

Drought Monitoring by Reconnaissance Drought Index (RDI) in Iran

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Abstract Drought is one of the most important natural hazards in Iran and frequently affects a large number of people, causing tremendous economic losses, environmental damages and social hardships. Especially, drought has a strong impact on water resources in Iran. This situation has made more considerations toward the study and management of drought. The present study is focused on two important indices; SPI and RDI, for 3, 6, 9, 12, 18 and 24 months time scales in 40 meteorological synoptic stations in Iran. In the case of RDI computation, potential evapotranspiration was an important factor toward drought monitoring. So, evapotranspiration was calculated by Penman-Monteith equation. The correlation of RDI and SPI was also surveyed. Drought severity maps for SPI and RDI were also presented in the driest year (1999–2000). The present results have shown that the correlation of SPI and RDI was more considerable in the 3, 6 and 9 months than longer time scales. Furthermore, drought severity maps have shown that during 1999–2000, the central, eastern and south-eastern parts of Iran faced extremely dry conditions. While, according to SPI and RDI trends, other parts of the country suffered from severe drought. The SPI and RDI methods showed approximately similar results for the effect of drought on different regions of Iran. Since, RDI resolved more climatic parameters, such as evapotranspiration, into account which had an important role in water resource losses in the Iranian basins, it was worthwhile to consider RDI in drought monitoring in Iran, too.

Keywords Drought monitoring · Evapotranspiration · Iran · Penman-Monteith · Precipitation · RDI · SPI

1 Introduction

Drought is a recurring natural phenomenon associated with a deficit availability of water resources over a large geographical area and extending along a significant period of time (Rossi 2000). The effects of drought often accumulate slowly over a considerable period of

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time that may linger for several years even after the termination of drought. Therefore, some authors have called it a creeping phenomenon (Wilhite 2000). It is difficult to precisely determine the onset and end of a drought event. A drought can be short, lasting for just a few months, or it may persist for years before climatic conditions return to normal.

Drought is considered as the most complex, but the least understandable phenomenon of all the natural hazards affecting more people than any other hazards (Mishra and Desai 2005). Approximately 85% of the natural disasters are related to extreme meteorological events (Obasi 1994) with drought being the one that causes most damages (CRDE 2003). Drought is a global phenomenon that is caused by the lack of precipitation and occurs virtually in all landscapes causing significant damage both in natural environment and in human lives. It causes huge losses in agriculture and has many negative effects on natural ecosystems. Drought causes degradation of soils, desert formation (Nicholson et al. 1990; Pickup 1998), famine and impoverishment.

Drought has been sorted into four types (Wilhite and Glantz 1985): meteorological, agricultural, hydrological and socio-economic. Meteorological drought is defined as the lack of precipitation over a region in a specific time period, lasting sufficiently to cause hydrological and agricultural hazards. It is determined in the form of deviation from normal precipitation. According to the meteorologists, a significant decrease in stream flow, water level of lakes or a change in the ground water levels is the signal of an upcoming drought event. While according to hydrologists, drought prevails with the lack of soil moisture to sustain the crop growth. Agricultural scientists determine the drought as a famine condition, while economists monitor it in the form of short supply of tap water to the urbanite (Dracup et al. 1980).

The identification of drought was realized by using drought indices. Spatial and temporal extent and severity of drought could be determined using these indices (Guttman 1998; Hayes 2000). Drought indices are essential elements for an efficient drought monitoring system, aimed at providing its overall concise picture (Mendicino et al. 2008). These indices make the transforming information of climatic anomalies easier and allow the scientists to quantitatively assess the climatic anomalies in terms of their intensity, duration, frequency and spatial extent (Wilhite et al. 2000). It allows the analysis of historical occurrence of droughts and the estimation of recurrence probability. This information is extremely useful for the management and application of water resource development schemes for the environment and human use as well (Tsakiris et al. 2007b).

Drought is a common environmental phenomenon, seen in different countries as well as in the central and eastern parts of Iran. Previous studies have revealed that Iran is experiencing the recurrent drought of different severities after every two and a half years (Badripour 2007). For instance, ten out of the 28 provinces of Iran have been affected by one of the worst and prolonged drought events within the period of 1998–2001, leaving approximately 37 million inhabitants (over half of the population of Iran) vulnerable to food and water shortage (Raziei et al. 2009). The Iranian Emergency Agency has reported that 278 cities and 1050 villages had been affected by severe drought. While, 4 and 2.7 million hectare of the crops of rain fed and irrigated areas have been completely destroyed by the drought of 1998–2001. The total agricultural and livestock loss was estimated to be US\$2.6 billion by the year 2001 (Shahabfar and Eitzinger 2008).

To get the intended results two drought indices were used in this paper: Standardized Precipitation Index (SPI) and the Reconnaissance Drought Index (RDI). SPI is used for defining and monitoring the drought, based on a single meteorological determinant, the precipitation (McKee et al. 1993). The Reconnaissance Drought Index (RDI) was first introduced by Tsakiris and colleagues in National Technical University of Athens (Tsakiris

and Vangelis 2005; Tsakiris et al. 2007a, b). The RDI is based on the ratio between two aggregated quantities of precipitation and potential evapotranspiration. It is advisable to use the periods of 3, 6, 9 and 12 months if RDI has to be calculated as a general index of meteorological drought. In its initial formulation, RDI, for a 12 months' time period can be directly compared with the Aridity Index produced for the area under study. If, for a certain year, α_{12} is lower than the Aridity Index calculated according to UNEP (1992), the area is said to be suffering from drought during that specific year. The interpretation of standardized RDI (RDI_{st}) and SPI is the same because same threshold levels can be used in both techniques. Severity and affected area are two basic characteristics of the meteorological drought analysis, especially in Iran. Severity is represented by two general indices, i.e., the SPI and RDI.

The present study deals with the extent of drought following its illustration and assessment with the help of severity maps and cumulative curves of the affected areas of Iran in relation to the severity level. Severity maps show the areas affected by drought whereas the cumulative curves directly produce the percentage of areas belonging to each class of drought severity. SPI and RDI were used to get the intended results for the effect of different severities of drought on the experimental areas of Iran.

2 Study Area and Data

Iran is located in the south west of Asia, between 25° to $40^{\circ N}$ and 24° to $64^{\circ E}$, bordering the Persian Gulf, Oman Sea and the Caspian Sea, between Iraq and Pakistan. Iran is one of the world's mountainous countries. The mountains enclose several broad basins or plateaus, in which major agricultural and urban settlements are located. The Alborz and Zagros are the main mountain ranges, extending from west to east and from northern west to southern east in the country, respectively. These mountain ranges have the most important role in tempo-spatial distribution of precipitation, so that the northern and western parts of Iran have sub-humid and Mediterranean climates. While, semi-arid to hyper arid climates are dominant in central parts of Iran. These regions, with hot summers and cold winters, have a continental climate, in which the yearly mean temperatures range from $22^{\circ C}$ to $26^{\circ C}$. While in some areas of country, the temperature reaches to $45^{\circ C}$ in the summer. The precipitation plays a key role in characterizing the climatic tempo-spatial variations in Iran. In most parts, the rainy period begins in November and ends in May, and the dry condition prevails in the remaining months. The annual mean precipitation in Iran has been recorded to be 240 mm. But this amount reaches to about 1800 mm at the Caspian coasts and the Alborz mountain range with 480 mm in the Zagros mountain range. Based on the local topography studies, in the central and interior plains of the country, the above described precipitation amounts decrease up to about 100 mm (Dinpashoh et al. 2004).

Mountainous basins and plains are the 53 and 47% of total area of Iran, respectively. Based on the statistics of Ministry of Energy, the annual mean precipitation is estimated to be $400 \times 10^9 \text{ m}^3$, of which $310 \times 10^9 \text{ m}^3$ happens on the mountainous basins and $90 \times 10^9 \text{ m}^3$ on the plains. In the mountainous areas, the annual mean rates of evapotranspiration reach up to $200 \times 10^9 \text{ m}^3$, and $84 \times 10^9 \text{ m}^3$ in the plains, representing the 71% of total annual mean precipitation of the country.

In this study, the homogeneous monthly rainfall, temperature, wind, relative humidity and sunshine data were taken from 40 meteorological stations, distributed over the Iranian territory and covering the hydrological years of 1975–1976 and 2004–2005 (Fig. 1). Hydrological year is from October to the September of every next year in Iran. Table 1 shows general

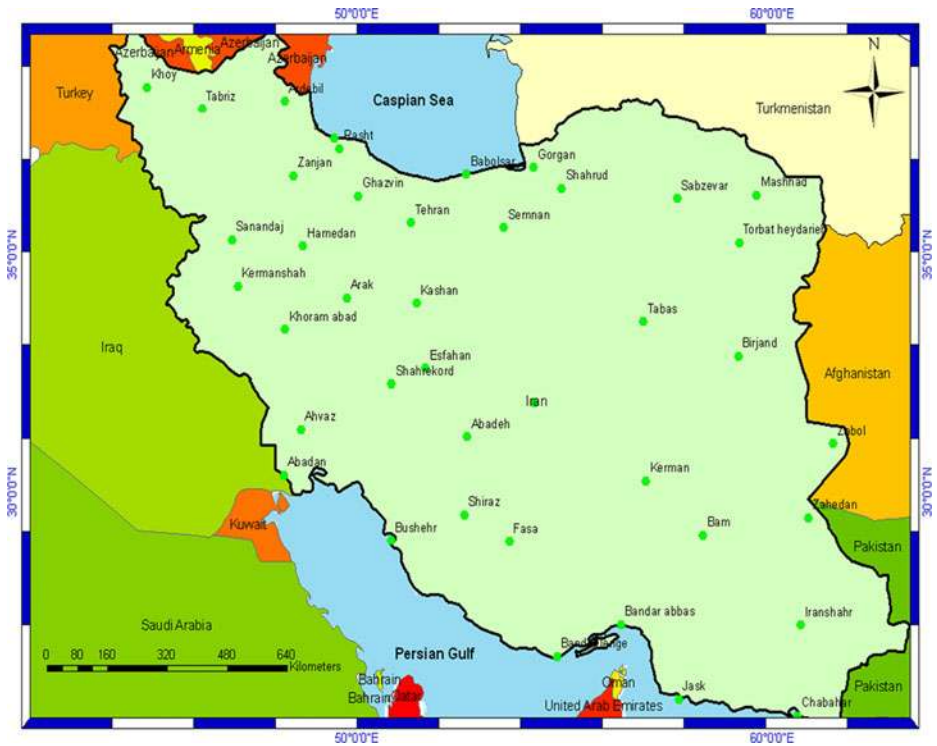


Fig. 1 Spatial distribution of selected experimental stations of Iran and its neighboring countries

characteristics of the surveyed stations. Precipitation and potential evapotranspiration were used for classifying the bioclimatic aridity in a globally comparable way. In mathematical terms, UNESCO (1979) used an aridity/humidity classification system based on average annual precipitation (P) divided by the average annual potential evapotranspiration (PET). According to UNESCO, the potential evapotranspiration was calculated according to the Penman formula. Based on this classification, Table 1 demonstrates the type of climatic condition, introduced for each experimental station.

3 Methods

3.1 Estimation of Evapotranspiration

During the present study, the PET rates were estimated with the Penman-Monteith equation (Monteith 1965), which is the most reliable way to estimate PET under various climatic conditions (Jensen et al. 1990). The Penman-Monteith method reflects changes in all meteorological factors affecting the evaporation and transpiration in the plants. Jensen et al. (1990) have proposed the term ‘reference evapotranspiration’ instead of PET to describe the same phenomenon. PET does not directly provide an indication of actual evapotranspiration rate, governed by the characteristics of soil (soil type and infiltration capacity), relief (slope, exposition and relief form), plant (vegetation type, soil cover, LAI, rooting depth) and climate (precipitation amount and intensity, PET and the temporal distribution of both variables). One

Table 1 General characteristics of 40 surveyed synoptic stations

| Row | Station name | X coordinate | Y coordinate | Elevation (m) | P (mm) | ETP (mm) | P/ETP | Zone |
|-----|------------------|--------------|--------------|---------------|--------|----------|-------|------------|
| 1 | Abadan | 48.25 | 30.37 | 6.6 | 169.8 | 2217.8 | 0.077 | Arid |
| 2 | Abadeh | 52.67 | 31.18 | 2030 | 143.3 | 1485.6 | 0.096 | Arid |
| 3 | Ahvaz | 48.67 | 31.33 | 22.5 | 240.9 | 1989.7 | 0.121 | Arid |
| 4 | Arak | 49.77 | 34.10 | 708 | 322.6 | 1222.0 | 0.264 | Semi-arid |
| 5 | Ardebil | 48.28 | 38.25 | 332 | 303.9 | 908.4 | 0.334 | Semi-arid |
| 6 | Babolsar | 52.65 | 36.72 | -21 | 943.1 | 886.9 | 1.063 | humid |
| 7 | Bam | 58.35 | 29.10 | 66.9 | 59.3 | 2040.3 | 0.029 | Hyper-arid |
| 8 | Bandar abbas | 56.37 | 27.22 | 9.8 | 152.9 | 1865.5 | 0.082 | Arid |
| 9 | Bandar lenghe | 54.83 | 26.53 | 22.7 | 205.6 | 1737.7 | 0.118 | Arid |
| 10 | Birjand | 59.20 | 32.87 | 1491 | 172.4 | 1681.5 | 0.103 | Arid |
| 11 | Bushehr | 50.83 | 28.98 | 19.6 | 277.2 | 1690.8 | 0.164 | Arid |
| 12 | Chabahar | 60.62 | 25.28 | 8 | 117.5 | 1575.3 | 0.075 | Arid |
| 13 | Esfahan | 51.67 | 32.62 | 1550.4 | 126.5 | 1394.6 | 0.091 | Arid |
| 14 | Fasa | 53.68 | 28.97 | 1288.3 | 316.5 | 1469.2 | 0.215 | Semi-arid |
| 15 | Ghazvin | 50.05 | 36.25 | 279.2 | 329.5 | 1222.9 | 0.269 | Semi-arid |
| 16 | Gorgan | 54.27 | 36.85 | 13.3 | 568.4 | 924.1 | 0.615 | Sub-humid |
| 17 | Hamedan | 48.72 | 35.20 | 679.7 | 323.1 | 1332.4 | 0.243 | Semi-arid |
| 18 | Iranshahr | 60.70 | 27.20 | 591.1 | 112.4 | 2073.4 | 0.054 | Arid |
| 19 | Jask | 57.77 | 25.63 | 5.2 | 139.0 | 1768.4 | 0.079 | Arid |
| 20 | Kashan | 51.45 | 33.98 | 982.3 | 137.0 | 1130.5 | 0.121 | Arid |
| 21 | Kerman | 56.97 | 30.25 | 1753 | 142.1 | 1667.7 | 0.085 | Arid |
| 22 | Kermanshah | 47.15 | 34.35 | 318.6 | 431.4 | 1394.6 | 0.309 | Semi-arid |
| 23 | Khoram abad | 48.28 | 33.43 | 147.8 | 500.3 | 1329.9 | 0.376 | Semi-arid |
| 24 | Khoy | 44.97 | 38.55 | 103 | 283.5 | 948.0 | 0.299 | Semi-arid |
| 25 | Mashhad | 59.63 | 36.27 | 999.2 | 271.0 | 1271.9 | 0.213 | Semi-arid |
| 26 | Rasht | 49.60 | 37.25 | -6.9 | 1367 | 795.9 | 1.718 | humid |
| 27 | Sabzevar | 57.72 | 36.20 | 977.6 | 205.1 | 1615.0 | 0.127 | Arid |
| 28 | Sanandaj | 47.00 | 35.33 | 1373.4 | 461.8 | 1278.6 | 0.361 | Semi-arid |
| 29 | Semnan | 53.55 | 35.58 | 130.8 | 145.6 | 1308.8 | 0.111 | Arid |
| 30 | Shahrekord | 50.85 | 32.28 | 48.9 | 335.4 | 1132.9 | 0.296 | Semi-arid |
| 31 | Shahrud | 54.95 | 36.42 | 345.3 | 162.6 | 1274.3 | 0.128 | Arid |
| 32 | Shiraz | 52.60 | 29.53 | 484 | 348.0 | 1640.5 | 0.212 | Semi-arid |
| 33 | Tabas | 56.92 | 33.60 | 711 | 88.3 | 1638.7 | 0.054 | Arid |
| 34 | Tabriz | 46.28 | 38.08 | 361 | 266.0 | 1338.5 | 0.199 | Arid |
| 35 | Tehran | 51.32 | 35.68 | 190.8 | 245.5 | 1577.1 | 0.156 | Arid |
| 36 | Torbat heydariéh | 59.22 | 35.27 | 1450.8 | 288.1 | 1355.8 | 0.213 | Semi-arid |
| 37 | Yazd | 54.28 | 31.90 | 1237.2 | 64.4 | 1742.7 | 0.037 | Arid |
| 38 | Zabol | 61.48 | 31.03 | 489.2 | 62.6 | 2813.5 | 0.022 | Hyper-arid |
| 39 | Zahedan | 60.88 | 29.47 | 1370 | 75.3 | 1870.2 | 0.040 | Arid |
| 40 | Zanjan | 48.48 | 36.68 | 663 | 295.2 | 1136.0 | 0.260 | Semi-arid |

main advantage of the concept of PET was that it provides a standardized value that allows the comparison of evaporative environments under different climatic conditions. This concept was developed by the Food and Agriculture Organization (FAO) of the United Nations during the last decade (Allen et al. 1998; Doorenbos and Kassam 1986; Doorenbos and Pruitt 1977; Smith 1992) and was applied globally for the land use studies (Fischer et al. 2000).

Reference Evapotranspiration (ET_o) was estimated using the Penman–Monteith (PM) method (Allen et al. 1998):

$$ET_o = \frac{0.408 \Delta(R_n - G) + \gamma[900/(T + 273)] U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34 U_2)} \tag{1}$$

Where, ET_o is the reference evapotranspiration [mm day^{-1}]; Δ , the slope of vapor pressure curve; R_n , the net radiation at the surface [W m^{-2}]; G , the soil heat flux density [W m^{-2}]; γ , psychrometric constant; T , the mean daily air temperature at the height of 2 m; u_2 , wind speed at 2-m height; e_s , saturated vapor pressure and e_a is the actual vapor pressure [kPa]. Equation 1 was specifically applied to a hypothetical reference crop with an assumed height of 0.12 m, a fixed surface resistance of 70 sm^{-1} and an albedo of 0.23.

3.2 Reconnaissance Drought Index (RDI)

Reconnaissance Drought Index (RDI) was characterized as a general meteorological index for the drought assessment. The RDI is expressed in three forms: the initial value (α_k), normalized RDI (RDI_n) and standardized RDI (RDI_{st}). The initial value (α_k) is presented in an aggregated form using a monthly time scale and may be calculated on a monthly, seasonal or annual basis. The α_k can be calculated by the following equation:

$$a_k^{(i)} = \frac{\sum_{j=1}^k P_{ij}}{\sum_{j=1}^k PET_{ij}}, i = 1 \text{ to } N \tag{2}$$

Where P_{ij} and PET_{ij} are the precipitation and potential evapotranspiration within the month “j” of hydrological year “i” that usually starts from October in Iran. Hence, for October $k=1$ and N were the total number of experimental years.

Equation 2 could be calculated for any period of the year. It could also be recorded starting from any month of the year apart from October, if necessary. A second expression, the Normalized RDI (RDI_n) was computed using the following equation, in which it is evident that the parameter \bar{a}_k is the arithmetic mean of a_k values.

$$RDI_{st}^{(i)} = \frac{a_k^{(i)}}{\bar{a}_k} - 1 \tag{3}$$

The initial formulation of RDI_{st} (Tsakiris and Vangelis 2005) used the assumption that α_k values follow the log-normal (LN) distribution. So, RDI_{st} was calculated as:

$$RDI_n^{(i)} = \frac{y_k^{(i)} - \bar{y}_k}{\hat{\sigma}_{y_k}} \tag{4}$$

In which, y_k is the $\ln(\alpha_k^{(i)})$, \bar{y}_k was the arithmetic mean of y_k and $\hat{\sigma}_{y_k}$ is the standard deviation. Based on an extended research on various data from several locations and

different time scales, it was concluded that α_k values follow both the ln and the gamma distribution values at almost all locations and time scales. But in most of the cases, the gamma distribution was proved to be more successful. Therefore, the calculation of RDI_{st} could be performed better by fitting the gamma probability density function (pdf) at the given frequency distribution of α_k , following the procedure described below. Like SPI computation by Gamma approach, this method tends to solve the problem of calculating RDI_{st} for the small time scales, such as monthly, which may include zero-precipitation values ($\alpha_k=0$), for which Eq. 3 could not be applied (Tsakiris et al. 2008). The gamma distribution is defined by its frequency or probability density function:

$$g(x) = \frac{1}{\beta^\alpha \Gamma(\alpha)} x^{\alpha-1} e^{-x/\beta} \text{ for } : x > 0 \tag{5}$$

Where $\alpha > 0$ is a shape factor; $\beta > 0$, a scale factor and $x > 0$ is the amount of precipitation (Tsakiris et al. 2008). $\Gamma(\alpha)$ is the gamma function, defined as:

$$\Gamma(\alpha) = \int_0^\infty y^{\alpha-1} e^{-y} dy \tag{6}$$

Fitting of distribution to data requires the estimation of α and β . Maximum likelihood estimations of α and β are:

$$\alpha = \frac{1}{4A} \left(1 + \sqrt{1 + \frac{4A}{3}} \right) \tag{7}$$

$$\beta = \frac{\bar{x}}{\alpha} \tag{8}$$

Where

$$A = \ln(\bar{x}) - \frac{1}{n} \sum_{i=1}^n \ln(x_i) \tag{9}$$

For n observations The resulting parameters were then used to find the cumulative probability of an observed precipitation event for the given month or any other time scale:

$$G(x) = \int_0^x g(x) dx = \frac{1}{\beta^\alpha \Gamma(\alpha)} \int_0^x x^{\alpha-1} e^{-x/\beta} dx \tag{10}$$

Substituting t for $\frac{x}{\beta}$ reduces the Eq. 6 to incomplete gamma function

$$G(x) = \frac{1}{\Gamma(\alpha)} \int_0^{\frac{x}{\beta}} t^{\alpha-1} e^{-t} dt \tag{11}$$

Since, the gamma function is undefined for $x=0$ and a precipitation distribution may contain zeros, where the cumulative probability becomes:

$$H(x) = q + (1 - q)G(X) \tag{12}$$

Where q is the probability of zero precipitation and $G(x)$ is the cumulative probability of the incomplete gamma function. If m be the number of zeros in a α_k time scales, then q

could be estimated by m/n . The cumulative probability $H(x)$ is then transformed to the standard normal random variable z with mean zero and the variance of one (Abramowitz and Stegun 1965), which is the value of RDI_{st} (Tsakiris et al. 2008).

During the present analysis, RDI calculations were performed by MATLAB software. As the Standardized RDI and SPI perform in a similar manner (McKee et al. 1993), they have the similar interpretation of results. Therefore, the RDI_{st} values could be compared to the same thresholds as that of the SPI technique (Table 2).

3.3 Time Scales

The primary impact of drought is usually apparent in agriculture through a decrease in soil moisture and high evapotranspiration. Soil water is rapidly depleted during the extended dry periods. Surface and subsurface water resources are usually the last ones to be affected by an extended period of dryness (Sönmez et al. 2005). So, the soil moisture is more influenced during the 3 months time periods and agricultural studies are needed to be carried out with more caution.

The main advantage of SPI is that it is calculated for several time scales (McKee et al. 1995). RDI quantifies the precipitation deficit during multiple time scales, which reflects the impact of precipitation deficiency on the availability of different water suppliers.

Monthly as well as annual RDI and SPI were calculated and organized, using the monthly precipitation and evapotranspiration data of 40 meteorological stations in Iran. In monthly time scales, RDI and SPI values were calculated for the time scales of 3, 6, 9, 12, 18 and 24 months for the period of hydrological years of 1975/76–2004/05.

Figs. 2, 3, 4 and 5 indicate the SPI and RDI curves during 4 types of climatic conditions: humid, semi arid, arid and hyper arid at the experimental stations of Babolsar, Zanjan, Tehran and Zabol, respectively. Therefore, the correlation coefficients of SPI and RDI for each station and each time scales are described in Table 3. For the computation of correlation, the criterion of correlation coefficient (R) was used. Correlation coefficient (R) was computed with the help of following equation:

$$R = \frac{\sum A.B - \frac{\sum A \sum B}{N}}{\sqrt{\left[\sum A^2 - \frac{(\sum A)^2}{N}\right] \left[\sum B^2 - \frac{(\sum B)^2}{N}\right]}} \tag{13}$$

Where A = RDI value; B, SPI amounts and N was the length of each SPI or RDI times series.

Table 2 Classification of drought according to the SPI and RDI_{st} values

| SPI and RDI_{st} range | Drought classes |
|--------------------------|-----------------|
| 2 or more | Extremely wet |
| 1.5 to 1.99 | Very wet |
| 1 to 1.49 | Moderately wet |
| 0.99 to 0.0 | Normal |
| 0.0 to -0.99 | Near normal |
| -1 to -1.49 | Moderately dry |
| -1.5 to -1.99 | Severely dry |
| -2 and less | Extremely dry |

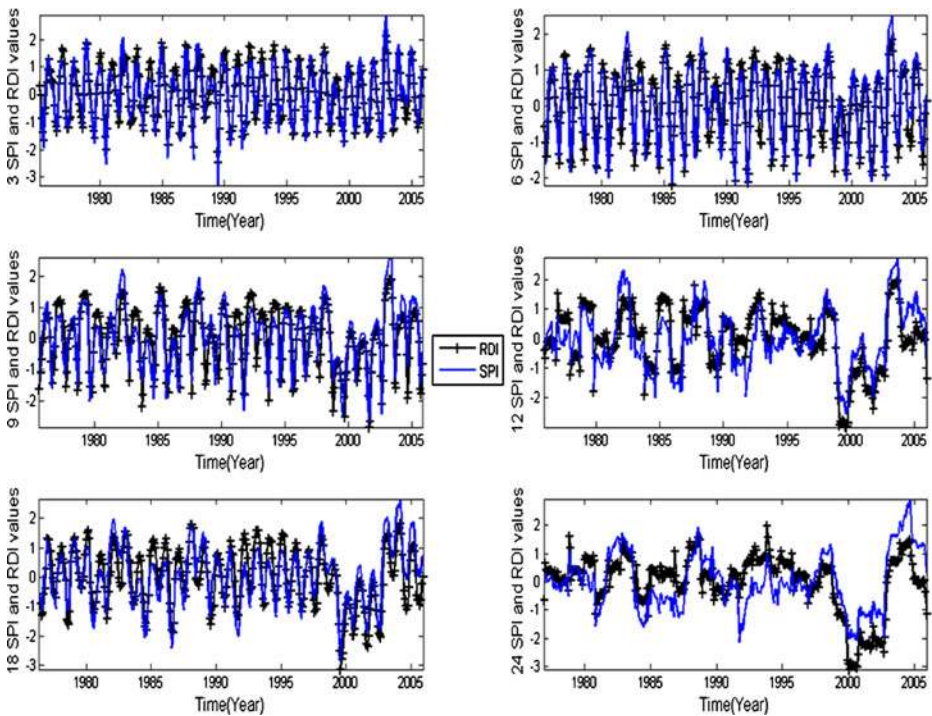


Fig. 2 RDI and SPI series of different monthly time scales at the climatic station of Babolsar

The Root Mean Squared Error (RMSE) was used to evaluate the performance of model by deriving useful information about the nature of difference between RDI and SPI values. The RMSE was calculated between RDI and SPI by using the following equation:

$$RMSE = \sqrt{\frac{\sum_{i=1}^N (RDI_i - SPI_i)^2}{N}} \tag{14}$$

In this equation, N is the length of each SPI or RDI time scales. Table 4 represents the RMSE amounts between SPI and RDI for each climatic station and all of the time scales.

3.4 Drought Severity Maps

Drought severity maps have been used in many studies during the last decade (Kim et al. 2002; Tsakiris and Vangelis 2004; Loukas and Vasilades 2004). Drought maps show the areas affected by the corresponding severity of drought. In this study, the kriging interpolation method was used in order to map the spatial extent of drought from point data. Geostatistical analysis tool of ArcMap 9.1 (Environmental System Research Institute 2004) was used for this purpose. Kriging is a stochastic interpolation method (Journal and Huijbregts 1981; Isaaks and Srivastava 1989), which was widely recognized as the standard approach for the surface interpolation, based on scalar measurements at different stations. Kriging attempts to express the trend in data, so that, “high points might be connected along a ridge, rather than isolated by bull’s-eye type contours” (Sönmez et al. 2005). Many studies

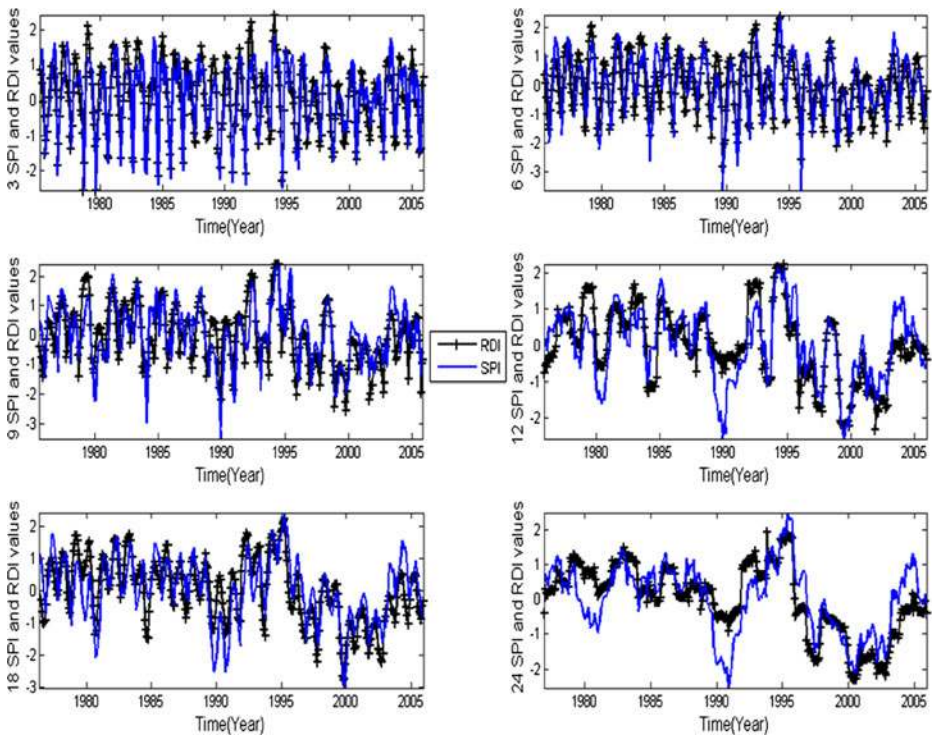


Fig. 3 RDI and SPI series of different monthly time scales at the climatic station of Zanjan

have shown that Kriging provides better estimates as compared to other methods (Oliver and Webster 1990; Zimmerman et al. 1999; van Beers and Kleijnen 2004).

Drought maps are very important tools for delineating the particular parts of the experimental area affected by drought (Figs. 6 and 7).

3.5 Cumulative “or More” Curves

A better representation of spatial extent of drought could be achieved using a specific type of curves known as cumulative “or more” curves (ogives). “or more” curves, also known as “drought severity—areal extent” curves, directly express the percentage of area being affected by drought, which then could be compared with the critical percentage area (Tsakiris et al. 2007a). It is customary to compare the areal extent of drought with a preset “critical area” percentage. These curves could be produced by plotting the severity of drought (y-axis) versus the percentage of the affected area (x-axis). The severity of drought is presented by a drought index and the affected area is recognized by the corresponding severity level. This type of graphs could be used not only for the characterization of drought and the determination of its areal extent, but also for comparisons within the critical percentage area (related to severity), directly. Clearly, more than one thresholds referring to the percentage of critical area could be used to define different levels of severity. Since, each class of drought severity has a different threshold; it is obvious that various critical percentage areas could be simultaneously adopted for characterizing a drought episode in relation to its area extent. Figures 8 and 9 indicate the cumulative SPI and RDI curves for the dry year of 1999–2000, respectively.

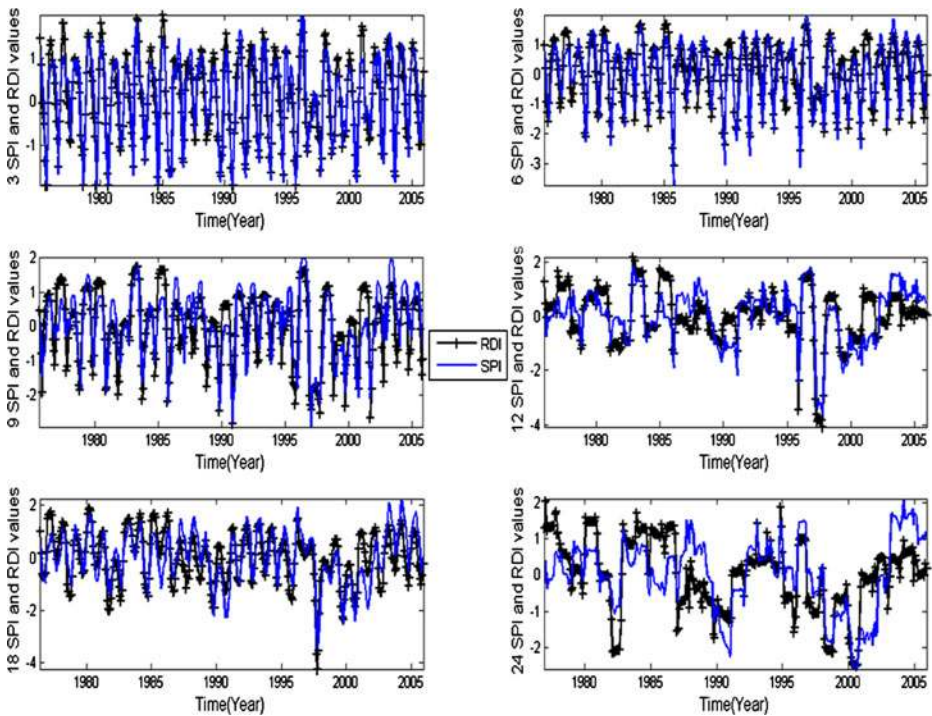


Fig. 4 RDI and SPI series of different monthly time scales at the climatic station of Tehran

4 Results

Generally the SPI and RDI results, plotted at different time scales indicate that the differences between the SPI and RDI indices increase by increasing the time scales. On the other hand, it could be found from Figs. 2, 3, 4 and 5 that in the dry climate, the RDI and SPI were more correlative than in those recorded in the humid conditions.

Table 3 indicates R (correlation coefficient) for SPI and RDI in the surveyed climatic stations at different time scales. It could be derived from the Table that the presented correlation coefficients had a decrease with an increase in the time scales. Table 4 indicates the RMSE for SPI and RDI in surveyed climatic stations at different time scales. It could be seen from Table that the RMSE between RDI and SPI in drier climatic conditions are less than the established ones in the humid climatic regions.

Table 5 represents the average values of R between SPI and RDI in arid, semi-arid and humid climatic zones in different time scales. The results show that the average value of R is lowest at the stations located in arid climate and is highest at humid climate for all time scales. This means classification of drought according RDI may be different in comparing with SPI at wetter climates. Analysis of the effect of time scale length (3, 6, 9, 12, 18, and 24 months) revealed more differences between these two drought indices. The highest value of R between SPI and RDI was obtained for 3-month time scale and the lowest value for 24-month time scale at all climate zones. The average Correlation coefficient values of 3-month time scale are 0.952, 0.913, and 0.890 and 0.870, 0.807, and 0.760 for 24-month time scale at arid, semi-arid, and humid regions, respectively. Comparing the average values of RMSE in stations located in arid, semi-arid and humid

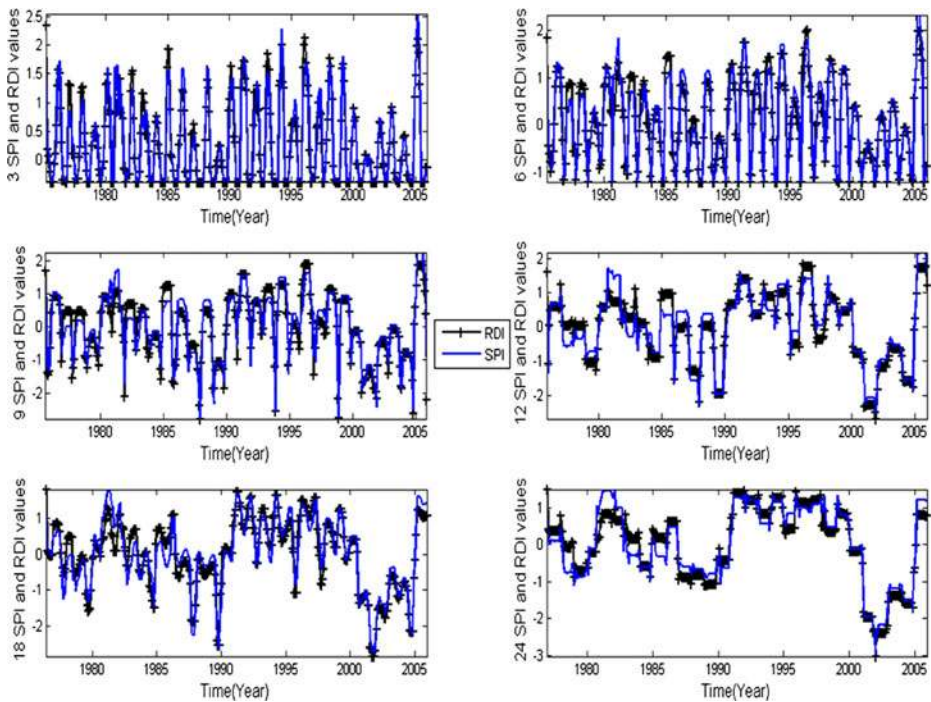


Fig. 5 RDI and SPI series of different monthly time scales at the climatic station of Zabol

climate conditions, showed that the values of this factor increases from arid to the humid regions. For example the average values of RMSE in 3-month time scale were 0.519, 0.575, and 0.677 for these three climate regions, respectively.

Furthermore, Fig. 6 represents RDI based analysis of the driest year (1999–2000) during the examined period of 1975–1976 to 2004–2005. It is apparent that the driest conditions were located at the central, eastern and south east parts of Iran. In fact, these regions faced extreme drought events while the remaining part affected by severe drought. To some extent, the same results of drought severity have been shown in Fig. 7, which indicates the drought severity map, based on the SPI values. Due to the presence of evapotranspiration factor in RDI, comparison of the Figs. 6 and 7 shows the RDI values are smaller than SPI values in the most parts of the country, especially in northern and western Iran.

Figure 8 shows the cumulative “or more” curves of both SPI and RDI for the year of 1999–2000. The boundaries of drought severity classes are prominent in Table 2. Focusing on the dry year of 1999–2000 it could be observed that various percentages of “critical area” might be adopted and directly compared with the area extent of each drought level. For example, drought is characterized as severe for a region if more than 50% of the area be affected by drought and more than 30% encountered with severe drought.

According to Fig. 8, it can be seen that about 29% of the experimental area was affected by extreme drought, while 60 and 80% was affected by severe and moderate drought, respectively. Considering the RDI, it could be seen that about 28% of the total experimental area was under extreme drought, whereas 59% was under extreme or severe drought and 85% was under the moderate drought conditions.

Table 3 Correlation coefficient (R) of SPI and RDI in surveyed climatic stations in different time scales

| Row | Station | Time scales | | | | | |
|-----|------------------|-------------|------|------|------|------|------|
| | | 3 | 6 | 9 | 12 | 18 | 24 |
| 1 | Abadan | 0.98 | 0.98 | 0.94 | 0.86 | 0.88 | 0.75 |
| 2 | Abadeh | 0.97 | 0.96 | 0.93 | 0.93 | 0.94 | 0.94 |
| 3 | Ahvaz | 0.98 | 0.98 | 0.95 | 0.91 | 0.93 | 0.88 |
| 4 | Arak | 0.93 | 0.89 | 0.78 | 0.74 | 0.77 | 0.70 |
| 5 | Ardebil | 0.81 | 0.71 | 0.68 | 0.69 | 0.66 | 0.67 |
| 6 | Babolsar | 0.91 | 0.90 | 0.83 | 0.79 | 0.83 | 0.69 |
| 7 | Bam | 0.95 | 0.94 | 0.90 | 0.90 | 0.89 | 0.88 |
| 8 | Bandar abbas | 0.99 | 0.99 | 0.98 | 0.97 | 0.97 | 0.96 |
| 9 | Bandar lenge | 0.99 | 0.99 | 0.99 | 0.99 | 0.99 | 0.99 |
| 10 | Birjand | 0.96 | 0.96 | 0.91 | 0.90 | 0.91 | 0.88 |
| 11 | Bushehr | 0.99 | 0.99 | 0.99 | 0.98 | 0.98 | 0.98 |
| 12 | Chabahar | 0.99 | 0.99 | 0.99 | 0.99 | 0.99 | 0.99 |
| 13 | Esfahan | 0.94 | 0.92 | 0.88 | 0.91 | 0.91 | 0.91 |
| 14 | Fasa | 0.99 | 0.99 | 0.97 | 0.97 | 0.97 | 0.96 |
| 15 | Ghazvin | 0.92 | 0.88 | 0.80 | 0.80 | 0.81 | 0.78 |
| 16 | Gorgan | 0.85 | 0.85 | 0.73 | 0.71 | 0.75 | 0.71 |
| 17 | Hamedan | 0.92 | 0.88 | 0.79 | 0.76 | 0.79 | 0.69 |
| 18 | Iranshahr | 0.96 | 0.95 | 0.94 | 0.95 | 0.95 | 0.96 |
| 19 | Jask | 0.99 | .99 | 0.99 | 0.99 | 0.99 | 0.99 |
| 20 | Kashan | 0.93 | 0.91 | 0.86 | 0.88 | 0.86 | 0.83 |
| 21 | Kerman | 0.97 | 0.96 | 0.91 | 0.88 | 0.89 | 0.86 |
| 22 | Kermanshah | 0.96 | 0.95 | 0.86 | 0.82 | 0.86 | 0.77 |
| 23 | Khoram abad | 0.97 | 0.95 | 0.90 | 0.90 | 0.91 | 0.88 |
| 24 | Khoy | 0.69 | 0.52 | 0.63 | 0.81 | 0.73 | 0.84 |
| 25 | Mashhad | 0.92 | 0.88 | 0.81 | 0.82 | 0.84 | 0.83 |
| 26 | Rasht | 0.91 | 0.90 | 0.83 | 0.83 | 0.88 | 0.88 |
| 27 | Sabzevar | 0.95 | 0.92 | 0.84 | 0.81 | 0.84 | 0.80 |
| 28 | Sanandaj | 0.95 | 0.92 | 0.86 | 0.90 | 0.91 | 0.91 |
| 29 | Semnan | 0.89 | 0.85 | 0.77 | 0.72 | 0.67 | 0.55 |
| 30 | Shahrekord | 0.97 | 0.96 | 0.91 | 0.90 | 0.92 | 0.87 |
| 31 | Shahrud | 0.87 | 0.82 | 0.77 | 0.82 | 0.80 | 0.81 |
| 32 | Shiraz | 0.99 | 0.98 | 0.96 | 0.96 | 0.95 | 0.93 |
| 33 | Tabas | 0.95 | 0.94 | 0.88 | 0.85 | 0.86 | 0.79 |
| 34 | Tabriz | 0.79 | 0.68 | 0.67 | 0.79 | 0.73 | 0.77 |
| 35 | Tehran | 0.95 | 0.91 | 0.82 | 0.75 | 0.79 | 0.65 |
| 36 | Torbat heydarieh | 0.95 | 0.92 | 0.85 | 0.82 | 0.85 | 0.81 |
| 37 | Yazd | 0.96 | 0.96 | 0.93 | 0.93 | 0.93 | 0.91 |
| 38 | Zabol | 0.97 | 0.97 | 0.95 | 0.95 | 0.95 | 0.96 |
| 39 | Zahedan | 0.97 | 0.97 | 0.96 | 0.96 | 0.97 | 0.98 |
| 40 | Zanjan | 0.87 | 0.79 | 0.73 | 0.79 | 0.76 | 0.76 |

Table 4 The Root Mean Squared Error (RMSE) of the SPI and RDI in surveyed climatic stations at different time scales

| Time scales | Station | Row | | | | | |
|-------------|------------------|------|------|------|------|------|------|
| | | 3 | 6 | 9 | 12 | 18 | 24 |
| 1 | Abadan | 0.92 | 0.71 | 0.50 | 0.53 | 0.36 | 0.21 |
| 2 | Abadeh | 0.43 | 0.35 | 0.34 | 0.36 | 0.36 | 0.29 |
| 3 | Ahvaz | 0.63 | 0.48 | 0.37 | 0.42 | 0.30 | 0.18 |
| 4 | Arak | 0.70 | 0.77 | 0.67 | 0.73 | 0.66 | 0.48 |
| 5 | Ardebil | 0.79 | 0.81 | 0.83 | 0.78 | 0.80 | 0.76 |
| 6 | Babolsar | 0.95 | 0.79 | 0.59 | 0.64 | 0.59 | 0.45 |
| 7 | Bam | 0.49 | 0.48 | 0.46 | 0.45 | 0.44 | 0.33 |
| 8 | Bandar abbas | 0.34 | 0.28 | 0.25 | 0.25 | 0.20 | 0.14 |
| 9 | Bandar lenge | 0.63 | 0.68 | 0.58 | 0.63 | 0.60 | 0.48 |
| 10 | Birjand | 0.19 | 0.17 | 0.16 | 0.17 | 0.16 | 0.12 |
| 11 | Bushehr | 0.61 | 0.50 | 0.42 | 0.44 | 0.42 | 0.28 |
| 12 | Chabahar | 0.18 | 0.22 | 0.19 | 0.21 | 0.17 | 0.10 |
| 13 | Esfahan | 0.15 | 0.14 | 0.14 | 0.13 | 0.12 | 0.10 |
| 14 | Fasa | 0.36 | 0.41 | 0.43 | 0.43 | 0.49 | 0.39 |
| 15 | Ghazvin | 0.26 | 0.27 | 0.25 | 0.26 | 0.23 | 0.16 |
| 16 | Gorgan | 0.60 | 0.67 | 0.61 | 0.63 | 0.64 | 0.50 |
| 17 | Hamedan | 0.69 | 0.76 | 0.71 | 0.76 | 0.73 | 0.55 |
| 18 | Iranshahr | 0.80 | 0.79 | 0.64 | 0.70 | 0.65 | 0.49 |
| 19 | Jask | 0.23 | 0.28 | 0.31 | 0.31 | 0.33 | 0.32 |
| 20 | Kashan | 0.09 | 0.10 | 0.11 | 0.12 | 0.12 | 0.09 |
| 21 | Kerman | 0.68 | 0.59 | 0.52 | 0.49 | 0.53 | 0.43 |
| 22 | Kermanshah | 0.53 | 0.54 | 0.47 | 0.50 | 0.43 | 0.29 |
| 23 | Khoram abad | 0.67 | 0.67 | 0.52 | 0.60 | 0.52 | 0.33 |
| 24 | Khoy | 0.50 | 0.49 | 0.43 | 0.46 | 0.46 | 0.31 |
| 25 | Mashhad | 0.59 | 0.57 | 0.74 | 0.62 | 0.86 | 0.98 |
| 26 | Rasht | 0.48 | 0.58 | 0.57 | 0.60 | 0.62 | 0.49 |
| 27 | Sabzevar | 0.37 | 0.41 | 0.54 | 0.47 | 0.66 | 0.67 |
| 28 | Sanandaj | 0.45 | 0.49 | 0.50 | 0.58 | 0.58 | 0.45 |
| 29 | Semnan | 0.64 | 0.63 | 0.56 | 0.62 | 0.56 | 0.40 |
| 30 | Shahrekord | 0.36 | 0.42 | 0.43 | 0.45 | 0.52 | 0.40 |
| 31 | Shahrud | 0.87 | 0.95 | 0.81 | 0.75 | 0.68 | 0.54 |
| 32 | Shiraz | 0.52 | 0.50 | 0.41 | 0.44 | 0.42 | 0.30 |
| 33 | Tabas | 0.56 | 0.61 | 0.64 | 0.60 | 0.68 | 0.59 |
| 34 | Tabriz | 0.35 | 0.36 | 0.31 | 0.30 | 0.27 | 0.19 |
| 35 | Tehran | 0.94 | 0.65 | 0.53 | 0.55 | 0.50 | 0.34 |
| 36 | Torbat heydarieh | 0.67 | 0.68 | 0.74 | 0.65 | 0.81 | 0.80 |
| 37 | Yazd | 0.72 | 0.84 | 0.65 | 0.70 | 0.60 | 0.41 |
| 38 | Zabol | 0.69 | 0.62 | 0.54 | 0.60 | 0.55 | 0.40 |
| 39 | Zahedan | 0.43 | 0.43 | 0.37 | 0.37 | 0.37 | 0.28 |
| 40 | Zanjan | 0.24 | 0.30 | 0.31 | 0.33 | 0.31 | 0.22 |

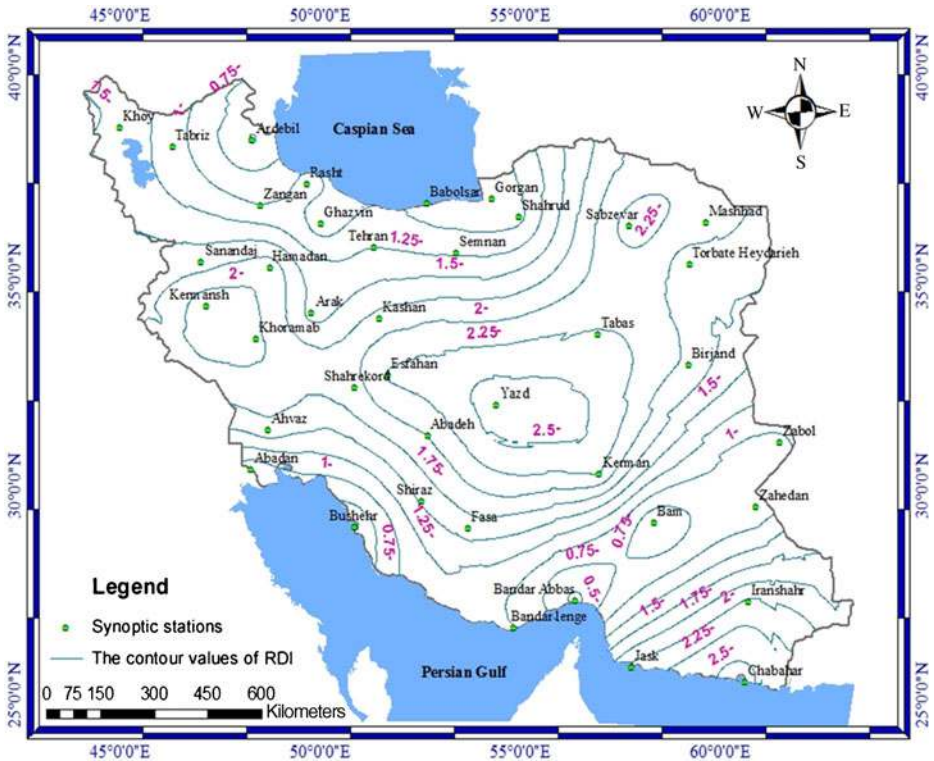


Fig. 6 The RDI based drought severity map for the driest year of 1999–2000

5 Discussion and Concluding Remarks

At the present study, the drought occurrences were monitored in Iran during the experimental years of 1975/76 to 2004/05. For this purpose, the drought indices of SPI and RDI were used and the estimations were carried out within the 30 years period of 1975/1976–2004/2005. SPI calculation in any specific site was based on a series of accumulated precipitations within a fixed time scale of interest. Such series was fitted to a probability distribution, which was then transformed into a normal distribution so that the mean SPI for the location and desired period was zero (Edwards and McKee 1997). Positive SPI values were found to be greater than median precipitation, and negative values were less than the median precipitation. As the SPI was normalized, wetter and drier climates could be represented in the same way and wet periods could also be monitored using the SPI.

Drought is a very common phenomenon in Iran and it has become a recurrent phenomenon in this country in the last few decades. The characteristics of past droughts provide the benchmarks for the future studies. Apart from the impacts that drought imposed on natural resources and environment, huge economic losses have affected the people i.e. the amount of losses caused by drought in just rain fed crops was calculated to be 6% of the GDP in 2000 (Badripour 2007).

The SPI has become a very widely used drought monitoring index. It is probably due to its simplicity, universality and least data demanding nature. But meteorological drought, conceived as a water deficit, should be approached by a sort of balance between input and output. The assumption that this deficit is represented only by the estimation of input could

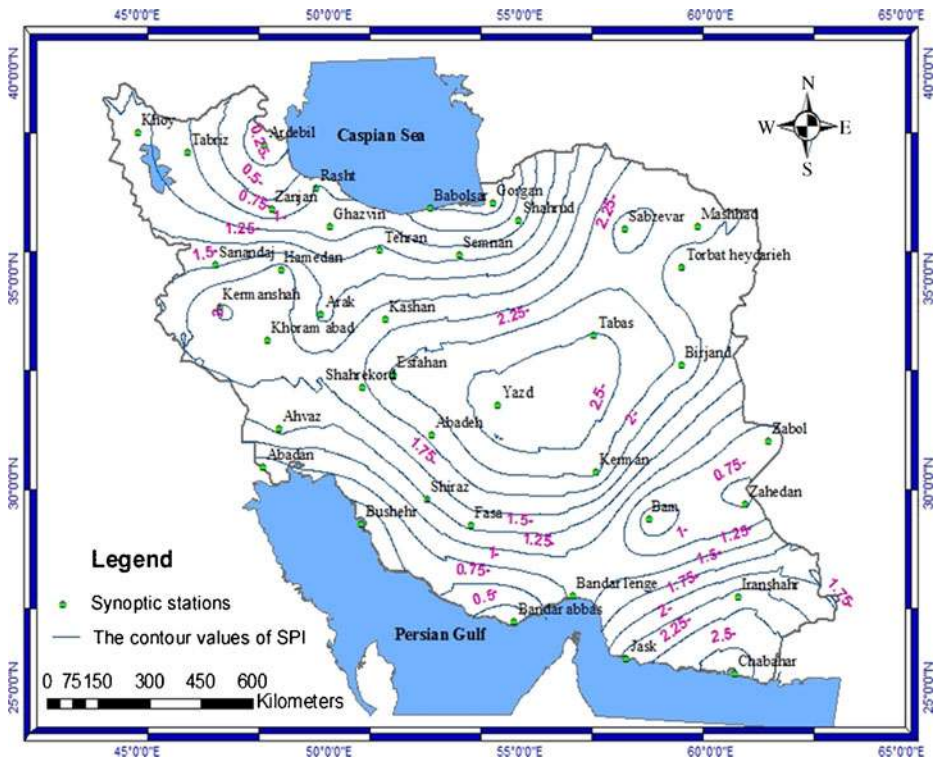


Fig. 7 The SPI based drought severity map for the driest year 1999–2000

Fig. 8 The cumulative “or more” curve of RDI for the dry year of 1999–2000

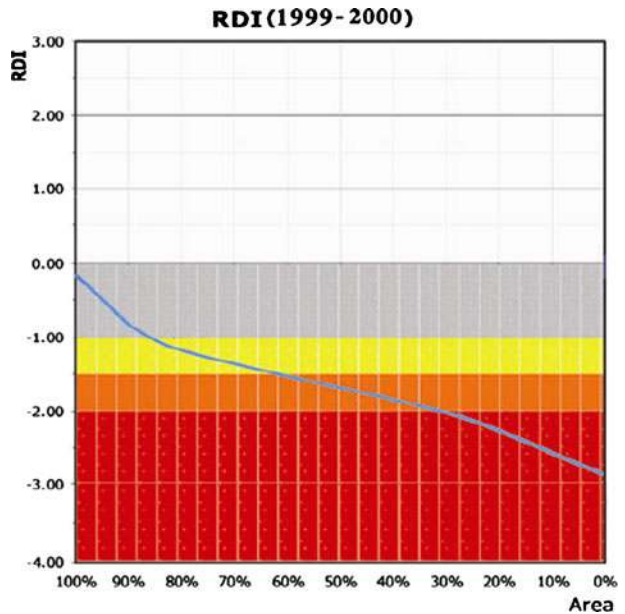
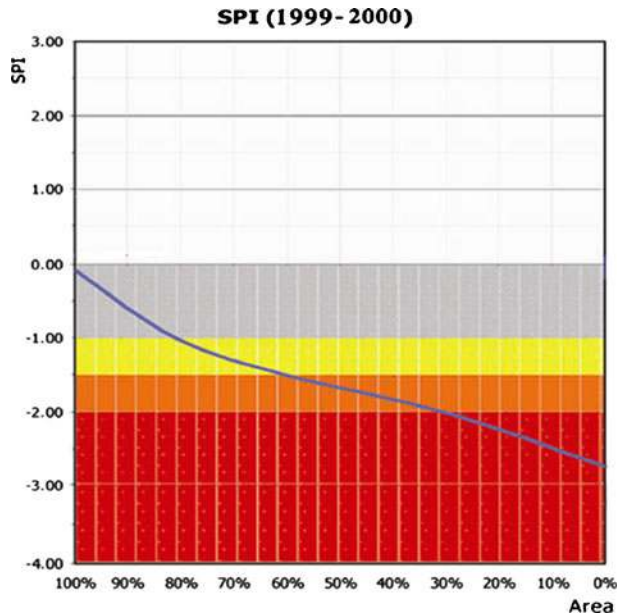


Fig. 9 The cumulative “or more” curve of SPI for the dry year of 1999–2000



not be valid in a wide variety of situations during the previous researches (Tsakiris and Vangelis 2005). A step forward was considered to make the balance between major meteorological parameters such as precipitation (P) (input) and potential evapotranspiration (PET) (output). Based on this logic, the RDI was proposed using the data of two above-stated determinants. Although, precipitation was the primary controlling factor for drought, other climatic factors such as high wind rate, high temperature or low relative humidity could be contributed to amplify its intensity (Sönmez et al. 2005). Usually, droughts accompanies with high temperatures, resulting in higher evapotranspiration rates. Potential evapotranspiration (PET) represents the environmental demand for evapotranspiration. It represents the evapotranspiration rate of a short green crop, completely shading the ground, with uniform height and adequate water status in the soil profile.

The RDI is expected to be a more sensitive index than those related only to precipitation, such as SPI. The calculation procedure of RDI is comparatively easy. PET can be calculated by empirical methods in an attempt to minimize the required data. Several authors have proposed the empirical Hargreaves (HG) equation (Hargreaves and Samani 1982) as the best alternative for the areas in which data were scarce, such as those where only daily air temperature data were available (Xu and Singh 2001; Droogers and Allen 2002). The HG equation required only the maximum and minimum air temperatures and extraterrestrial radiations. Because extraterrestrial radiation could be calculated theoretically (Droogers and

Table 5 Average correlation coefficient (R) of SPI and RDI in three climatic zone in differernt time scales

| Climatic zone | Time scales | | | | | |
|---------------------|-------------|-------|-------|-------|-------|-------|
| | 3 | 6 | 9 | 12 | 18 | 24 |
| Arid | 0.952 | 0.936 | 0.902 | 0.896 | 0.897 | 0.870 |
| Semi-arid | 0.913 | 0.871 | 0.817 | 0.826 | 0.828 | 0.807 |
| Humid and Sub-humid | 0.890 | 0.883 | 0.797 | 0.777 | 0.781 | 0.760 |

Allen 2002), the required parameters are only the observed maximum and minimum air temperatures. More than 72% of the annual precipitation of Iran was due to the loss of water by evapotranspiration. In fact, temperature, wind speed, relative humidity, aridity of climate and enough sunshine are the adjutant parameters causing excess evapotranspiration in Iran.

In general, the comparison of drought severity maps for SPI and RDI indicate that these maps were, to some extent, the same. But, the differences between RDI and SPI were more in humid and sub-humid parts of Iran, located in the north (Caspian Sea coasts), west and north-west (the western and eastern areas of Zagros chain) and the southern parts near the Persian Gulf. On the other hand, the differences between these two indices in the arid and semiarid parts of Iran (especially in the central parts of the country) were less than other parts of the country. Comparing the average values of RMSE in stations located in different climate conditions, indicates that the values of this factor increases from arid to the humid regions. Time scale length influences on the values of the two drought indices. The higher values of correlation coefficient between SPI and RDI were obtained for shorter time scales (3-, and 6-month) and the lowest value for 24-month time scale at all climate zones.

The survey of drought maps, derived from RDI and SPI values, has indicated the prevalence of drought within a specific period of time, but the drought in hydrological year of 1999–2000 was the most severe of all. This drought had the most severe impact on the country during the past three decades, in which most parts of Iran were affected by climatic drought. Based on the RDI results, during the hydrological year of 1999–2000, 28% of Iranian territory was under extreme drought, 31% under severe drought and 26% was affected by moderate drought.

Although, the present study used SPI and RDI indices for drought monitoring in Iran, a complete survey of the correlation of RDI and SPI is also needed during some other time series, which are the important indices of water resources management and balance such as; the time series of ground water or surface water levels in different regions of Iran. It is recommended to know that which one of the RDI and SPI indices have more correlation with the data of ground water level. In general, the present results have shown that the most part of Iran has been affected by drought but the severity and increased frequency of this phenomenon has been seen in the central and eastern parts of the country. So, there is a need to undergo future researches on these regions so as to improve the water resource management and development programs and to resolve the socio-economic and agricultural problems faced by the people in these parts of the country.

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