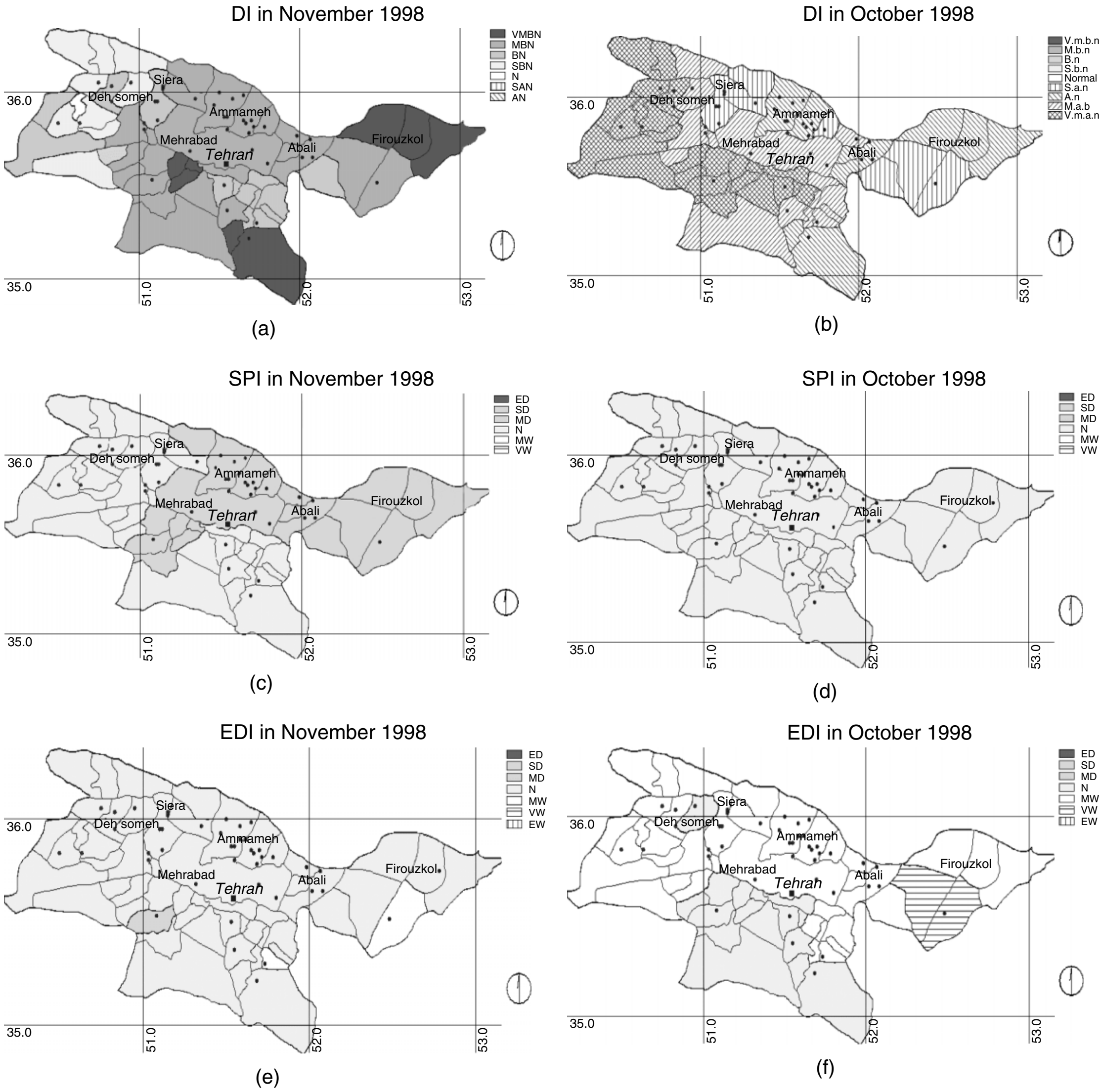

Figure 9. Drought class of the indices during October and November 1998 in the Tehran province

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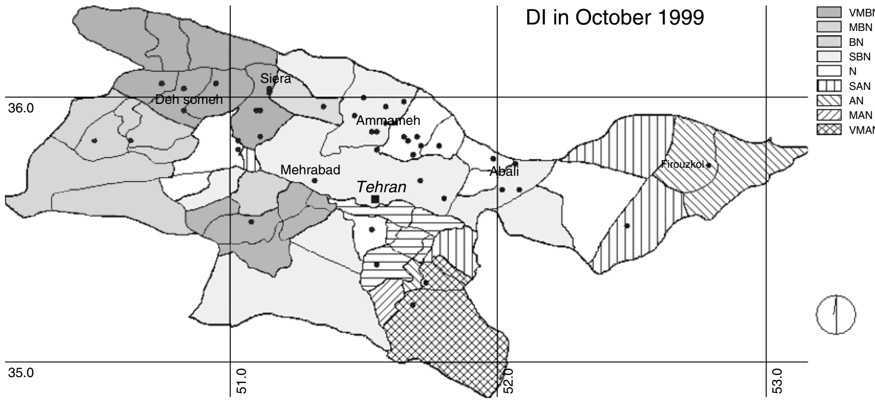
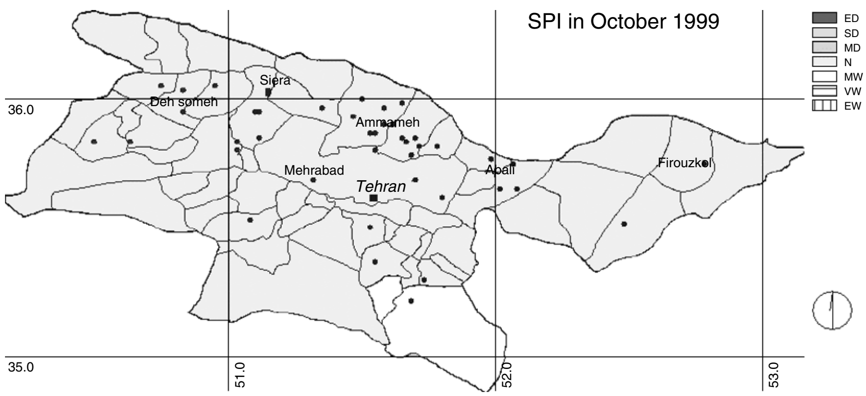


(a)



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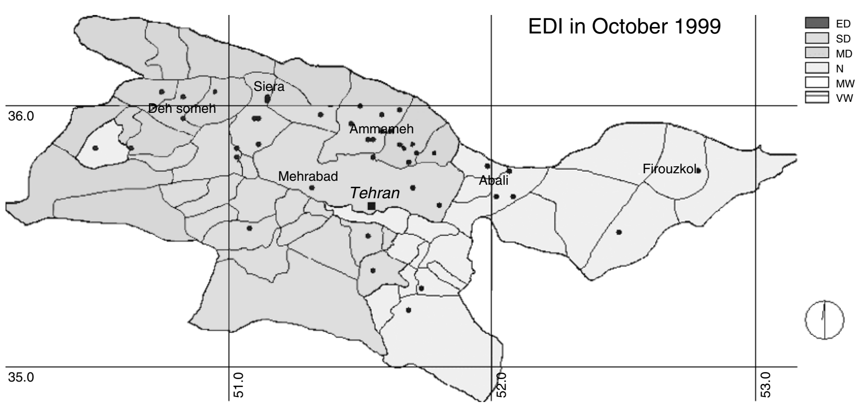

(c)

Figure 10. Drought class of the indices during October 1999 in the Tehran province

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