**ORIGINAL PAPER**

# Assessment of drought risk index using drought hazard and vulnerability indices

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## Abstract
This study attempts to determine the spatial and temporal patterns of drought hazard and risk in Semnan province, Iran. Drought risk assessment has been conducted in eight counties of Semnan province using a conceptual framework which emphasizes on the combined role of hazard and vulnerability in defining droughts. The standardized precipitation index (SPI) at synoptic stations at 3 and 12-month time step for period 1985–2011 were used to provide drought hazard index (DHI) map using kriging interpolation and natural break methods by ArcGIS 9.3 software. Eight obtainable/quantifiable socioeconomic and physical indicators including population density, rural ratio, agricultural occupation, irrigated land, food production, and municipal, industrial, and agricultural water consumption were used to provide the map of drought vulnerability index (DVI). Finally, the map of drought risk index (DRI) was provided through the integration of DHI and DVI maps. The overall results showed that at 3-month timescale Shahroud and Damghan and at 12-month timescale Shahroud, Damghan, and Semnan are the most susceptible regions to drought in central Iran. Therefore, consideration of virtual water, cultivation of products with less water requirement and use of appropriate irrigation methods can be two important factors in water demand management which should be addressed by water resource managers.

**Keywords** Drought · Risk management · Hazard · Vulnerability · Semnan province

## Introduction

Droughts are common phenomena in Iran and often cause major damage to socioeconomic environment and human-natural system. Droughts are much more devastating in arid and semi-arid provinces of Iran especially such as Semnan. Crop damage and suffering of people due to lack of water are almost every year phenomena in central Iran (Nasrollahi 2015). The government initiatives on drought management have been largely on response and recovery of drought, and very little attention has been paid to mitigation, preparedness, and monitoring of droughts in Iran. A shift in drought management from crisis management approach to risk management approach has been urged across

the world. One of the main aspects of drought management includes reliable drought risk assessment, since it provides the relationship between a hazard and society (Noorian et al. 2004).

Droughts can be classified into different categories such as meteorological, hydrological, agricultural, and socioeconomic (Wilhite and Glantz 1985; Zhang et al. 2011). Among all types of droughts, meteorological droughts are the most important one as it is the trigger of all other types of droughts. Meteorological drought refers to precipitation deficit and defined as a lack of precipitation over a region for a period of time (Dash et al. 2012). Several indices have been developed for the estimation of meteorological droughts which include Palmer modified drought index[1] (Palmer 1965; Vasiliades and Loukas 2009), rainfall anomaly index[2] (Van Rooy 1965), quartiles and deciles (Gibbs and Maher 1967), Bhalme and Mooly drought index[3] (Bhalme and Mooley 1980), standardized precipitation index[4] (Mckee et al. 1993a, b, 1995), effective drought index[5]

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[1] PMDI
[2] RAI
[3] BMDI
[4] SPI
[5] EDI

(Park et al. 2014), reconnaissance drought index[6] (Tsakiris et al. 2007), standardized precipitation evapotranspiration index (SPEI) (Beguería et al. 2014), etc. Among all the drought indices, SPI is the most widely used. The World Meteorological Organization (WMO) has also recommended SPI for characterization of droughts (Soltani 2007).

SPI developed by Mckee et al. (1993a, b) is used for defining and monitoring drought and determining the lack of rainfall for different timescales such as, 3, 6, 9, 12, 24, and 48 months. Numerous studies have been conducted across the world to assess droughts using SPI. National Drought Mitigation Center (NDMC) used SPI to monitor drought and water storage conditions (Kim et al. 2013). Sonmez et al. (2005) investigated on spatial and temporal dimensions of meteorological drought using the SPI in Turkey. Their results showed that with increasing timescales, required rainfall amounts for non-drought conditions decrease from the coasts toward the internal area. Shahid and Behrawan (2008) and Kim et al. (2013) used SPI to evaluate the spatial and temporal patterns of drought hazard in Bangladesh and South Korea, respectively. They also prepared drought risk maps using drought concept developed by NDMC. He et al. (2011) analyzed agricultural drought risk based on three main crop (wheat, corn, and rice) using SPI method. The results showed that eastern parts of China have had high hazard area in comparison to the western part.

Nasaji Zavareh (2001) studying of the economic, environmental, and social consequences of drought in Iran showed that the most important consequences of the drought in the economic and environmental dimensions include reducing farmers' incomes, increase in input prices, rising unemployment and migration, the decline in agricultural land prices, rising food prices, reducing diversity and vegetation, reduced soil quality, damage to plant genetic reserves, and shortening the length of the planting period.

Wilhelmi and Wilhite (2002) evaluated the drought vulnerability in Nebraska. The results showed that the most vulnerable areas to agricultural drought were no irrigated field and rangelands in sandy soil located in areas with a high probability of shortage of seasonal product moisture. Also, Poortaheri et al. (2013) conducted a research to reduce the vulnerability of rural farmers to drought consequences with emphasis on risk management in west Azerbaijan, Iran. The results showed that the economic and social factors are the most important dimensions of vulnerability.

Drought vulnerability in southwestern Hungary was studied using soil data sets, land use, groundwater level, and geomorphology of the region (Bella and Nemath 2006). The combined map of the three main parameters including precipitation, soil, and groundwater was prepared. Then, the provided

map was overlaid with land use and geomorphology maps, which ultimately resulted in drought vulnerability map.

Wu et al. (2011) explored the spatial characteristics of drought vulnerability in China. In this research, three factors of seasonal moisture reduction, water-holding capacity in soil, and irrigation were considered as factors indicative of drought vulnerability. The results showed that on a regional scale, southern and eastern parts of China have a low to moderate vulnerability to drought. While the highest vulnerability was observed in the northern and western parts of the study area.

So far, there has been little research done on preparing drought risk map using combination of meteorological information (drought hazard index) and socioeconomic and physical/structural information (drought vulnerability index) in Iran. The aim of this study was to characterize the spatial and temporal patterns of drought hazard and finally preparing drought risk maps in Semnan province, Iran.

## Materials and methods

### Study area

Semnan is one of the 31 provinces of Iran located between 51° 51′ and 57° 03′ eastern longitudes and 34° 13′ and 37° 20′ northern latitudes. The province is bounded by Mazandaran and Golestan provinces in the north, Esfahan province in the south, Tehran and Qom in west, and Khorasan and Razavi in the east to north. It is one of the widest provinces of Iran. It covers an area of 97,491 km$^2$ with an elevation of 1630 m above sea level at the center. Semnan is located on the southern slopes of the Alborz Mountains, and its elevation decreases from north to south. Semnan has arid, semi-arid, and dry climate due to geographical location. Due to limitations of soils and water, it does not have conducive agricultural situation (Solgi 2013). Figure 1 shows geographical location of the province. According to the census of the Iran Bureau of Statistics, the population of the province is 636,000, out of which 75% live in urban areas and the rest 25% in rural areas. Population density is 6.6 people per km$^2$.

### Assessment of drought hazard index

In this study, a data-based framework was proposed using a drought risk concept presented by the National Drought Mitigation Center, USA, for drought hazard and vulnerability (Kim et al. 2013; Fig. 2). SPI was used to estimate drought hazard patterns. Monthly rainfall data from 37 raingauge stations and 3 synoptic stations for period 1985–2011 were used to prepare drought hazard maps.

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[6] RDI

**Fig. 1** The extent of the study area and the location of synoptic and raingauge stations in Semnan province
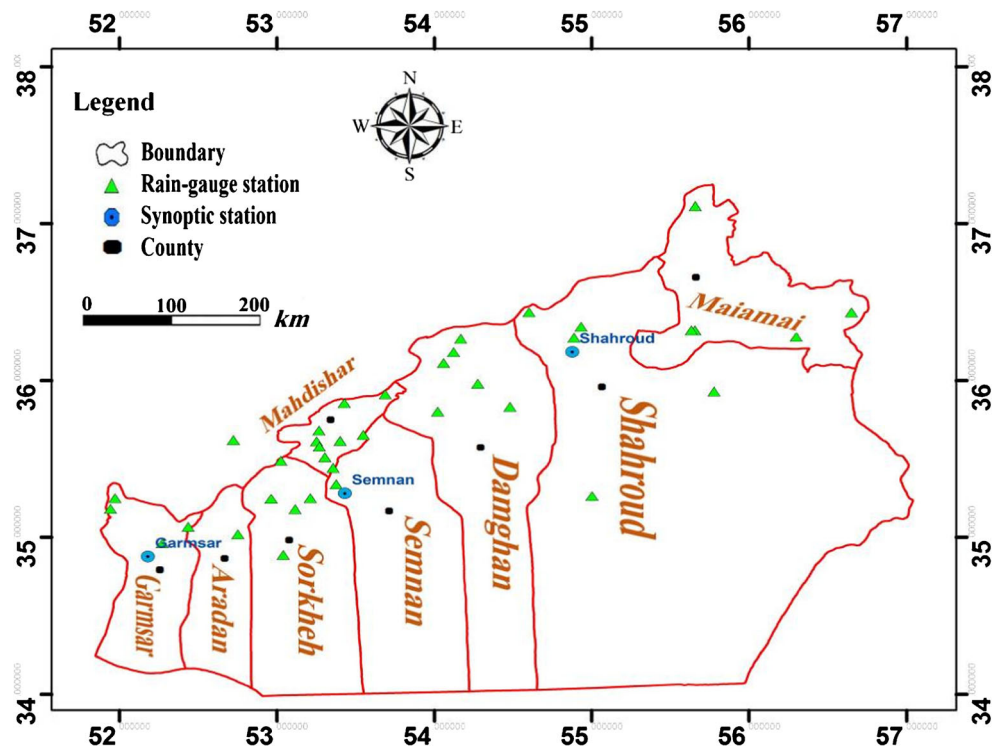


## Calculate standardized precipitation index using rainfall data

The SPI provides a comparison of the precipitation over a certain period with the total precipitation from the same period for all the years included in the historical record (McKee et al. 1995; Guttman 1998, 1999; Hayes et al. 1999). In this study, SPI with 3 and 12-month timescales were calculated to study the characteristics of drought in short and long timescales. In order to calculate SPI,

**Fig. 2** Procedure used for calculation of drought risk index
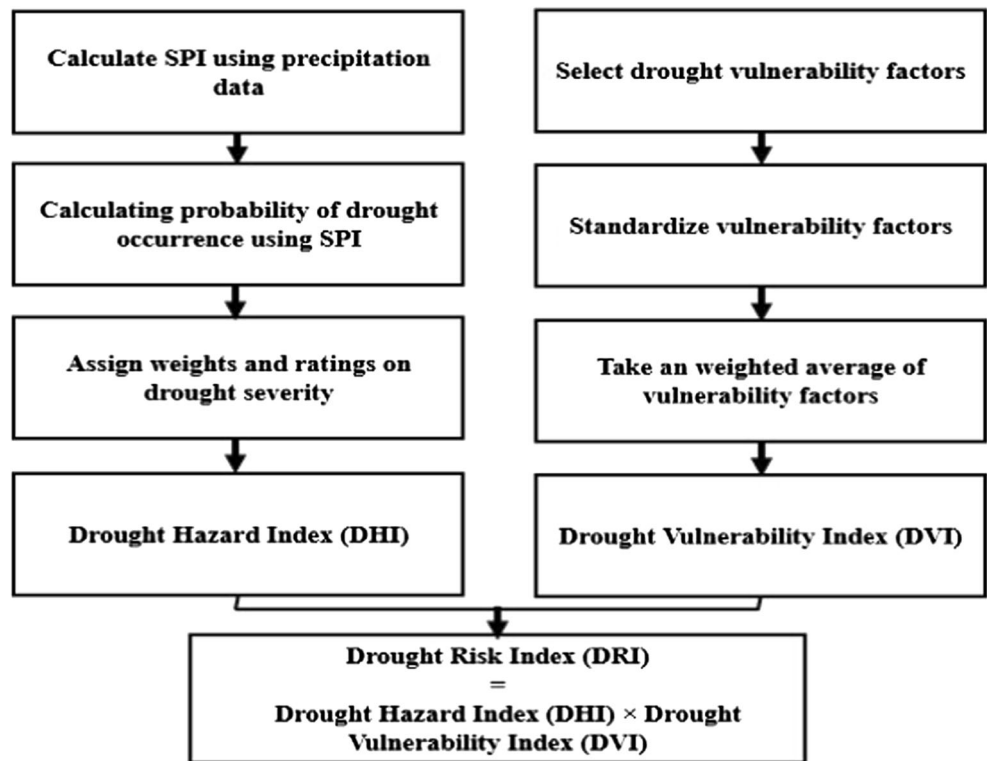
historical rainfall data of each station were fitted to a gamma probability distribution function:

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

where $x > 0$ is the amount of precipitation, $\alpha > 0$ is a shape parameter, $\beta > 0$ is a scale parameter, and $\Gamma(\alpha)$ defines the gamma function.

$$\alpha = \frac{1}{4A} \left( 1 + \sqrt{1 + \frac{4A}{3}} \right) \tag{2}$$

$$\beta = \frac{\overline{x}}{4A} \tag{3}$$

$$A = \ln\left(\overline{x}\right) - \frac{\sum \ln\left(\overline{x}\right)}{n} \tag{4}$$

In this equation, $n$ is the number of observed precipitation. In addition, $\overline{x}$ for a specific month is the average cumulative rainfall for a month during the historical period. Calculated parameters allow rainfall distribution in station effectively shown by a mathematical cumulative probability function as follows:

$$G(x) = \int_{0}^{x} \frac{1}{\beta^{\alpha} \Gamma(\alpha)} \int_{0}^{x} x^{\alpha-1} e^{\frac{-x}{\beta}} dx \tag{5}$$

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

$$H(x) = q + (1-q)G(x) \tag{6}$$

$q$ is the probability of a zero. The cumulative probability $H(x)$ was then transformed to the standard normal distribution to yield the SPI (McKee et al. 1993a, b).

As the precipitation rate of each time step for each month is fitted to a gamma distribution function, obtained function indicates the cumulative probability of a rainfall event for a station for a given month of the dataset and at different timescales. This allows establishing classification values for SPI. McKee et al. (1993a, b) classified drought severity based on SPI values (Table 1). An SPI of −2 or more means that a very severe drought occurs about 2.3% of the time or has a return period of 50 years, SPI between −1.5 and −1.99 means which a severe drought occurs about 4.4% of the time or has a return period of 25 years, and SPI between −1.0 and −1.49 means that moderate drought occurs about 9.2% of the time or has a return period of 10 years.

## Calculating the probability of drought occurrence using SPI

Vulnerability of area to drought in different timescale was determined based on the percentage of occurrences to drought. The percentage of drought occurrence was calculated by taking ratio of drought occurrences in each timescale to the total drought occurrences in the same timescale and drought category (Sonmez et al. 2005). The results of drought probability calculation at 3 and 12 timescales and drought categories are shown in Tables 2 and 3, respectively. Drought intensity was estimated from SPI values using the classification given in Table 1. The frequency of each drought categories was then calculated for each timescale. Finally, the percentage of drought occurrence probability was calculated by dividing the frequency of droughts in each category to all possible scenarios in each category and timescale (Tables 2 and 3).

## Assign weights to drought severity

Since the occurrences of the various drought intensities do not have the same value in determining the hazard of drought in a

**Table 1**  The SPI drought category classification

| Drought category | SPI values | Drought occurrence (%) |
|---|---|---|
| Near-normal (NND) | $-0.99 < SPI < 0.99$ | 68.2 |
| Moderate drought (MD) | $-1.49 < SPI < -1$ | 9.2 |
| Severe drought (SD) | $-1.99 < SPI < -1.5$ | 4.4 |
| Very severe drought (VSD) | $SPI < -2$ | 2.3 |

**Table 2**  Weight and rate assigned to drought category at 3-month time step

| Severity | Weight | Occurrence probability (%) | Rate | Area (%) |
|---|---|---|---|---|
| Near-normal drought | 1 | $70.67 \geq$ | 1 | 8 |
| | | 70.67–71.68 | 2 | 10 |
| | | 71.68–72.77 | 3 | 36 |
| | | $72.77 \leq$ | 4 | 46 |
| Moderate drought | 2 | $5.42 \geq$ | 1 | 12 |
| | | 5.42–6.50 | 2 | 41 |
| | | 6.50–7.10 | 3 | 33 |
| | | $7.10 \leq$ | 4 | 14 |
| Severe drought | 3 | $2.58 \geq$ | 1 | 21 |
| | | 2.58–2.94 | 2 | 21 |
| | | 2.94–3.24 | 3 | 42 |
| | | $3.24 \leq$ | 4 | 16 |
| Very severe drought | 4 | $1.02 \geq$ | 1 | 16 |
| | | 1.02–1.50 | 2 | 36 |
| | | 1.50–1.82 | 3 | 42 |
| | | $1.82 \leq$ | 4 | 6 |

**Table 3** Weight and rate assigned to drought category at 12-month time step

| Severity | Weight | Occurrence probability (%) | Rate | Area (%) |
|---|---|---|---|---|
| Near-normal drought | 1 | 67.49 ≥ | 1 | 16 |
| | | 67.49–68.67 | 2 | 27 |
| | | 68.67–69.71 | 3 | 26 |
| | | 69.71 ≤ | 4 | 31 |
| Moderate drought | 2 | 8.14 ≥ | 1 | 14 |
| | | 8.14–8.21 | 2 | 54 |
| | | 8.21–8.27 | 3 | 19 |
| | | 8.27 ≤ | 4 | 12 |
| Severe drought | 3 | 3.36 ≥ | 1 | 7 |
| | | 3.36–3.99 | 2 | 6 |
| | | 3.99–4.47 | 3 | 24 |
| | | 4.47 ≤ | 4 | 63 |
| Very severe drought | 4 | 1.92 ≥ | 1 | 31 |
| | | 1.92–2.24 | 2 | 29 |
| | | 2.24–2.59 | 3 | 21 |
| | | 2.59 ≤ | 4 | 19 |

region, it is required to quantify the impact of drought hazard for each drought category (Table 1). In this study, weightage 1 was given for normal drought and weightage 4 was given for very severe drought as it causes the greatest hazard (Tables 2 and 3).

## Mapping droughts using kriging method

The values of the probability of occurrences of drought calculated for each stations and drought category were interpolated to prepare map using GIS software ArcMap 9.3. Kriging method available in geostatistical analysis tool of ArcMap was used for this purpose. Kriging is a stochastic interpolation method (Isaaks and Srivastava 1989) widely used for surface interpolation of numerical measurements at different points (Ghahroudi Talli 2002). Studies have shown that kriging method provides better predictions than other interpolation methods (Oliver and Webster 1990; Van Beers and Kleijnen 2004; Izadi et al. 2010).

## Assign ratings to drought severity based on the percentage of occurrences

To provide the maps, the percentage of occurrence of each category of drought was classified into four classes using natural break method, a data clustering method designed to determine the best arrangement of values into different classes. This method is based on a mathematical algorithm that tries to minimize the differences between data values in the same class and maximize the differences between classes.

Therefore, it makes large distances between classes (Slocum Terry 2009). This method gives better results for data that is non-uniformly distributed. Because the data was non-uniformly distributed, natural break method was used. This method can be used to classify in all interpolation methods (Poortaheri et al. 2013; Kim et al. 2013). In this study, ArcGIS 9.3 software was used to identify natural breaks in the data set. A rate of 1 was given to the class with the lowest percentage probability of drought hazard and a rate of 4 to the class with the highest percentage probability of drought hazard. Tables 2 and 3 show weights and ratings assigned to drought severity.

## Drought hazard index

In this study, the maps of drought occurrence and severity for 3 and 12-month timescales were prepared. The maps were integrated to provide maps of drought hazard index. Drought hazard index (DHI) of integrated layer was calculated using Eq. 7.

$$DHI = (NND_r \times NND_w) + (MD_r \times MD_w)$$
$$+ (SD_r \times SD_w) + (VSD_r \times VSD_w) \qquad (7)$$

In above equation, NNDr, MDr, SDr, and VSDr are ratings assigned to near-normal drought (NND), moderate drought (MD), severe drought (SD), and very severe drought (VSD), respectively; NNDw, MDw, SDw, and VSDw are weights assigned to NND, MD, SD, and VSD, respectively. According to Eq. 7, DHI can have a value between a minimum of 10 to a maximum of 40.

## Assessment of drought vulnerability

### Selecting drought vulnerability factors

Drought vulnerability is different for different nations and individuals. In developing countries, drought vulnerability constitutes a threat to livelihoods, the ability to maintain production systems, and economies. In developed economies, drought poses significant economic risks and costs for individuals, public enterprises, commercial organizations, and governments (Downing and Bakker 2000). Therefore, the selection of vulnerability indicators is directly relevant to the local study context and the particular hazard (UNDP 2004). A holistic drought vulnerability index should take into account of ecological, socioeconomic, and production conditions (Shahid and Behrawan 2008). However, all indicators are not easily obtainable or quantifiable in Semnan province based on the above definitions. After careful consideration of obtainable/quantifiable indicators, eight indicators were

selected to represent the vulnerability of various geographic populations to the impact of droughts in Semnan province. Each of the indicators is explained below.

**Population density (PD)** Population density is most often calculated by the number of people per square kilometer. From a human or economic perspective, the degree of calamity associated with a disaster will be associated with the population density of the affected area. Disasters with similar severity will affect more people if they occur in a highly populated area compared to less populated area.

**The ratio of rural to urban population (Rr)** Vulnerability and capacity to combat are completely connected with each other. The effect of droughts on people living in villages and towns is different. Rural people generally have less access to all forms of capital and therefore they are more vulnerable to drought.

**Agricultural occupation (AO)** Nomads are more concerned with nature by livestock and agriculture, and therefore highly dependent on climatic conditions, especially amount of rainfall. So the degree of vulnerability will be higher for them than others. Agricultural sector is most vulnerable to drought, particularly in arid regions like Iran and Semnan province. Farmers in these areas are not able to plant, or a large portion of their crop is lost due to drought.

**Irrigated land (IL)** It represents the percentage of irrigated land to total land area. About 38% of agricultural lands are under irrigation in Semnan province. Over 90% of agricultural water is obtained from groundwater resources (Nasrollahi 2015). Access to surface and groundwater water is directly affected by the meteorological drought. Low precipitation reduced both groundwater table and river level (Nasrollahi 2015). Therefore, irrigation will be costly and sometimes impossible.

**Food production (FP)** It represents the amount of food produced in terms of kilogram per hectare. Droughts in higher food production area will have higher negative impact on economy compared to lower food production area.

**The share of municipal (MW), industrial (IW), and agricultural (AW) water consumption** It represents the amount of water consumed in terms of million cubic meters by different sectors such as municipal, industry, and agriculture. The greater dependence on water consumption means the greater vulnerability to drought. In Semnan province, 87, 9, and 4% of water are used in agricultural, municipal, and industrial sectors, respectively (Nasrollahi 2015).

**Standardized vulnerability factors** Factors used in the multi-criteria evaluation often have different nature. Therefore, the units of measurement criteria may be different. For effective use of all indices for analyzing and linking between them, they should be normalized under certain rules. This operation is named data standardization (Sadeghiravesh et al. 2015). The standardization means that the criteria with different units are transferred to the same level unit to have a common unit so that they can be compared to each other. Therefore, all the vulnerability factors were standardized in the present study. There are several methods for standardization. In this study, the fuzzy function method was used to standardize the indices. This method converts all values of the map layers to the same range from zero to one or zero to 255. To standardize the data by fuzzy method, the SDM function was first added to the ArcGIS and linear functions were used for standardization (Sui 1999).

## Assigning average weights to the vulnerability factors

For each vulnerability factor, four classes (ranging from lowest to highest value) were defined. The natural break method was used to extract the classes. ArcGIS 9.3 software was used to identify natural breaks in the data.

## Drought vulnerability index

The composite drought vulnerability index (DVI) of the integrated layers was calculated by using Eq. 8. For this purpose, each class of indicator was assigned a rating in the scale of 1–4 according to their values. Classes with higher values were given higher ratings, and the classes with lower values were assigned with lower ratings.

$$DVI = \frac{PD_n + Rur_n + AO_n + IL_n + FP_n + MW_n + AW_n + IW_n}{N} \quad (8)$$

where $PD_n$, $Rur_n$, $AO_n$, $IL_n$, $FP_n$, $MW_n$, $AW_n$, and $IW_n$ are ratings assigned to population density, rural ratio, agricultural occupation, irrigated land, food production, and municipal, industrial, and agricultural water consumption, respectively. DVI was estimated for each county as the basic unit of study. The DVI values of counties were standardized in a range between zeros to one. Finally, the counties were classified into four classes based on DVI values.

## Drought risk index

Drought risk index was calculated from drought hazard index and drought vulnerability index using Eq. 9 (Blaikie et al. 1994; Downing and Bakker 2000; Wilhite 2000).

$$DRI = DHI \times DVI \quad (9)$$

The DHI represents the probability of drought occurrence; DVI represents the most extensive concept of drought vulnerability within area, and drought risk index (DRI) represents

drought risk pattern in area. According to Eq. 9, if there is no chance for hazard or there is no vulnerability, the drought risk is zero. The greater DRI value indicates the greater DHI and DVI value. Drought risk map was prepared by multiplying the drought hazard map to drought vulnerability map. Finally, the drought risk map of the study area was classified into four classes including low, medium, high, and very high using natural break method.

## Results

SPI time series for all stations were investigated in order to examining temporal drought patterns. Figure 3 shows SPI time series on 3 and 12-month scales in synoptic stations of the study area. Although the results obtained from each studied stations had somewhat temporal correlation, the overall results did not show temporal correlation among all stations. This may be due to changes of elevation from 450 to 3900 m above sea level which lead to non-uniform distribution of rainfall in the province (0 mm in the central desert of Iran to more than 400 mm in the northern regions of the province) and different climates through the province. Although the results of the case study of the stations used in this study are somewhat correlated with time series. However, the overall results of the time series indicate the occasional of droughts in all of the studied stations. On the other hand, common drought period is not found for all stations. This is very



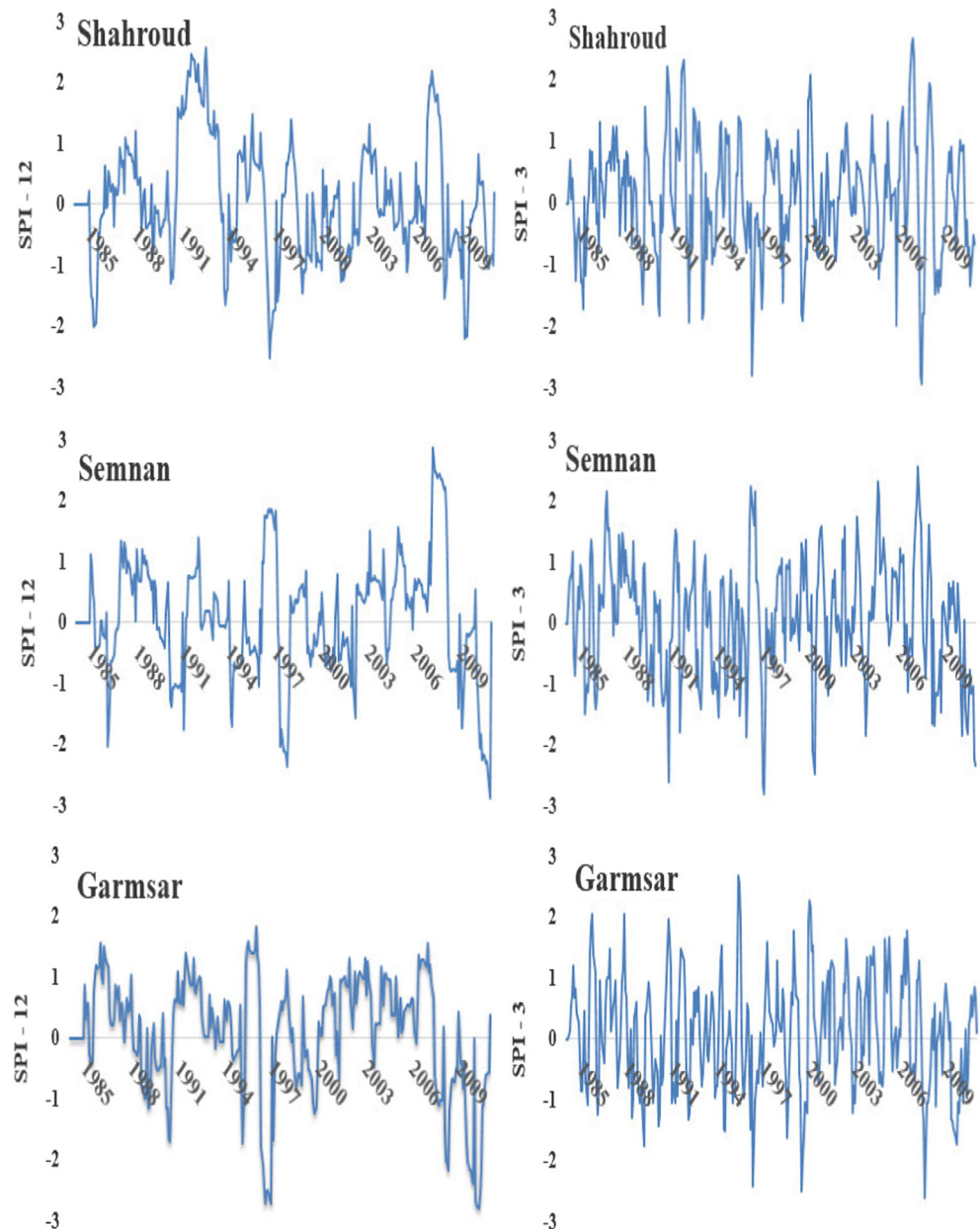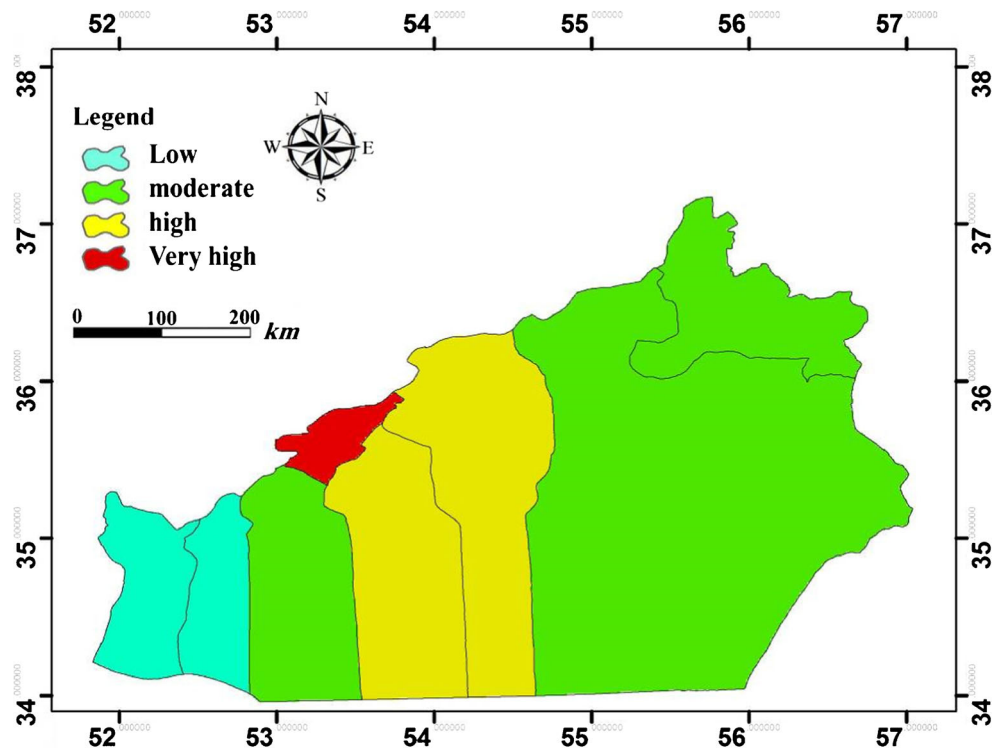Fig. 3 SPI time series at synoptic stations at 3 and 12-month time step

Fig. 4 Map of drought hazard index (DHI) for Semnan province at 3-month timescale



important due to the semi-arid climate of the study area and the characteristics of drought such as frequency and continuity of time. Since rainfall changes in the study area were very high and rainfall and temperature do not follow a particular pattern in the region, the standard spatial rainfall index (SPI) method

can be used to determine the extent and areas of drought potential.

To assess spatial distribution of drought hazard at 3 and 12-month timescales, the maps of drought occurrence severity in different timescales were investigated. The DHI maps at 3 and

Fig. 5 The map of drought hazard index (DHI) for Semnan province at 12-month timescale
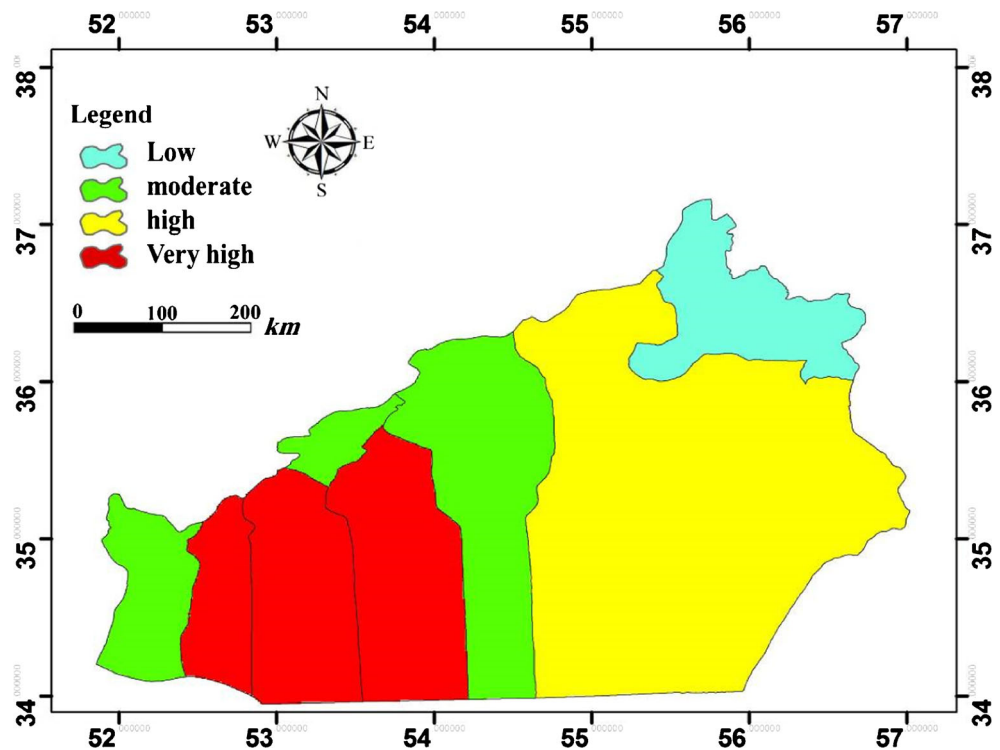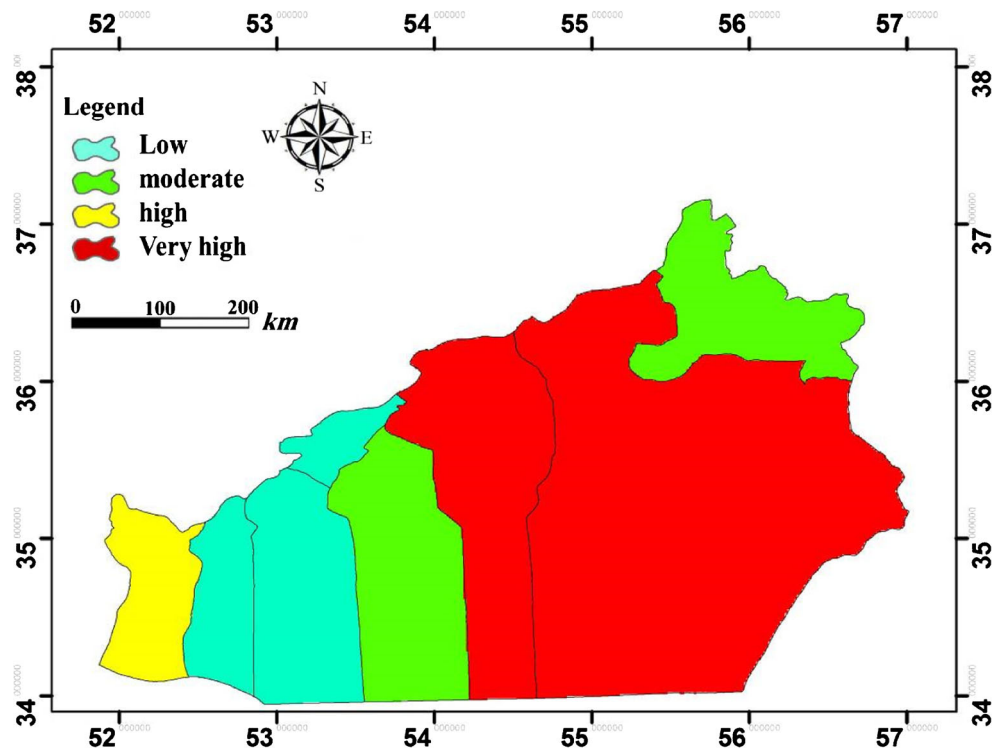
**Fig. 6** Drought vulnerability index (DVI) map of Semnan province

12-month timescales are shown in Figs. 4 and 5, respectively. Spatial distribution of drought hazard at 3-month timescale showed that drought hazard severity was high at northern parts of province, which gradually decreases toward south and western parts of the province. While at 12-month timescale, most drought hazardous zone was found in southern parts, which gradually decreases toward northern parts of the province. Most parts of the study area at 3 and 12-month timescales were found under moderate drought risk (62.46%) and very severe (53.12%), respectively. The percentage of area covered by drought hazard classes at 3 and 12-month timescales are provided in Tables 2 and 3.



**Fig. 7** Drought risk index (DRI) map of Semnan province at 3-month time step
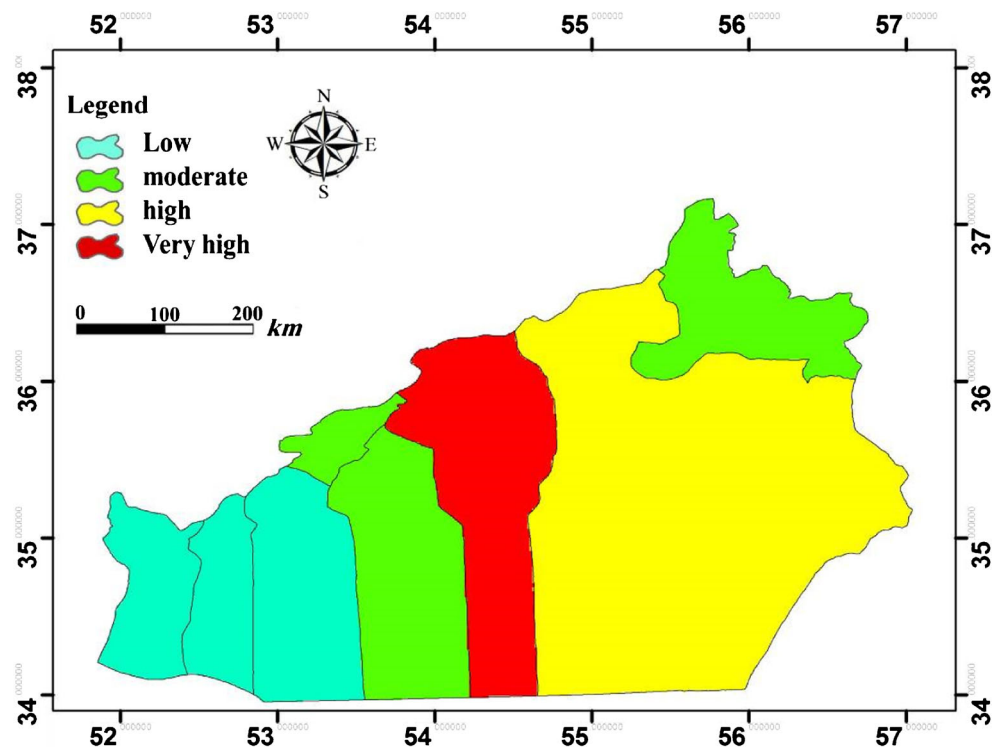
**Fig. 8** Drought risk index (DRI) map of Semnan province at 12-month time step
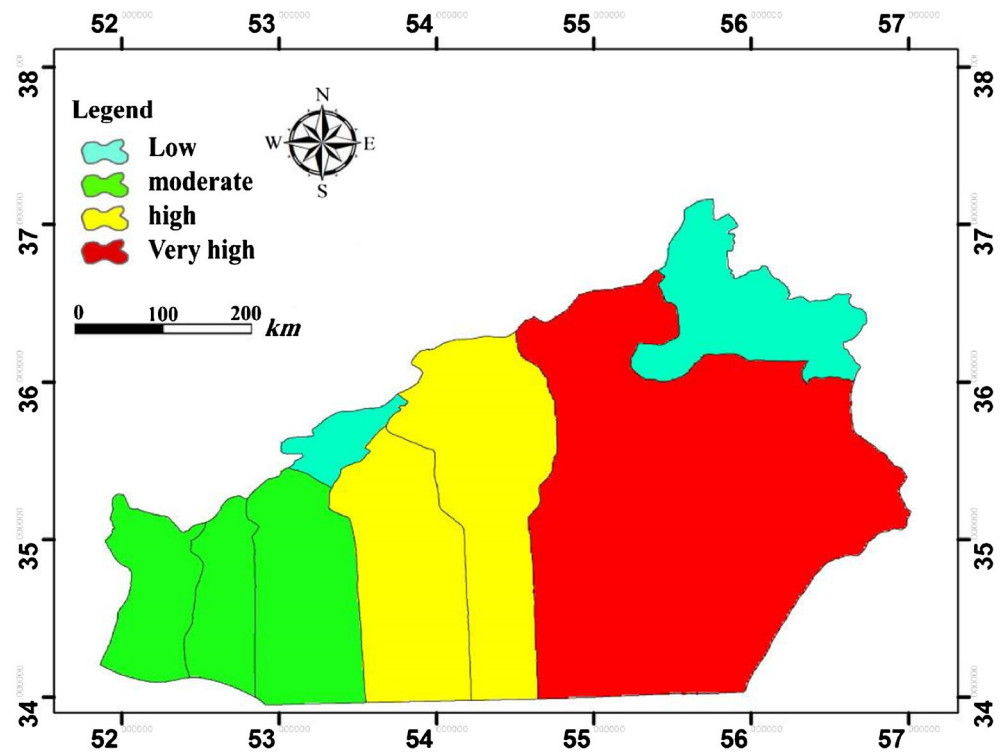


## Discussion and conclusion

Figure 6 shows the map of DVI prepared using the conceptual framework described in "Materials and methods" section (Fig. 2). The obtained results from eight socioeconomic factors showed that Damghan and Shahroud were the most vulnerable counties to drought. Pourtaheri et al. (2013) conducted a study in Western Azerbaijan and stated the socioeconomic factors as the most important aspects of drought vulnerability at the regional level. Mapping of vulnerability factors using natural break point method showed better results. Shahid and Behrawan (2008) and Kim et al. (2013) also found similar results when they used natural break method to unevenly distributed data. Since drought vulnerability in this conceptual framework was assessed in terms of supply and demand for water, Damghan and Shahroud were found more vulnerable to drought. This is because of surface water limitation and overuse of groundwater resources leading to the fall of groundwater table as well as the lack of accessing to new water resources. The study suggests that water management in the region should be shifted from supply-based management to demand control management. Consideration of the virtual water and planting crops with lower water requirements as well as using suitable irrigation methods could be the important demand management measures in the area.

DRI map of Semnan province at 3 and 12-month timescales is shown in Figs. 7 and 8, respectively. Overall results show that at 3-month timescale Shahroud and Damghan and at 12-month timescale Shahroud, Damghan, and Semnan are the most susceptible regions to drought risk.

The present study was conducted in Semnan province for drought risk assessment in order to aid drought preparedness. The spatial and temporal drought hazard patterns were prepared using the map of drought risk in eight counties of Semnan province. The results show that the drought risk in Semnan was a function of climate and local vulnerability level. In general, high-risk areas observed in the regions where simultaneously the drought hazard and vulnerability are high. The results also confirmed that the conceptual framework used in this study could overcome the limitations of the drought assessment methods which are based only on several monthly drought indices such as SPI and PDSI. As those indices do not consider vulnerability factors, they cannot be used effectively in establishing regional drought plans.

The present study showed the effectiveness and usefulness of a conceptual framework which emphasizes on combined role of hazard and vulnerability in assessing drought risk within region. For example, although high drought hazard is common in Mahdishar at 3-month timescale, drought risk is not high at Mahdishar because of the low vulnerability. This is also the case for Sorkheh and Aradan at 12-month timescale. The conceptual framework presented in this study assesses vulnerability factors in terms of water demand and supply management, and therefore, it could be useful in understanding drought in different areas, especially for dry areas.

Since drought vulnerability is calculated from the perspective of water supply and demand therefore, in two cities of Damghan and Shahroud being the most vulnerable to drought due to the limited surface resources and the extraction of underground resources and consequently a drop in groundwater table and the lack of access to new water resources, management needs to be changed from supply management to demand management to manage optimal water resources. Therefore, consideration of virtual water, cultivation of products with less water requirement and use of appropriate irrigation methods can be two important factors in water demand management which should be addressed by water resource managers. The drought risk maps prepared in this study using conceptual framework can be used for operational management of drought. For example, the expenditures should be shifted to the most vulnerable areas identified at 3 and 12-month time steps. Since it is not possible to change the natural events, coordinated actions in the political and institutional level can help to create capacity and reduce vulnerability of people to the drought.

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