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Evaluation of meteorological, hydrological and groundwater resources indicators for drought monitoring and forecasting in a semi-arid climate

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Abstract

Drought as a natural phenomenon characterized by a significant decrease of water availability during a period of time and over a large area. In recent years, droughts and its frequent in arid and semi-arid regions like Iran on the one hand, and water demand has been rising on the other hand and, as a result, their impacts are being aggravated. Therefore, the meteorological and hydrological droughts are receiving much more attention. This research focused on the Standardized Precipitation Index (SPI), Streamflow Drought Index (SDI) and Groundwater Resources Index (GRI) to investigate the correlation between these indices and overlapping periods of 3 to 48-months in the centeral Iran over the period of 1970–1971 to 2014–2015. Furthermore, the driest year based on the SPI were 2007–2008 and 2011-2012, while they were detected to be 1999–2000 and 2003-2004 based on the SDI and GRI, respectively. The decreasing time series trends using Spearman's rho and Kendall's tau tests were more evident for the all three indices at most of the years. SPI on time scales of 18, 24 and 48-months, with SDI and GRI showed a significant relationship in 0.01 and 0.05 percent levels that it can be confirmed directly affected by a groundwater drought in the plains. The Spearman correlation analysis indicated a strong correlation between SPI on time intervals of 18, 24 and 48-months, with SDI and GRI that showed a significant relationship in 0.01 and 0.05 percent levels that it can be confirmed directly affected by a groundwater drought in the plain. In general, the results showed that the study area suffered from the meteorological drought more than the other two types of droughts. Moreover, the results revealed that the study area has become drier over the last three decades.

Keywords: Meteorological drought; SPI; Hydrological drought; SDI; Groundwater resources drought; GRI; Correlation coefficient

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1. Introduction

Global climate change, including both gradual and abrupt changes, has a profound impact on land surface-atmosphere interactions and regional social development. On the one hand, the global warming, or gradual climate change, has a significant effect on atmospheric circulation and the hydrological cycle, and it alters the intensity and spatial distribution of precipitation (IPCC, 2007; Arnell, 1999), which in turn changes local dry/wet conditions and affects the regional agriculture sector. On the other hand, within the context of climate change, change can also occur in the frequency of extreme weather events (Rosenzweig *et al.* 2001; Du *et al.*, 2012), which can induce various meteorological hazards, such as floods, droughts and rainstorms. Drought is a natural phenomenon characterized by a significant decrease of water availability during a significant period of time and over a large area. Drought events and their related impacts on the socioeconomic and natural environments are expected to increase in severity due to changing climate (Bates *et al.*, 2008; Dai, 2011; Romm, 2011; Van Huijgevoort *et al.*, 2013; Kazemzadeh and Malekian, 2015; Tabari *et al.*, 2013). Drought is not only the world's costliest natural event, collectively affecting more people

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than any other form of natural hazard (Wilhite, 2000), but it is also one of the most difficult phenomena to define. An objective evaluation of drought condition in a specific area is difficult to carry out, because its consequences are felt by the socio-economic contexts after a considerable delay with respect to its inception. Specifically, the reduced precipitation observed in the last century in the Mediterranean region (IPCC, 2007) and the frequent drought events that have recently occurred have highlighted the need for an improvement of the current strategies for mitigating drought impacts on the different socio-economic sectors related to water use (Rossi *et al*., 2007; Mendicino *et al*., 2008; Zhang *et al*., 2012).

The efficiency of a drought monitoring system is deeply influenced by an accurate selection of indices for drought identification, providing a synthetic and objective description of drought conditions (Mendicino *et al*., 2008). Over the years several indices have been developed, each one essentially related to one of the four categories in which the American Meteorological Society (1997) has grouped drought definitions and types: meteorological, agricultural, hydrological and socio-economic. Among them, the most widely used are the Palmer Drought Severity Index (PDSI); (Palmer, 1965), the most classical drought index formulated to evaluate prolonged periods of both abnormally wet and abnormally dry weather conditions, and the Standardized Precipitation Index (McKee *et al*., 1993), a meteorological drought index based on the precipitation amount in a period of ‘n’ months (WMO, 2012). Since SPI just needs precipitation data to be calculated, it has found widespread application.

Other indices can be found in the literature considering additional quantities: Liu *et al*. (2012) presented Standardized Runoff Index (SRI), Vicente-Serrano (2012) introduced the Standardized Streamflow Index (SSI), Nalbantis and Tsakiris (2009) presented the Streamflow Drought Index (SDI), Tsakiris *et al*. (2007) recommended the Reconnaissance Drought Index (RDI), accounting also for temperature. Narasimhan and Srinivasan (2005), using the Soil and Water Assessment Tool (SWAT) model, derived two drought indices for agricultural drought monitoring, the Soil Moisture Deficit Index (SMDI) and the Evapotranspiration Deficit Index (ETDI), based respectively on weekly soil moisture and evapotranspiration (ET) deficit. Also Matera *et al*. (2007) derived a new agricultural drought index, called DTx, based on the daily transpiration deficit calculated by a water balance model. Obviously, the simpler the hydrological model, the easier the derivation of the index will be.

When dealing with complex systems, one single index is often not able to capture the different features of drought. On the other hand, it is more practical to declare drought condition considering only one indicator. Thus, there is a growing interest in aggregating more indices (Mendicino *et al*., 2008). Steinemann and Cavalcanti (2006) use the probabilities of different indicators of drought and shortage, selecting the trigger levels on the basis of the most severe level of the indicator or the level of the majority of the indicators. Keyantash and Dracup (2004) used an Aggregate Drought Index that considers all relevant variables of the hydrological cycle through Principal Component Analysis, but they do not include groundwater in the suite of variables for three reasons concerning: historic groundwater heights prior to human disturbances that are typically unknown; groundwater flow between distinct, heterogeneous aquifers across sizeable climate divisions being difficult to assess and; groundwater response to drought that may be asynchronous with other variables. Actually, drought in groundwater systems is mainly analyzed simulating groundwater recharge, discharge and hydraulic heads (e.g. Schoups *et al*., 2006), considering in some cases a threshold level approach to define the drought event and evaluating the performance of the systems through performance indicators (Peters *et al*., 2005 and 2006).

One of drought indicators that is associated with the streamflow, is hydrological drought. Hydrological drought is defined as a significant decrease in the availability of water in all its forms appearing in the land phase of the hydrological cycle. These forms are reflected in various hydrological variables such as streamflow (including snowmelt and spring flow), lake and reservoir level, and groundwater level. Among these variables, streamflow is, by far, the most significant variable from the viewpoint of quantity of water. It is the key variable for expressing surface water resources. Hence, a hydrological drought event is related to streamflow deficit with respect to normal conditions. Each drought event is characterized through four attributes: (a) its severity expressed by a drought index, (b) its time of onset and its duration, (c) its areal extent, and (d) its frequency of occurrence (Nalbantis and Taskiris, 2009).

Therefore, main objectives of this research are ccomparative analysis of the SPI, SDI and GRI (Groundwater Resources Index) based on the data from selected rain-gauges, hydrometric station and piezometers in the study area, then applying two nonparametric approaches to detect the meteorological, groundwater and hydrological drought trends and their relationships over the last decades, after that analysis of overlapping periods of 3, 6, 9, 12, 18, 24 and 48-months in each year over a 35 years period (1970–1971 to 2014–2015), and finally assessing the correlation coefficient between the indices. The novelty of this research is that in this region and in general in Kerman province, simultaneous study and relationship between these three droughts indices has not been done so far.

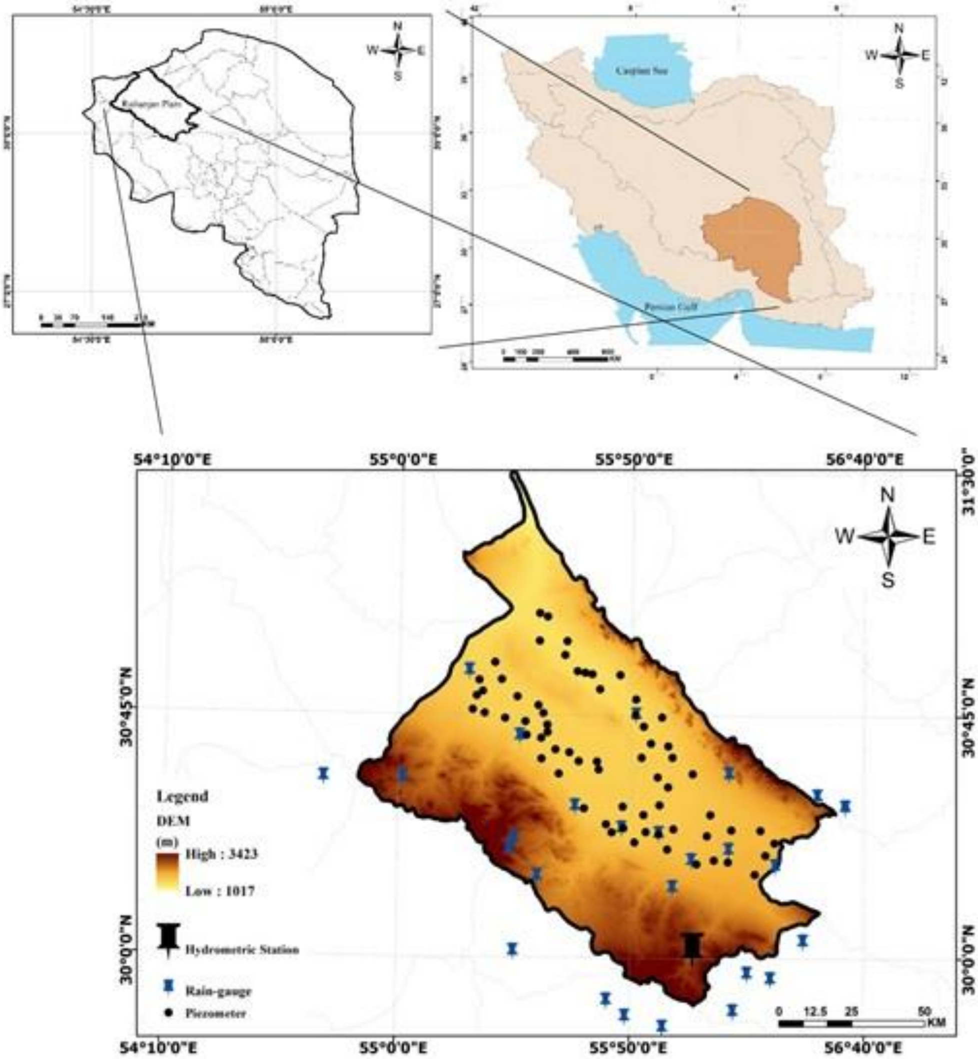

Fig. 1. The extent of the study area (Rafsanjan plain) in Iran and Kerman province and rain-gauge and streamflow (hydrometric) stations in and around of Rafsanjan plain

2. Materials and Methods

2.1. Study area and data

The study area, Rafsanjan plain, with an area of 12421 km^2, is located in the west of Kerman province and in the middle of Iran. In this area, many people are engaged in agriculture. It is a susceptible area in terms of annual precipitation variable (70-170 mm) and a prohibited plain in terms of withdrawal of groundwater resources. Long-term average temperature and rainfall in the region are 18.6°C and 82.3 mm, respectively Kerman Meteorological Department (KMD), 2015). Totally, 27 rain-gauges and hydrometric stations in the region with valid and adequate data (after the reconstruction of data), and 28 piezometers, were selected (Fig.1).

The monthly observed precipitation, streamflow and groundwater depth data were collected for the period of 1970-1971 to 2014–2015. Before using data for drought analysis, at first step, reconstruction of data was done, then some statistical tests including the homogeneity test via double mass curve method, normal distribution test and the normality test were applied. All of the meteorological and hydrometric stations are presented in Fig. 1.

2.2. Standardized Precipitation Index (SPI)

In order to investigate the spatial and temporal extents and severity of drought occurrence in the study area, Standardized Precipitation Index (SPI) was used. SPI is a widely used drought index based on the probability of precipitation on multiple time scales. It has been demonstrated by several researches (McKee *et al*., 1995; Guttman, 1998, 1999; Hayes *et al*., 1999). This Index is a simple way for defining and monitoring drought events which was developed by McKee *et al.* (1993) and has become a popular measure of drought across the globe (Do-Woo *et al*., 2009; Duggins *et al*., 2010; Utzkuzova *et al*., 2015). Positive SPI values indicate greater than mean precipitation (or rainfall surplus), negative values represent less than mean precipitation (or deficit rainfall) (Patel *et al*., 2007), and the magnitude of SPI values represent the intensity of drought and wet events. The SPI is calculated in the following sequence. A monthly precipitation data set is prepared for a period of m months, ideally a continuous period of at least 30 years. A set of averaging periods is selected to determine a set of timescales of period j months where j is3, 6, 12 months. Then, the SPI is calculated according to the procedure described by McKee *et al*. (1993). Table 1 summarizes the classification of the SPI values and the corresponding drought category.

2.3. Streamflow Drought Index (SDI)

Nalbantis and Tsakiris (2009) developed SDI following the methodology of the SPI for characterizing hydrological droughts. It is assumed that a time series of monthly streamflow volumes $Q_{i,j}$ is available, where i denotes the hydrological year and j the month within that hydrological year (j = 1 for October and j = 48 for September in two years later). Based on this series, the cumulative streamflow volume is computed as follows:

$$V_{i,k} = \sum_{j=1}^{3k} Q_{i,k} \qquad i = 1 \quad , \quad j = 1 \quad , \qquad k = 1, 2, 3, 4, 5, 6, 7, 8 \tag{1}$$

where $V_{i,k}$ is the cumulative streamflow volume for the i-th hydrological year and the *k*-th reference period, *k* = 1 for October–December, *k* = 2 for October–March, *k* = 3 for October–June, and *k* = 4 for October–September, *k* = 5 for October–March (in the next year), *k* = 6 for October–September (in the next year), *k* = 8 for October–September (two years later).

Based on the cumulative streamflow volumes $V_{i,k}$, the Streamflow Drought Index (SDI) is defined for each reference period k of the i-th hydrological year as follows:

$$SDI_{i,k} = \frac{V_{i,k} - \bar{V}_k}{s_k} \qquad i = 1, 2, \ldots \qquad k = 1, 2, 3, 4, 5, 6, 7, 8 \tag{2}$$

Where $\bar{V}_K$ and s_k are, respectively, the mean and the standard deviation of the cumulative streamflow volumes of the reference period k. (Nalbantis and Tsakiris, 2009; Tigkas *et al*., 2012). While positive SDI values indicate wet conditions, negative values reflect a hydrological drought. States of the hydrological drought are defined based on the SDI which is identical to those used in the meteorological drought indices, including the SPI and RDI. Therefore, five states of hydrological drought are defined which are denoted by an integer number ranging from 0 (non-drought) to 4 (extreme drought). The different states are defined through the criteria stated in Table 2.

Table 1. Wet and dry period classification according to the SPI (McKee *et al*., 1993)

Description of state	Criterion
SPI ≥ 2.0	Extremely wet
1.5 ≤ SPI < 2.0	Very wet
1.0 ≤ SPI < 1.5	Moderately wet
-1.0 ≤ SPI < 1.0	Near normal
-1.5 ≤ SPI < -1.0	Moderate dry
-2.0 ≤ SPI < -1.5	Severe dry
SPI ≤ - 2	Extreme dry

Table 2. Definition of states of hydrological drought based on the SDI (Nalbantis and Taskiris, 2009)

State	Description	Class	Probability (%)
0	Non-drought	SPI ≥ 0.0	50.0
1	Mild drought	-1.0 ≤ SPI < 0.0	34.1
2	Moderate drought	-1.5 ≤ SPI < -1.0	9.2
3	Severe drought	-2.0 ≤ SPI < -1.5	4.4
4	Extreme drought	SPI ≤ - 2.0	2.3

2.4. Groundwater Resource Index (GRI)

The Groundwater Resource Index (GRI) is suggested based on study of Mendicino *et al.* (2008) in a form like this:

$$GRI_{y,m} = \frac{D_{y,m} - \mu_{D,m}}{\delta_{D,m}} \qquad (3)$$

where $GRI_{y,m}$ and $D_{y,m}$ are respectively the values of the index and of the groundwater detention for the year y and the month m, while $\mu_{D,m}$ and $\sigma_{D,m}$ are respectively the mean and the standard deviation of groundwater detention values *D* simulated for the month m in a defined number of years (at least 30). The main characteristics and the performance of this index in assessing and forecasting the real status of groundwater resources are analyzed in the next section (Kumar *et al.*, 2015).

3. Results and Discussion

3.1. Reconstruction of data

Monthly rainfall, streamflow and groundwater depth data for the period of 1970-1971 to 2014-2015 from 27 rain-gauge, streamflow stations and 28 piezometers of Kerman Meteorological Department (KMD) and Kerman Regional Water Authority (KRWA) was used for severity and frequency of occurrence of droughts in this area. Fig. 1 shows location of rain-gauges and piezometers in the study area. The main problem encountered during drought study is the missing rainfall data. The missing rainfall data is random in most of the stations, however, data missing for years is also evident in some stations. Percentage of missing rainfall data in different stations are presented in Table 3. There are different methods to reconstruct the missing data such as Markov chain (Sharma and Panu, 2012) and Artificial Neural Network (ANN). A feed-forward Artificial Neural Network (ANN) based approach by Teegavarapu and Chandramouli (2005), Shahid and Behrawan (2008) is used for estimation of missing rainfall data. The topology of ANN used for the estimation of missing rainfall data is 6:4:1. which was determined through a trial and error procedure. The input neurons use values from six neighboring stations around the station of interest and output neuron of the ANN provides the missing value at the station of interest. Historical rainfall data of 23 KMD rain-gauge stations (shown by black bold dot in Fig. 1) of Kerman were used for this purpose. The neural network training is done by using supervised back-propagation training algorithm (Haykin, 1994). The performance of ANN method tested by its applying in estimating historic rainfall data at different rain-gauge stations situated in the Rafsanjan plain. Monthly mean rainfall data from October 1970 to September 2015 used for this purpose. Root Mean Squared Error (RMSE) given by equations used to measure the efficiency of the method.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(e-a)^2} \qquad (4)$$

where *n* is the total number of observations, e is the estimated value and a is the actual value of the observation.

At first step, approximately 60% of the historical data (Oct 1970–Sep 1996) are used to train ANN and the rest of the data (Oct 1996–Sep 2015) are used for validation. In the next step, the training data is increased to approximately 70% and 80% of the historical data. The RMSE Values during validation of the network at different stations are given in Table 3. The results show that the performance of the ANN-based method increases with the increase of percentage of training data. However, it is clear from the Table that it is possible to estimate the missing rainfall data with reasonable error by training the ANN with only 60% of historic data. In the present study, 80% historic rainfall data is used for the training of ANN to estimate the missing rainfall data of all stations.

3.2. Normality tests of data series

The Kolmogorov–Smirnov (K–S) test at the 0.05 significance level was used to check the goodness of fit of the precipitation, groundwater depth and streamflow data by means of an adjusted normal distribution. The higher *p* values indicate the acceptance of the null hypothesis of K–S test which means that the observed data are coming from this distribution. The results showed that all of the series follow a normal distribution. they showed that for October–March (6 month), October–June (9 month), October–September (12 month),18 month, 24 months and 48 months the *p* values are greater than 0.29 while for October–December (3 month), are greater than 0.19 which means that the normal distribution provides an adequate fit to the precipitation, groundwater depth and streamflow series. The lowest *p* values are obtained for the Anar, Sadegh-Abad and Biaz stations of the streamflow series, which is mainly due to the fact that many of the series had zero values.

Table 3. Percentage of missing data and RMSE during validation of ANN at different stations

No	Station	Percentage of missing data	RMSE (for percentage of training data)		
			60%	70%	80%
1	Ahmad-Abad	8.2	2.4	2.0	1.5
2	Anar	15.9	1.9	1.4	1.1
3	Bagh-Khosh	3.9	1.7	1.2	1.0
4	Bibihayat	31.0	2.0	1.7	1.3
5	Biaz	36.2	2.3	2.0	1.5
6	Bidestan	14.2	1.7	1.3	1.0
7	Pariz	10.4	2.1	1.7	1.4
8	Paghaleh	1.5	0.8	0.7	0.5
9	Pamazar	17.1	1.7	1.3	1.0
10	Taj-Abad	19.7	2.0	1.5	1.1
11	Titoieh	5.8	1.6	1.4	1.1
12	Jozam	8.0	1.9	1.6	1.2
13	Hossein-Abad	3.9	1.4	1.2	0.9
14	Katoun-Abad	2.6	1.2	0.9	0.7
15	Dastjerd	7.6	1.5	1.3	1.0
16	Dehouieh	7.7	0.9	0.6	0.5
17	Raviz	10.7	3.4	3.2	2.4
18	Rafsanjan-1	0.3	1.2	1.1	0.8
19	Riseh	0.9	0.9	0.6	0.4
20	Saadat-Abad	28.3	2.6	2.4	1.8
21	Sadegh-Abad	14.7	1.7	1.3	1.0
22	Ali-Abad	6.7	2.1	1.6	1.2
23	Kaboutarkhan	4.0	1.4	1.2	0.8
24	Hejin	10.1	2.2	1.7	1.3
25	Davaran	11.3	2.6	2.2	1.7
26	Rafsanjan-2	21.4	2.1	1.6	1.1
27	Shahzadeh-Abbas	10.0	2.0	1.6	1.3

3.3. SPI and SDI series

The SPI and SPI/SDI series for 24 and 48-months cumulative periods for some stations, are represented in Figs. 2, 3 and 4. We used the hydrometric and rain gauge stations close to each other to study the meteorological and hydrological droughts. As shown, the majority of drought events for the reference periods of 24 and 48-months were found in the last 13years from (2002–2003 to 2014–2015) and 33 years (1981-1982 to 2013-2014). Moreover, almost all of the rain gauge and hydrometric stations experienced at least one extreme drought event over the studied periods. The most severe meteorological drought was identified at the Sadegh-Abad and Anar stations located along with Givdari River in 2007–2008 and 2011–2012, respectively. Compared with the meteorological drought, the most severe hydrological droughts were detected in the Shahzadeh-Abbas station over 1999–2000 with the SDI values of -0.95 and -0.83, respectively. Furthermore, the long-term meteorological droughts were found at Anar station in 1979-1980 to 1991-1992, while the long-term hydrological drought in Shahzadeh-Abbas station was detected in 2005-2006 to 2014-2015. In other words, approximately all of the hydrometric and meteorological stations had severe drought events in 2008–2009.

The results of SPI and SDI series for all of the different reference periods (3 to 48-months) showed that in the precipitation series, a moderate drought for the years of 1989–1990, 1992–1993, 2001–2002, 2005–2006, in contrast, the SDI series indicate moderate drought state only in 2007–2008 and 2009–2010. Hence, the results of area-averaged SPI and SDI revealed that the Rafsanjan plain has been under moderate drought condition for the last three decades.

Therefore, it is important that water resource planners carefully consider the last drought events. Givdari River is located at the center of the study area and drains to the one of the main branches of the main river of Tangoyieh dam reservoir in order to supply drinking water of Sirjan city and villages in downstream. More importantly, almost all of the major areas of pistachio orchards in Kerman province, are located in Rafsanjan plain.

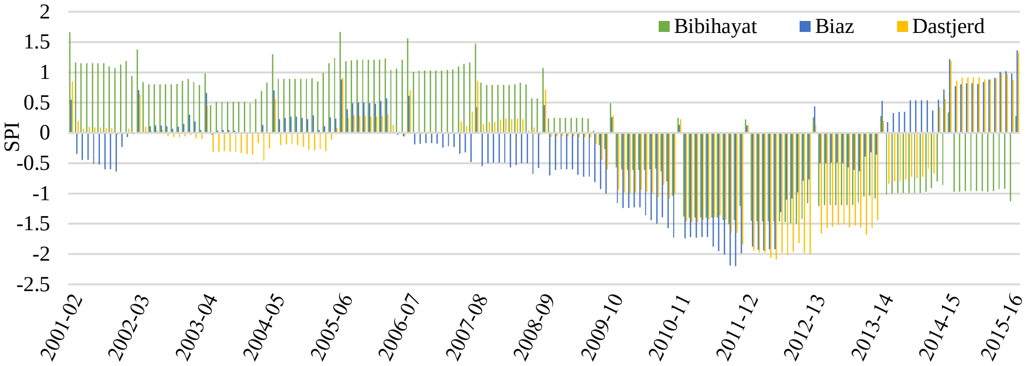

Fig. 2. SPI series of the reference period 48-month in three rain-gauges

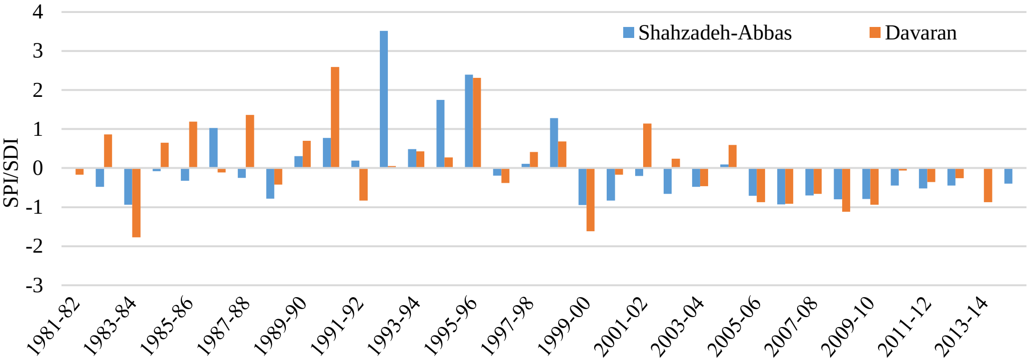

Fig. 3. SPI and SDI series of the reference period 24-month

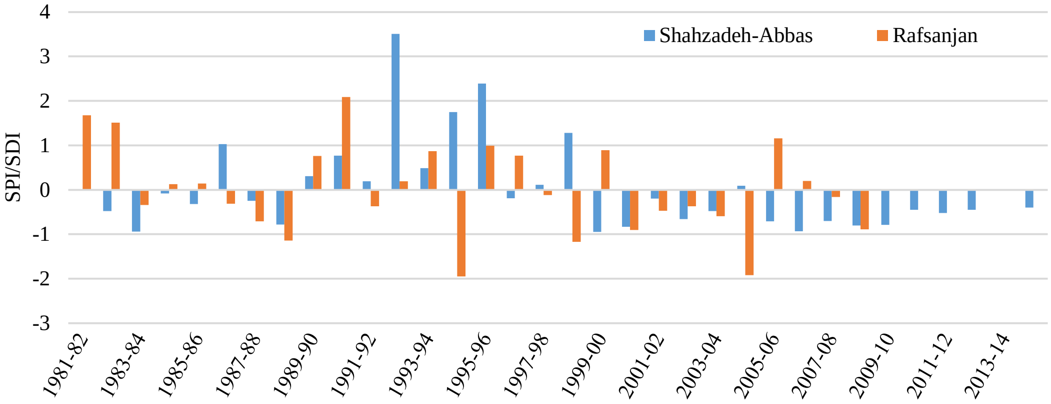

Fig. 4. SPI and SDI series for reference period 24-month

Based on the results, both streamflow and precipitation series were deficient from the expected or normal conditions during the period of 1998–1999 to 2003–2004. Nikbakht *et al.* (2012) characterized most severe streamflow droughts in 1999–2000 and 2000–2001. Prolonged droughts over 1998–2001 period had an effect on over half of the Iran’s population (Raziei *et al.* 2008; Tabari *et al.* 2013; Shahabfar *et al.* 2012).

3.4. GRI series

The GRI series of the studied periods, based on the 17-year time series data for some piezometers, are represented in figs 5 and 6 for 24 and 48-months cumulative periods, respectively. We selected 28 piezometers based on the record length for the consideration of the groundwater drought events. As shown, the majority of drought events for the reference periods of 24 and 48-months were found in the 17 years from 2001–2002 to 2014–2015. Moreover, almost all of the piezometers experienced at least two extreme drought events over the studied period. Compared with the meteorological and hydrological droughts over the considered periods, the most severe groundwater drought was identified at the piezometer no. 28 and 7 located in the central parts of the plain both in 2003–2004 with the GRI values of -1.8 and -1.7, respectively. Furthermore, the long-term groundwater drought was found at the piezometers no 7, 16, 22, 28.

The results of GRI series for the different reference periods showed that six moderate drought events were found in the period of 2004–2005 to 2012–2013. Hence, the results of GRI series revealed that the Rafsanjan plain has been under moderate drought condition for the last two decades.

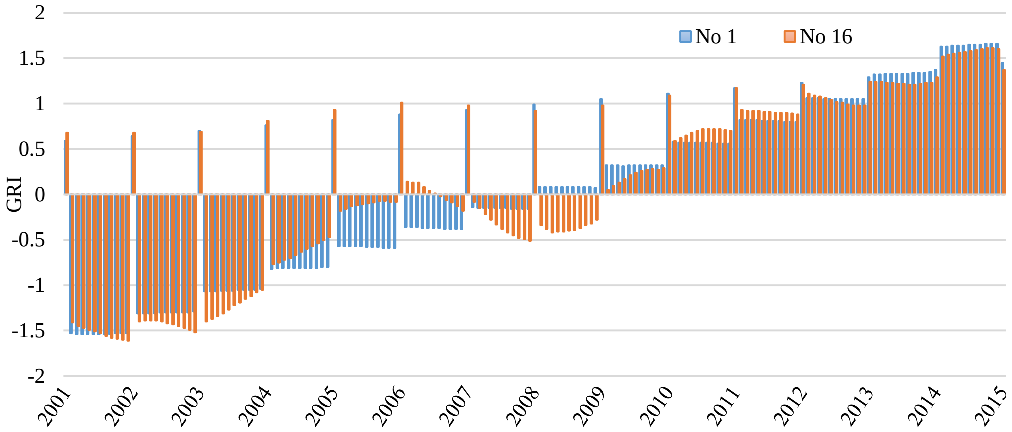

Fig. 5. GRI series for reference period 24-month in piezometers no 1 and 16

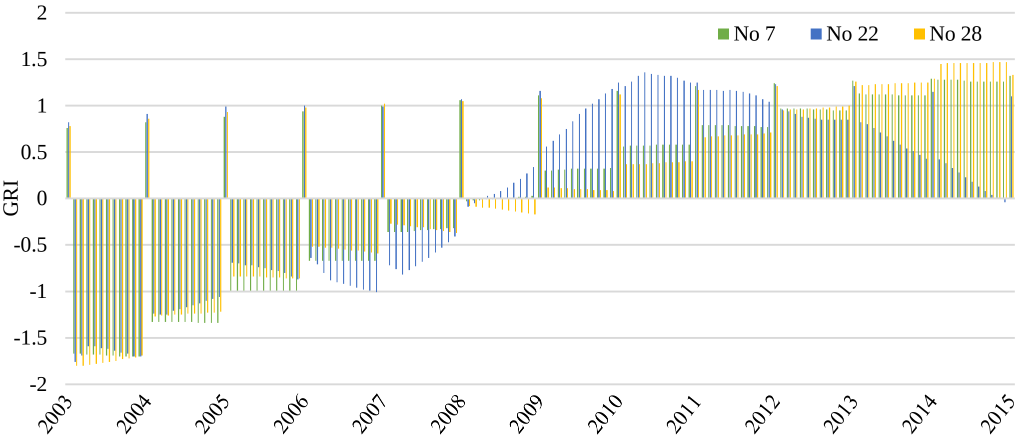

Fig. 6. GRI series for reference period 48-month in piezometers no 7, 22 and 28

3. 5. Trend and correlation tests

In this section, of the meteorological, hydrological and groundwater droughts trends are analyzed and their relationships are explored. Two nonparametric tests, the Spearman’s rho and Kendall’s tau, were applied for the drought indices over the period of 1997–1998 to 2014–2015.

The results of Spearman’s rho and Kendall’s tau tests for the SPI and GRI series identify decreasing trends in 81% and 87% of the stations and piezometers over the last three decades, respectively. Meanwhile, negative trends are observed in the SDI series in Shahzadeh-Abbas station at the 0.01 significance level, in the SPI series in 81% of the stations, except for Bagh-Khosh, Pariz and Jozam, in the GRI series in 95% of the piezometers at the 0.01 significance. Comparing the results of the trends for the SPI, GRI and SDI series, it can be concluded that the negative trend of the meteorological drought is stronger than that of the Groundwater and hydrological droughts.

As shown in Table 2 the *P* values of the Spearman’s rho and Kendall’s tau tests for the SPI suggest a negative trend at the 0.01 and 0.05 significance level for 21stations. Moreover, the tests showed a negative trend in the 3 to 48-monthsSDI series at the 0.01 significance level for Shahzadeh-Abbas station (Table 4). Also in Table 4 the *P* values of the Spearman’s rho and Kendall’s tau tests for the GRI were shown that suggest a negative trend for 20 piezometers.

The negative trends in most of the SPI, SDI and GRI series suggest that the study area has become drier over the last three decades. However, the decreasing trends are much more evident for the groundwater droughts index than for the precipitation drought index series. This means that the study area has suffered from the groundwater drought more than from the meteorological drought.

3.6. Seasonal and annual correlation analysis between SPI and SDI

The Spearman correlation test was further applied to explore the relationships between meteorological and hydrological droughts based on the SPI and SDI series, respectively. In doing so, different combinations of periods including 1, 2, 3, 6, 9, 12, 18, 24 and 48 month-lag between the meteorological and hydrological droughts were considered. The results are listed in Table 7 show that the majority of the significantly correlated series between the SPI and SDI occur for the 18, 24 and 48 month-lag cases. Moreover, the highest correlations between two droughts are identified for the annual and biennial (2-years).

Based on the results of all cases of correlation between SPI and SDI indices in all rain-gauge stations (216 cases), 14.81% has a significant positive correlation, 44.45% has a no-significant positive correlation, 7.4% has a significant negative correlation and 33.34% has a no-significant negative correlation.

Generally, the results indicate that in some of the years between the meteorological and hydrological drought in some rain-gauge stations (stations located in the southern plain) there is a time delay between 24 to 48-month which varies depending on the severity of the drought. In Figure 7, stations with the highest correlation with the SDI at Shahzadeh-Abbas station were showed bigger.

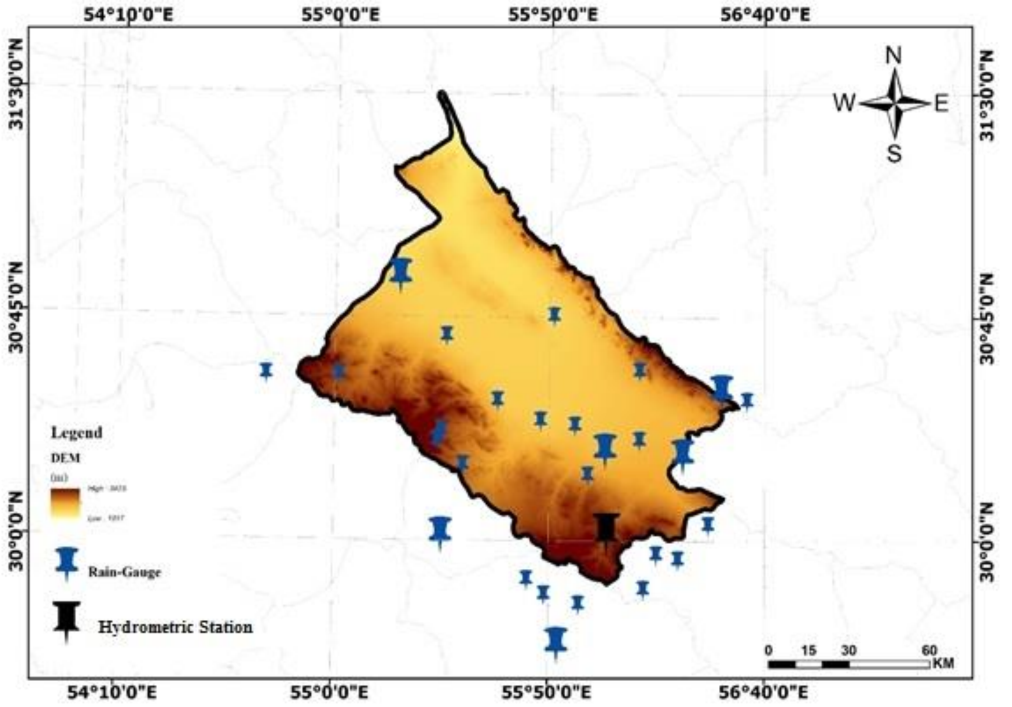

Fig. 7. Stations with the highest correlation with the SDI at Shahzadeh-Abbas rain-gauge station

Table 4. *P* values of Spearman's rho and Kendall's tau tests for the different reference periods of SPI series

Stations	Spearman's rho							Kendall's tau						
	3	6	9	12	18	24	48	3	6	9	12	18	24	48
Ahmad-Abad	(-) 0.47	(-) 0.5	(-) 0.62	(-) 0.78	(-) 0.86	(-) 0.86	(-) 0.98	(-) 0.53	(-) 0.58	(-) 0.64	(-) 0.76	(-) 0.87	(-) 0.9	(-) 0.99
Anar	(-) 0.74	(-) 0.51	(-) 0.75	(-) 0.8	(-) 0.86	(-) 0.88	(-) 0.92	(-) 0.73	(-) 0.53	(-) 0.77	(-) 0.81	(-) 0.89	(-) 0.9	(-) 0.93
Bagh-Khosh	(+) 0.54	(+) 0.5	(+) 0.41	(+) 0.36	(+) 0.23	(+) 0.19	(+) 0.16	(+) 0.51	(+) 0.5	(+) 0.39	(+) 0.32	(+) 0.21	(+) 0.17	(+) 0.14
Bibihayat	(-) 0.008	(-) 0.004	(-) 0.004	(-) 0.03	(-) 0.04	(-) 0.05	(-) 0.07	(-) 0.007	(-) 0.003	(-) 0.003	(-) 0.02	(-) 0.03	(-) 0.04	(-) 0.06
Biaz	(-) 0.84	(-) 0.59	(-) 0.71	(-) 0.74	(-) 0.69	(-) 0.7	(-) 0.78	(-) 0.82	(-) 0.57	(-) 0.7	(-) 0.72	(-) 0.59	(-) 0.69	(-) 0.75
Bidestan	(-) 0.35	(-) 0.29	(-) 0.65	(-) 0.71	(-) 0.77	(-) 0.8	(-) 0.85	(-) 0.38	(-) 0.27	(-) 0.68	(-) 0.73	(-) 0.79	(-) 0.82	(-) 0.8
Pariz	(+) 0.28	(+) 0.26	(+) 0.27	(+) 0.14	(+) 0.19	(+) 0.12	(+) 0.15	(+) 0.32	(+) 0.29	(+) 0.17	(+) 0.15	(+) 0.21	(+) 0.14	(+) 0.18
Paghaleh	(-) 0.74	(-) 0.65	(-) 0.49	(-) 0.38	(-) 0.32	(-) 0.28	(-) 0.22	(-) 0.72	(-) 0.63	(-) 0.47	(-) 0.34	(-) 0.3	(-) 0.24	(-) 0.19
Pamazar	(-) 0.7	(-) 0.79	(-) 0.77	(-) 0.63	(-) 0.67	(-) 0.71	(-) 0.84	(-) 0.67	(-) 0.76	(-) 0.75	(-) 0.62	(-) 0.65	(-) 0.7	(-) 0.81
Taj-Abad	(+) 0.66	(+) 0.7	(+) 0.75	(-) 0.54	(-) 0.55	(-) 0.59	(-) 0.60	(+) 0.58	(+) 0.74	(+) 0.000	(-) 0.38	(-) 0.51	(-) 0.65	(-) 0.57
Titoieh	(-) 0.28	(-) 0.32	(-) 0.37	(-) 0.42	(-) 0.48	(-) 0.5	(-) 0.58	(-) 0.29	(-) 0.35	(-) 0.39	(-) 0.45	(-) 0.51	(-) 0.53	(-) 0.59
Jozam	(+) 0.002	(+) 0.04	(+) 0.02	(+) 0.05	(+) 0.07	(+) 0.09	(+) 0.12	(+) 0.003	(+) 0.05	(+) 0.02	(+) 0.06	(+) 0.08	(+) 0.11	(+) 0.15
Hossein-Abad	(-) 0.12	(-) 0.24	(-) 0.28	(-) 0.33	(-) 0.39	(-) 0.36	(-) 0.44	(-) 0.14	(-) 0.25	(-) 0.3	(-) 0.34	(-) 0.4	(-) 0.38	(-) 0.46
Katoun-Abad	(-) 0.004	(-) 0.003	(-) 0.002	(-) 0.04	(-) 0.17	(-) 0.51	(-) 0.62	(-) 0.001	(-) 0.05	(-) 0.03	(-) 0.06	(-) 0.19	(-) 0.55	(-) 0.64
Dastjerd	(-) 0.27	(-) 0.3	(-) 0.38	(-) 0.42	(-) 0.51	(-) 0.61	(-) 0.74	(-) 0.26	(-) 0.28	(-) 0.34	(-) 0.4	(-) 0.49	(-) 0.59	(-) 0.72
Dehouieh	(-) 0.63	(-) 0.68	(-) 0.71	(-) 0.76	(-) 0.82	(-) 0.79	(-) 0.81	(-) 0.64	(-) 0.69	(-) 0.75	(-) 0.78	(-) 0.83	(-) 0.8	(-) 0.85
Raviz	(-) 0.28	(-) 0.37	(-) 0.54	(-) 0.43	(-) 0.27	(-) 0.79	(-) 0.8	(-) 0.26	(-) 0.36	(-) 0.52	(-) 0.41	(-) 0.25	(-) 0.76	(-) 0.78
Rafsanjan-1	(-) 0.75	(-) 0.64	(-) 0.71	(-) 0.6	(-) 0.61	(-) 0.63	(-) 0.68	(-) 0.73	(-) 0.61	(-) 0.7	(-) 0.56	(-) 0.58	(-) 0.6	(-) 0.65
Riseh	(-) 0.67	(-) 0.23	(-) 0.43	(-) 0.56	(-) 0.28	(-) 0.51	(-) 0.58	(-) 0.69	(-) 0.2	(-) 0.41	(-) 0.55	(-) 0.26	(-) 0.49	(-) 0.56
Saadat-Abad	(-) 0.48	(-) 0.34	(+) 0.87	(-) 0.61	(-) 0.69	(-) 0.74	(-) 0.8	(-) 0.51	(-) 0.31	(+) 0.89	(-) 0.65	(-) 0.7	(-) 0.77	(-) 0.82
Sadegh-Abad	(+) 0.24	(+) 0.37	(+) 0.54	(+) 0.48	(-) 0.29	(-) 0.37	(-) 0.41	(+) 0.25	(+) 0.38	(+) 0.55	(+) 0.49	(-) 0.3	(-) 0.38	(-) 0.43
Ali-Abad	(-) 0.38	(-) 0.42	(-) 0.51	(-) 0.47	(-) 0.54	(-) 0.59	(-) 0.65	(-) 0.39	(-) 0.43	(-) 0.52	(-) 0.49	(-) 0.55	(-) 0.6	(-) 0.66
Kaboutarkhan	(-) 0.57	(-) 0.51	(-) 0.46	(-) 0.49	(-) 0.53	(-) 0.59	(-) 0.64	(-) 0.54	(-) 0.49	(-) 0.44	(-) 0.47	(-) 0.31	(-) 0.58	(-) 0.63
Hejin	(-) 0.008	(-) 0.005	(-) 0.02	(-) 0.06	(-) 0.14	(-) 0.28	(-) 0.37	(-) 0.003	(-) 0.004	(-) 0.01	(-) 0.05	(-) 0.12	(-) 0.25	(-) 0.35
Davaran	(-) 0.27	(-) 0.53	(-) 0.47	(-) 0.58	(-) 0.62	(-) 0.69	(-) 0.73	(-) 0.26	(-) 0.51	(-) 0.46	(-) 0.55	(-) 0.61	(-) 0.66	(-) 0.72
Rafsanjan-2	(-) 0.6	(-) 0.72	(-) 0.71	(-) 0.61	(-) 0.54	(-) 0.59	(-) 0.48	(-) 0.54	(-) 0.68	(-) 0.67	(-) 0.57	(-) 0.51	(-) 0.56	(-) 0.45
Shahzadeh-Abbas	(-) 0.22	(-) 0.34	(-) 0.53	(-) 0.57	(-) 0.64	(-) 0.69	(-) 0.71	(-) 0.28	(-) 0.37	(-) 0.56	(-) 0.6	(-) 0.66	(-) 0.71	(-) 0.72

The bold values indicate significant trend at 0.01 intervals

Table 5. *P* values of Spearman's rho and Kendall's tau tests for the different reference periods of SDI series

Stations	Spearman's rho							Kendall's tau						
	3	6	9	12	18	24	48	3	6	9	12	18	24	48
Shahzadeh-Abbas	(-) 0.34	(-) 0.38	(-) 0.42	(-) 0.46	(-) 0.37	(-) 0.49	(-) 0.57	(-) 0.33	(-) 0.36	(-) 0.4	(-) 0.42	(-) 0.35	(-) 0.45	(-) 0.53

Table 6. Some of *P* values of Spearman's rho and Kendall's tau tests for the different reference periods of GRI series

PiezometerNo.	Spearman's rho							Kendall's tau						
	3	6	9	12	18	24	48	3	6	9	12	18	24	48
2	(-) 0.18	(-) 0.24	(-) 0.51	(-) 0.59	(-) 0.64	(-) 0.69	(-) 0.78	(-) 0.18	(-) 0.25	(-) 0.54	(-) 0.61	(-) 0.66	(-) 0.72	(-) 0.79
9	(-) 0.004	(-) 0.006	(-) 0.002	(-) 0.003	(-) 0.000	(-) 0.000	(-) 0.000	(-) 0.005	(-) 0.04	(-) 0.07	(-) 0.004	(-) 0.8	(-) 0.14	(-) 0.19
17	(-) 0.41	(-) 0.36	(-) 0.31	(-) 0.48	(-) 0.52	(-) 0.62	(-) 0.69	(-) 0.43	(-) 0.34	(-) 0.32	(-) 0.49	(-) 0.53	(-) 0.63	(-) 0.71
25	(+)0.18	(+)0.24	(+)0.4	(+)0.41	(-)0.26	(-)0.32	(-)0.56	(+)0.17	(+)0.22	(+)0.45	(+)0.39	(-)0.27	(-)0.34	(-)0.57
28 (26)	(-) 0.54	(-) 0.57	(-) 0.52	(-) 0.56	(-) 0.59	(-) 0.67	(-) 0.73	(-) 0.53	(-) 0.55	(-) 0.55	(-) 0.54	(-) 0.58	(-) 0.66	(-) 0.72

The bold values indicate significant trend at 0.01 intervals

Table 7. Relationships between meteorological and hydrological droughts (Cc: correlation coefficient) in all of rain gauges (SPI) and Shahzadeh-Abbas (SDI) stations

	SDI		
	Cc (18-month)	Cc (24-month)	Cc (48-month)
Ahmad-Abad	0.02	0.06	0.27
Ali-Abad	0.06	0.13	0.29
Anar	0.12	0.26	0.40
Bagh-Khosh	(-)0.06	(-)0.03	0.07
Biaz	0.01	0.03	0.07
Jozam	(-) 0.02	(-) 0.03	0.12
Kaboutarkhan	0.14	0.25	0.26
Khatoun-Abad	0.05	0.13	0.26
Paghaleh	(-) 0.05	(-) 0.03	0.12
Rafsanjan-1	0.08	0.18	0.22
Riseh	(-) 0.27	(-) 0.18	(-) 0.11
Saadat-Abad	0.24	0.37	0.42
Davaran	(-) 0.23	(-) 0.10	0.08
Rafsanjan-2	0.02	0.07	0.11
Shahzadeh-Abbas	0.05	0.10	0.15
Dastjerd	0.01	0.02	0.06
Dehouieh	(-) 0.03	(-) 0.17	(-) 0.24
Pamazar	(-) 0.04	(-) 0.23	(-) 0.15
Pariz	0.07	0.09	0.26
Sadegh-Abad	0.032	0.09	0.23
Taj-Abad	(-) 0.38	(-) 0.23	(-) 0.04
Bibihayat	(-) 0.08	(-) 0.07	0.10
Bidestan	0.05	0.07	0.28
Hejin	0.01	0.06	0.20
Hossein-Abad	(-) 0.34	(-) 0.22	(-) 0.13
Raviz	0.07	0.11	0.17
Titoieh	(-) 0.34	(-) 0.29	(-) 0.08

3.7. Seasonal and annual correlation analysis between SPI and GRI

The Spearman correlation test was further applied to explore the relationships between meteorological and groundwater droughts based on the SPI and GRI series, respectively. In doing so, different combinations of periods including 1, 2, 3, 6, 9, 12, 24 and 48 month-lag between the meteorological and groundwater droughts were considered. The results of relationship between SPI and GRI in piezometer No. 22 and all of stations listed in Table 8.

Table 8. Relationships between meteorological and Groundwater droughts (Cc: correlation coefficient) in all of rain gauges (SPI) and piezometers No 22 (GRI)

Stations	GRI (piezometer No 22)		
	Cc (18-month)	Cc (24-month)	Cc (48-month)
Ahmad-Abad	(-) 0.05	(-) 0.04	0.32
Ali-Abad	0.12	0.16	0.33
Anar	(-) 0.1	(-) 0.1	0.48
Bagh-Khosh	(-) 0.18	(-) 0.2	0.4
Biaz	(-) 0.09	(-) 0.13	(-) 0.25
Jozam	(-) 0.04	(-) 0.05	0.42
Kaboutarkhan	(-) 0.4	(-) 0.27	(-) 0.37
Khatoun-Abad	() 0.02	(-) 0.03	0.36
Paghaleh	(-) 0.01	0	0.06
Rafsanjan-1	(-) 0.05	(-) 0.06	0.27
Riseh	(-) 0.35	(-) 0.26	0.14
Saadat-Abad	0.58	0.64	0.56
Davaran	0.38	0.23	0.13
Rafsanjan-2	(-) 0.34	(-) 0.22	(-) 0.26
Shahzadeh-Abbas	0.27	0.19	0.14
Dastjerd	(-) 0.65	(-) 0.32	(-) 0.42
Dehouieh	(-) 0.44	(-) 0.47	(-) 0.52
Pamazar	(-) 0.23	(-) 0.19	(-) 0.03
Pariz	0.38	0.24	0.31
Sadegh-Abad	0.09	0.12	0.23
Taj-Abad	(-) 0.41	(-) 0.31	0.19
Bibihayat	() 0.41	(-) 0.39	0.13
Bidestan	(-) 0.01	() 0.02	0.29
Hejin	(-) 0.3	(-) 0.22	0.34
Hossein-Abad	(-) 0.48	(-) 0.55	(-) 0.14
Raviz	0.05	0.06	(-) 0.09
Titoieh	(-) 0.52	(-) 0.42	(-) 0.02

The bold values indicate significant trend at 0.01 or 0.05 intervals

The results of this Table shows that the majority of the significantly correlated series between the SPI and GRI occur for the 18, 24 and 48 month-lag case. Moreover, the highest correlations between the meteorological and groundwater droughts are identified for the annual and biennial (2-years) periods.

As it is clear from the results of Table 8, can be seen that the strong correlation between these two indices in the cases of 24 and 48-months from 6048 studied cases in all piezometers and stations, 2376 piezometers (39.3%) have a significant positive correlation, which its 76.6% are as for 24 and 48-months scales. Table 9 shows correlation between two GRI and SPI indices in Shahzadeh-Abbas rain-gauge station.

Table 9. Relationships between meteorological and Groundwater droughts (Cc: correlation coefficient) in Shahzadeh-Abbas station (SPI) and all of piezometers (GRI)

Piezometer No.	SPI (Cc) (Shahzadeh-Abbas)							
	1-month	3-month	6-month	9-month	12-month	18-month	24-month	48-month
1	0.010	0.020	0.050	0.110	0.160	0.240	0.280	0.500
2	0.030	0.060	0.100	0.170	0.240	0.320	0.310	0.440
3	0.020	0.030	0.050	0.110	0.160	0.260	0.290	0.500
4	0.006	0.010	0.030	0.080	0.130	0.200	0.220	0.390
5	0.020	0.040	0.060	0.130	0.190	0.280	0.310	0.500
6	0.010	0.030	0.060	0.120	0.180	0.260	0.300	0.520
7	0.010	0.030	0.060	0.120	0.180	0.270	0.290	0.460
8	0.020	0.020	0.050	0.120	0.160	0.250	0.300	0.520
9	0.010	0.030	0.050	0.110	0.190	0.30	0.320	0.550
10	0.020	0.030	0.050	0.110	0.180	0.260	0.280	0.440
11	(-) 0.020	(-) 0.002	0.010	0.050	0.130	0.220	0.210	0.290
12	0.020	0.040	0.060	0.130	0.180	0.270	0.290	0.480
13	0.006	0.009	0.020	0.080	0.110	0.160	0.200	0.440
14	0.020	0.010	0.040	0.100	0.140	0.230	0.270	0.510
15	0.010	0.030	0.060	0.120	0.180	0.270	0.300	0.500
16	0.010	0.030	0.060	0.160	0.190	0.270	0.310	0.500
17	(-) 0.080	(-) 0.060	(-) 0.070	(-) 0.13	(-) 0.200	(-) 0.340	(-) 0.390	(-) 0.410
18	0.004	0.020	0.050	0.110	0.160	0.25	0.270	0.460
19	0.070	0.005	0.060	0.190	0.290	0.400	0.440	0.630
20	0.030	0.020	0.050	0.120	0.170	0.260	0.290	0.510
21	0.010	0.040	0.070	0.140	0.190	0.290	0.330	0.520
22	0.010	0.020	(-) 0.007	0.010	0.060	0.130	0.190	0.140
23	0.040	0.030	0.0500	0.120	0.170	0.260	0.290	0.490
24	0.090	0.140	0.250	0.290	0.340	0.360	0.370	0.240
25	(-) 0.060	(-) 0.120	(-) 0.160	(-) 0.170	(-) 0.190	(-) 0.200	(-) 0.160	0.230
26	0.020	0.010	0.020	0.070	0.120	0.190	0.210	0.360
27	(-) 0.060	(-) 0.030	(-) 0.030	0.030	0.080	0.140	0.190	0.440
28	0.002	0.020	0.040	0.100	0.160	0.260	0.280	0.530

The bold values indicate significant trend at 0.01 or 0.05 intervals

According to this Table it can be seen that the correlation between the two indices has increased from 1 to 48-months and most of the correlations are on 24 and 48-months and in some piezometers are in 18-months (eg. piezometers No. 19 and 24). According to Tables 6 and 7 it can be said that whatever the SPI time scales are larger in Rafsanjan plain, its correlation is more with GRI that this case is in 26 piezometers out of 28 piezometers. This result is identical with the findings of Mendicino *et al*. (2008). For example, Table 9 shows the correlation between the GRI in all piezometers and SPI of Shahzadeh-Abbas rain-gauge station. In Figure 8 piezometers with the highest correlation with the SPI at Shahzadeh-Abbas station has been shown bigger.

3.8. Investigating all cases of correlation

Table 10 shows all investigated states of correlation between the SPI, SDI and GRI indices.

Table 10. Number and percentage of investigated states between investigated indices

Drought Index	Number of Reviews	SPI							
		Positive Correlation				Negative Correlation			
		Sig		No-Sig		Sig		No-Sig	
		Number	%	Number	%	Number	%	Number	%
GRI	6048	2376	39.3	216	3.6	2808	46.4	648	10.7
SDI	216	32	14.81	96	44.45	16	7.4	72	33.34

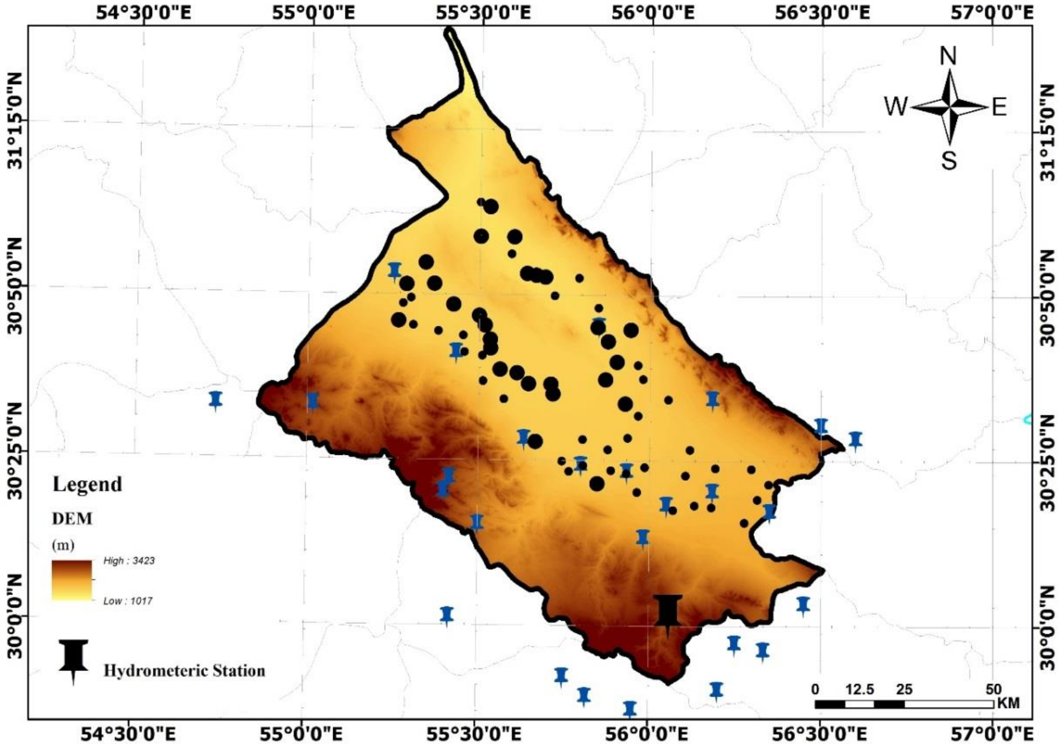

Fig. 8. Piezometers with the highest correlation with the SPI at Shahzadeh-Abbas rain-gauge station

According to Table 10, most of the significant positive correlation between SPI and GRI 39.3%; the largest amount of state without significant positive state correlation with SDI 44.45%, the largest amount of significant negative correlation state with GRI 46.4% and the largest amount of without significant negative state correlation with SDI is 33.34%.

4. Conclusion

In this study, the meteorological, hydrological and groundwater droughts were quantified based on the SPI, SDI and GRI in Rafsanjan plain located in the middle of Iran over the period of 1970–1971 to 2014–2015. The K–S test was applied to all time series in order to test which distribution fitted the time series best. The latter were calculated the SPI, SDI and GRI. The results showed that the majority of drought events for all of the reference periods occurred in the last 30 years from 1979–1980 to 2014–2015. Furthermore, the results of SPI, SDI and GRI series exhibited that the study region has been in moderate and severe drought states over the study period. Generally, the driest year based on the meteorological drought indexwere2007–2008 and 2011-2012, while the driest year based on the hydrological and groundwater drought index were identified to be 1999-2000 and 2003-2004, respectively.

The nonparametric tests of Spearman's rho and Kendall's tau were used for the temporal trends analyses of the meteorological, hydrological and groundwater droughts. The results showed decreasing trends of the SPI series for 81% of the stations, and also of the GRI series for 87% of the piezometers respectively. Additionally, comparing the results of the trends for the SPI and SDI series suggested that the negative trend of the meteorological droughts is stronger than that of the hydrological and groundwater droughts. In general, for most of the SPI and GRI series, negative trends were found; hence, the study area has become drier over the last three decades. Finally, the Spearman correlation test, which was used to check the relationship between meteorological, hydrological and groundwater droughts, revealed strong correlations between (18, 24 and 48-months) series. This research showed that the study region has suffered from the meteorological, hydrological and groundwater droughts over the study period, and meteorological drought is greatly increased and delayed in the hydrological and groundwater systems, so that appropriate management strategies should be implemented to mitigate their effects on the water resources in the region.

Because of importance of groundwater as the only source of water for various uses in Rafsanjan plain, and unfortunately the area affected by meteorological and groundwater droughts, with a sharp drop in the aquifer and reduce the capacity of the aquifer, and therefore it has been ground subsidence, therefore, according to the delay resulting between investigated droughts, this should be in the planning of relevant organizations in particular, the Kerman province's Regional Water Authority and given that the Rafsanjan plain is one of the critical and forbidden plain in Iran and Kerman province in the field of water resources management plans in this plain included long-term attitudes and at least two years for each period after the drought.

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