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Utilization of Time-Based Meteorological Droughts to Investigate Occurrence of Streamflow Droughts

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Abstract Complexities of streamflow drought analyses motivate utilization of simple, alternative methods, which can provide timely information for effective water resources management. For this purpose time-based meteorological drought characteristics, identified by $SPI_{3-month}$, $SPI_{6-month}$ and SPI_{Anuual} are investigated. A boxplot approach is used to exclude non-rainy months from the analysis. Streamflow drought characteristics are described by drought intensities, and are calculated by the threshold level method. The non-parametric Wilcoxon–Mann–Whitney test is used to investigate relations between streamflow drought intensities and $SPI_{3-month}$, $SPI_{6-month}$ and SPI_{Anuual}. The study area is the Doroodzan Watershed and Reservoir in southwestern Iran, with four rain gauge and two hydrometric stations. According to the results, most of time-based SPI values show significant relations (at 5% level of significance) with streamflow drought intensities. However, the most significant relation is between SPI_{Anuual} of Jamalbeik rain gauge station (centrally located in the study area) and drought intensities of Chamriz hydrometric station (located at the reservoir inlet). Comparison of study results with available records of documented droughts, confirms applicability of the proposed procedures. The SPI_{Anuual} is based on one-year-ahead moving average rainfalls. Then, SPI_{Anuual} of Jamalbeik station can be used to investigate occurrence of streamflow drought in Chamriz hydrometric station.

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1 Introduction

Drought is a natural and worldwide phenomenon, usually explained by periods of less than normal water availability. Droughts possess both temporal and spatial behaviors, with the capability to impact vast areas of land. One major consequential aspect of droughts is the socio-economic outcome, which can have devastating effects on the society at large. Coping with droughts requires a thorough understanding of different aspects (categories) of droughts, as well as possible linkage that may exist between the associated categories. Identification of such linkages can be of value in water resources planning and management.

Drought categorization as defined by Dracup et al. (1980) is of meteorological, hydrological, agricultural nature, or any combination there of. According to Wilhite and Glantz (1985), drought is either conceptual or operational. The operational aspect of drought attempts to identify the onset, severity and drought termination. Wilhite and Glantz (1985), provide four categorizations associated with droughts. When a region experiences an extended period of less than normal precipitation, the term meteorological drought is used. Over time shortage of precipitation can result in soil moisture deficit. Since this type of water shortage influences crop growth, it is referred to as the agricultural drought. Also over time and as a result of precipitation deficit, a region may experience periods of low streamflow or groundwater, leading to the so called hydrological drought. The socio-economic drought discusses the consequential societal impacts of drought occurrences.

Precipitation as the primary variable to study meteorological drought, has been used to develop a variety of indices. The standard precipitation index (SPI), developed by McKee et al. (1993) has been applied quite extensively to study drought. Another more commonly used index is the Palmer drought severity index (PDSI), developed by Palmer (1965). The PDSI is probably the first comprehensive developed drought index, which explains soil moisture temporal variability based on precipitation and other hydrological variables. The reconnaissance drought index (RDI), developed by Tsakiris et al. (2007), uses ratios of potential evapotranspiration over precipitation as a measure of meteorological drought.

Research on streamflow drought, as a form of hydrological drought, has been on a parallel course with studies on low flow behavior and analysis. One of the earliest approaches to hydrological drought definition is due to Yevjevich (1967). In a later study, McMahon and Diaz Arenas (1982) discussed methods of computation of low streamflow. A few years later, Beran and Rodier (1985) distinguished hydrological droughts from low flows and discussed the associated drought characteristics, i.e., duration, severity and seasonal variability. A detailed description of streamflow drought quantification and analysis was provided by Zelenhasic and Salvai (1987). A comprehensive review of the low flow characteristics and methodologies has been given by Smakhtin (2001). In a recent study, Benyaha et al. (2009) analyzed the low-flow frequency behavior, using the annual minimum flow and the deficit below threshold.

In streamflow drought studies, drought events are to be distinguished from drought indices. As explained by Tallaksen and van Lanen (2004), in a streamflow time series, drought events are identified by a threshold level below which the flow deficit occurs. flow deficit can be characterized by duration, severity, time of occurrence, or spatial extent. Any characteristic, i.e., drought deficit duration can be used to derive a drought deficit index, usually presented as a mean value. As a matter of reference, Pandey et al. (2008) developed the drought severity index (DSIe), which was used in a study of the Betwa river in India. In another study, the spatial and temporal trends associated with streamflow drought characteristics in Nebraska were discussed by Wu et al. (2008). Also, the streamflow drought index (SDI) has been developed by Nalbantis and Tsakiris (2009), as a characteristic of hydrological drought severity.

Establishment of relations between different categories of droughts can be complicated, due to the underlying characteristics and respective times of occurrences. As described by Tallaksen and van Lanen (2004), the impact of meteorological drought on groundwater drought may take several months or years. However, a meteorological drought may turn into streamflow in a few days for a flashy catchment, or in several months for a groundwater-fed catchment. A few reported researches have focused on comparison and relationships between different drought categories. Santos et al. (2001) made a comparison between computed hydrological drought and meteorological drought. Hisdal and Tallaksen (2003) compared the characteristics of meteorological droughts in terms of precipitation and hydrological droughts in terms of streamflow deficit for Denmark. More recently, Edossa et al. (2010), analyzed drought characteristics in the Awash River Basin, Ethiopia, using meteorological and hydrological drought variables. Considering the extensive amount of research devoted to the analyses of individual drought categories, it would seem appropriate to search for the possible linkages or relations that may exist between drought categories. Of particular interest would be relations between streamflow and time-based meteorological droughts. This type of information would seem to be of value in water resources planning and management.

Considering limited available research on the linkages between drought categories, the main objective of this research is to investigate relationships between time-based meteorological and streamflow droughts. Meteorological droughts are identified by time-based *SPI* values, and streamflow droughts are described by drought intensities, using the threshold level method. The non-parametric Wilcoxon–Mann–Whitney test is used to evaluate relationships between the corresponding drought categories. When statistically justified timely occurrence of meteorological drought events can be used to investigate occurrence of streamflow droughts. The case study area is Doroodzan Watershed and Reservoir in southwestern Iran. In order to confirm applicability of research findings, study results are compared with available records of documented droughts.

2 Study Area

The Doroodzan Watershed and Reservoir with a drainage area of 3,60 km^2, is located in Fars province, southwestern Iran (Fig. 1). The Doroodzan Reservoir is

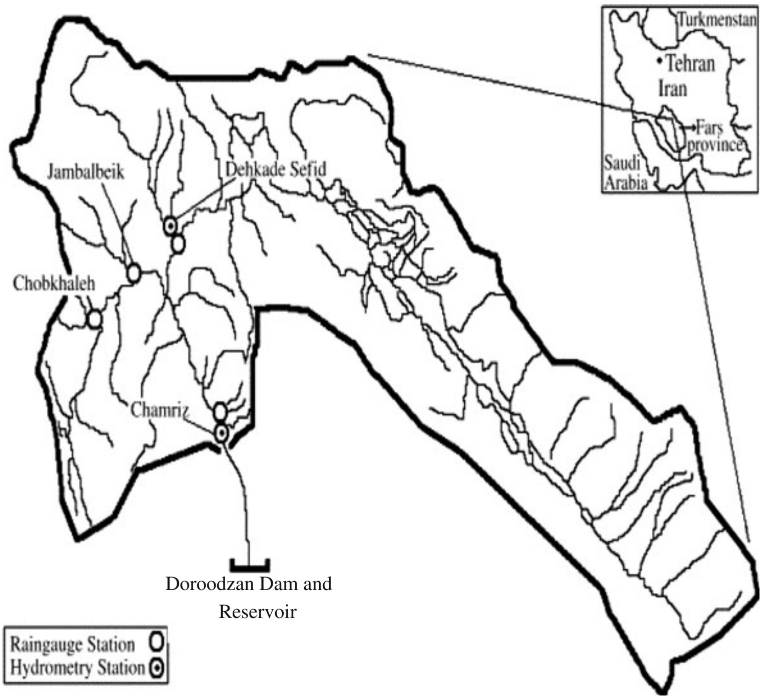

Fig. 1 Map of study area with rain gauge and hydrometric station locations

the main supplier of water to the area's agricultural, domestic and industrial sectors. Watershed streamflows discharge into the Kor river which, as the primary river has a continuous streamflow regime. Sources of water include direct overland flow, snowmelt, and spring discharges. Much of the so called spring discharges are actually delayed flows from rainfall or snowmelt, which may take several weeks or months to reach the streamflow system. As a result, while a continuous streamflow regime is maintained throughout the year, the rainy season is only 7 months long (October to April). The mean annual rainfall over the watershed is about 443 mm. A rainfall event may last several days; however, it is possible to have rainfall events of one day or less. It is possible to have over 200 mm of rainfall during an event, with daily depths of more than 50 mm.

As illustrated by Fig. 1, the watershed system has four rain gauge stations; Dehkade Sefid, Jamalbeik, Chobkhaleh and Chamriz; and two hydrometric stations, Dehkade Sefid and Chamriz. Station maintenance and data archiving are under the supervision of the Fars Regional Water Organization. For the purposes of the present study, it was possible to select a 31-year time series of data (1974–2005), for all of the rain gauge stations under study. Data quality control was done by checking for discrepancies or missing items. Annual trend and homogeneity of rainfall and streamflow data were evaluated by utilizing the Mann-Kendall test and data independency was checked by the Kendall's τ-test, accessed via the http://pubs.usgs.govsite. Table 1 gives a summary of the results.

Table 1 Summary of Mann–Kendall and tau (τ) tests on annual rainfall and streamflow time series data, accessed via http://pubs.usgs.gov

Station	S^{a}	Z^{a}	P^{a}	τ^{b}
Chobkhaleh precipitation	49.0	0.816	0.4146	0.105
Jamalbeik precipitation	–37.0	−0.612	0.5406	−0.080
Chamriz precipitation	–19.0	−0.306	0.7597	−0.041
Dehkade Sefid precipitation	–4.0	−0.051	0.9593	−0.009
Chamriz streamflow	–21.0	−0.340	0.7339	−0.045
Dehkade Sefid streamflow	–27.0	−0.442	0.6586	−0.058

[a]Values for Z are calculated from S (the Mann–Kendall parameter), which is used to find P for a two-tailed standard normal test. Accordingly, data homogeneity and lack of trend are meaningful at 1% level for Dehkade Sefid precipitation, and at 5% in other cases.

[b]Calculated τ values present data autocorrelation, indicating data independency.

3 Methodologies

3.1 Meteorological Drought Evaluation

Investigation of meteorological drought characteristics was based on the SPI procedures by McKee et al. (1993). Computation of the SPI requires long-term data on precipitation, which can be arranged to represent a desired time scale, e.g., 3-month, 6-month, etc., time periods. For a normally distributed data set. The SPI is calculated in a manner similar to "normal standardization", as:

$$SPI = \frac{x_i - \bar{x}_i}{\sigma} \tag{1}$$

where, $x_i - \bar{x}_i$ is the difference of precipitation value for a time scale of interest from the mean precipitation value and σ is the standard deviation. The SPI is a dimensionless index, where, negative and positive calculated values represent occurrence of drought and wet scenarios, and values close to zero are indication of a normal condition. Furthermore, drought characteristics, i.e., intensity, magnitude, and duration can also be determined.

Since the available precipitation data is not usually normally distributed, Thom (1958) proposed that the gamma distribution can be used to properly fit precipitation data. The probability density function (PDF) of the gamma distribution is given by:

$$g(x) = \frac{1}{\beta^{\alpha}\Gamma(\alpha)} x^{\alpha-1} e^{\frac{-x}{\beta}} \text{ for x} > 0 \tag{2}$$

where $\alpha > 0$ is the shape parameter, $\beta > 0$ is the scale parameter, and $x > 0$ is precipitation depth and $\Gamma(\alpha)$ is the gamma function. Model parameters α and β are estimated for a sample size n, for each time step of interest (3, 6, 12 months, etc.), by the maximum likelihood estimation method (Thom 1958):

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

$$\hat{\beta} = \frac{\bar{x}}{\hat{\alpha}} \tag{4}$$

$$A = \ln(\bar{x}) - \frac{\sum \ln(x)}{n} \tag{5}$$

The cumulative density function (CDF) for gamma distribution, used to represent monthly precipitation amounts, is actually an integration of the PDF over x:

$$G(x) = \int_0^x g(x)dx = \frac{1}{\beta^\alpha \Gamma(\alpha)} \int_0^x x^{\alpha-1} e^{\frac{-x}{\beta}} dx \tag{6}$$

Since the gamma CDF does not have a closed form, it is not possible to solve it explicitly. Alternatively, approximation tables are available for this purpose. It is possible to have several zero values in a sample set. In order to account for zero value probability, the CDF for Gamma distribution is modified as:

$$H(x) = q + (1-q)\, G(x) \tag{7}$$

where, q represents the probability of zero precipitation. The precipitation probabilities calculated from Eq. 7 are transformed into the corresponding standard normal values, from which the SPI values are calculated.

3.2 Selection of Rainy Months

The study area experiences a long non-rainy season (5 months), which last from May to September. During this period it is possible to have a few individual rainfall events. However, consideration of this type of very limited data may not realistically represent wet and dry periods as required in the SPI analysis. The problem is lack of proper distribution of data around a central measure of tendency such as the mean or median value, which is also quantitatively very small during the non-rainy season. As a result it is important to examine appropriateness of this type of data for inclusion in the SPI analysis. Additional information on selection of rainy months can be found in Abolverdi and Khalili (2010).

For the purposes of the present study, the boxplot scheme (Tukey 1977), has been used for monthly data selection. A boxplot is a visual illustration of the distributed data on either side of the median value. A box plot also illustrates data locations for the 75%, 25% levels, minimum, maximum and extreme values with respect to the median value. Then, those months lacking proper data distribution can be easily identified and eliminated from SPI analysis. As a result, the so called annual SPI, (SPI_{Annual}) would only include data of the rainy season. Additional information is provided in the section on results.

3.3 Streamflow Drought Investigation

Streamflow drought characteristics are developed from streamflow time series data. As outlined by Tallaksen and van Lanen (2004), drought characteristics should be investigated in terms of low flow characteristics and deficit characteristics. In the low flow characteristics approach, a low flow index (also referred to as threshold level), is established as a percentile from the flow duration curve (FDC). Among the techniques available for the analyses of deficit characteristics, threshold level method is the most commonly used technique. This method is based on a defined threshold, Q_0, below which is defined as a drought. The threshold level method was first used by Yevjevich (1967), when the statistical theory of runs was applied in time series analyses. Once the threshold level, Q_0, is identified, statistical properties of the distribution of drought deficit, drought deficit duration and volume or severity are obtained as typical drought characteristics (Tallaksen and van Lanen 2004). Selection of a threshold level is based on several considerations, including the streamflow regime. A summary of the reported threshold levels worldwide has been given in Tallaksen and van Lanen (2004). In the present study, Q_{70} and Q_{90} were investigated, as suggested for perennial streams.

Investigation of deficit flow characteristics requires identification of a time interval, i.e., annual, seasonal or weekly. Selection of daily time interval may result in the separation of adjacent drought events, which are actually dependent, or may be due to minor droughts. To avoid the problem, pooling methods are used. As discussed by Tallaksen et al. (1997), several pooling methods are available. In the present research, the Inter-event criterion (IC), introduced by Zelenhasic and Salvai (1987) was used. In the *IC* method, two adjacent drought events (d_i, V_i) and (d_{i+1}, V_{i+1}), can be pooled, if the number of days between the events (t_i) is less than the defined Critical Duration (t_c), and the excess volume between drought events (Z_i) is less than the defined Critical Volume, Z_c. Then the following relationships hold:

$$d_{pool} = d_i + d_{i+1} + t_i \tag{8}$$

$$V_{pool} = V_i + V_{i+1} - Z_i \tag{9}$$

where, d_{pool} is combined drought duration, d_i and d_{i+1} are adjacent drought durations, t_i is number of days between the events; V_{pool} is combined drought deficit volume, V_i and V_{i+1} are adjacent drought deficit volumes and Z_i is excess volume between drought events. The computational procedures of the streamflow drought events were carried out by the NIZOWKA software, developed by Jakubowski and Radczuk (2003). This package provides the best fitted statistical distribution function from a partial duration series (PDS) of drought events, which are selected from time series of daily discharges. Deficit characteristics are obtained by using the threshold level method. Threshold levels are calculated from flow duration curves (FDCs).

3.4 Meteorological and Streamflow Drought Relations

Investigation of time-based relation between meteorological and streamflow drought characteristics is rather complicated. This is because the characteristics associated with the drought categories are not similar in nature, they occur at different times during the year and they do not establish identical sample sizes. For this type of situation non-parametric methods can be appropriate since these techniques search for similar behavior based on ranked values of individual sample points.

In the present study, the non-parametric Wilcoxon–Mann–Whitney rank-sum test was used (Wilks 2006). The null hypothesis is that the two samples are independent, i.e., that they do not have a common relation. This test can be used on two unequal sample sizes n_a and n_b. First, the two samples are pooled and ranked as one sample (1 to $n_a + n_b$), and sum of the ranks (W) is determined. Then, the statistics U is estimated from:

$$U = n_a n_b + \frac{n_a(n_b + 1)}{2} - W \tag{10}$$

For cases of n_a and n_b greater than 8, U can be assumed as being approximately normally distributed with the following parameters:

$$\mu = \frac{n_a n_b}{2} \tag{11}$$

and

$$\sigma = \sqrt{\frac{n_a n_b (n_a + n_b + 1)}{12}} \tag{12}$$

The level of significance of U is determined from the Z statistics as follows:

$$Z = \frac{U - \frac{n_a n_b}{2}}{\sqrt{\frac{n_a n_b (n_a + n_b + 1)}{12}}} \tag{13}$$

In the above equation Z is a random variable, which is approximately of standardized normal distribution, so the rejection region of Z can be identified from the standard normal table.

4 Results

Annual trend, homogeneity and independency were evaluated for the time series of the rain gauge and stream gage data, by utilizing the Mann-Kendall and the associated τ-test, accessed via the http://pubs.usgs.govsite. Table 1 shows a summary of the results. As Table 1 shows, for the Dehkede Sefid data, homogeneity and lack of trend is established at 1% significance level, and for all other stations 5% significance level. Furthermore, time series data independency was verified in all cases by the associated τ-test.

4.1 Determination of Non-Rainy Months

As discussed earlier, it is necessary to identify suitability of the rainy months in terms of their contributions to dry and wet periods. For this purpose, the boxplot approach was utilized. Figure. 2 (a, b, c, d) illustrate the results for the Dehkade Sefid (a), Jamalbeik (b), Chobkhaleh (c) and Chamriz (d) rain gauge stations. According to the results for the period from November to May, adequate distribution of rainfall exists in all cases, as shown by the line inside the rectangular box, which is the location of data median ($q_{0.50}$) The top and the bottom sides of the rectangle represent

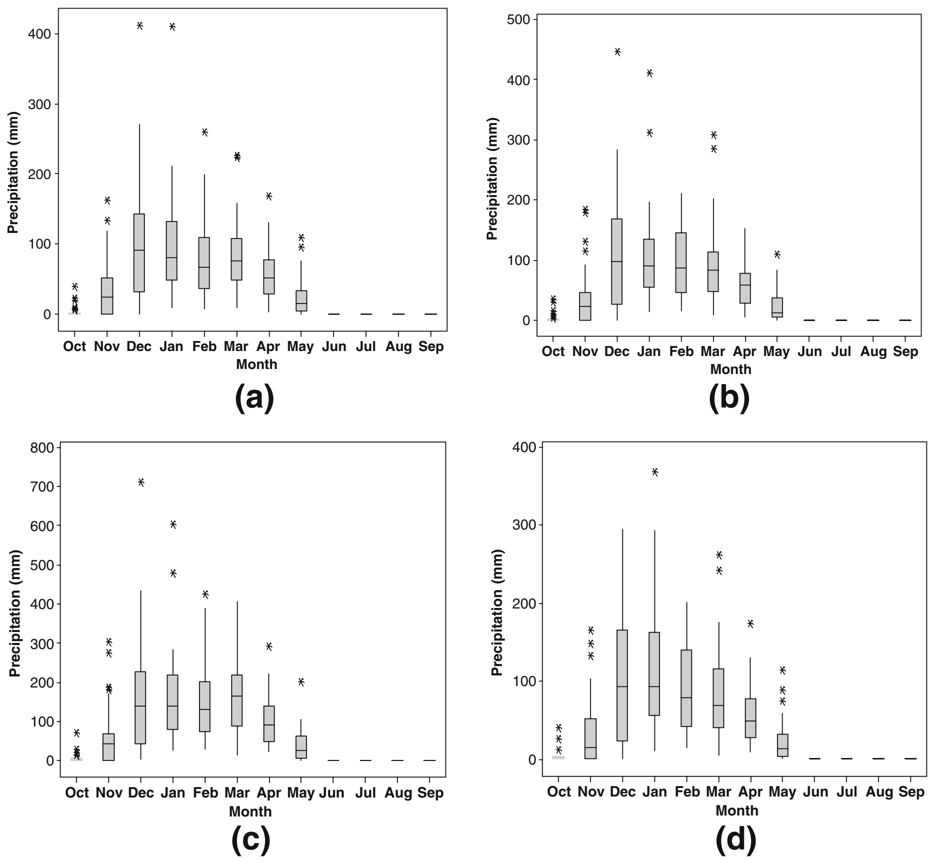

Fig. 2 Distribution of monthly rainfall for Dehkade Sefid (**a**), Jamalbeik (**b**), Chobkhaleh (**c**) and Chamriz (**d**) rain gauge stations

75% and 25% levels, with respect to the median value and are identified as $q_{0.75}$ and $q_{0.25}$ respectively. The top and bottom extents of the lines show the maximum and minimum values. One or more data points may represent the data tails, with values larger than a typical maximum, or smaller than a typical minimum. Such data points are viewed as extreme value data, and are identified by an astrix. As explained by Wilks (2006), if data points are larger than $q_{0.75} + 1.5(q_{0.75} - q_{0.25})$, they are treated as extreme values (larger than the maximum point), and if they are smaller than $q_{0.25} - 1.5(q_{0.75} - q_{0.25})$, they are treated as extreme values (smaller than the minimum point). The period of June through September is represented by practically zero rainfall, in all of the rain gauge stations, and should not be used in the *SPI* analysis, which is due to lack of contribution to dry and wet periods. October has been represented by a zero median, and a few rainfall events, which if used in the *SPI* analysis would result in artificial inclusion of wet periods. Then the data time series includes a 7-month period, extending from November to May, which is used to establish moving averages for the corresponding $SPI_{3-month}$, $SPI_{6-month}$ and SPI_{Anuual} values. Furthermore, the case of the 7-month moving average is referred to as SPI_{Anuual}.

4.2 *SPI* Indices and Meteorological Drought Characteristics

The data from the four rain gauges were used for the development of *SPI* indices for 3-month, 6-month, and annual moving averages. Meteorological drought characteristics, i.e., drought magnitude, duration, average SPI (SPI_{Avg}) and minimum SPI (SPI_{Min}) were developed, for the time periods of interest. As an illustration the information for $SPI_{3-month}$ of Dehkade Sefid rain gauge station is given in Table 2. An analysis was done to evaluate the linear correlations between each pair of the

Table 2 Meteorological drought characteristics for Dehkade Sefid station ($SPI_{3-month}$)

Starting month	Ending month	Drought magnitude	Duration (month)	Average SPI	Minimum SPI	Date of minimum SPI
Nov-76	May-77	−3.4448467	7	−0.49212	−0.806779	Apr-77
Apr-78	May-78	−1.475922	2	−0.73796	−1.082509	Apr-78
Nov-78	Nov-78	−0.4438974	1	−0.4439	−0.443897	Nov-78
Jan-79	May-79	−2.6966824	5	−0.53934	−0.937074	May-79
Nov-79	Nov-79	−1.0174143	1	−1.01741	−1.017414	Nov-79
Jan-80	Jan-80	−0.0165826	1	−0.01658	−0.016583	Jan-80
Nov-80	Mar-81	−1.902171	5	−0.38043	−0.516479	Jan-81
Dec-81	Feb-82	−2.2346068	3	−0.74487	−0.977243	Jan-82
Jan-83	May-83	−4.4283947	5	−0.88568	−1.459711	Apr-83
Nov-83	Apr-84	−9.7894577	6	−1.63158	−2.152491	Feb-84
Feb-85	May-85	−2.905692	4	−0.72642	−1.360625	May-85
Nov-85	Nov-85	−0.1433195	1	−0.14332	−0.14332	Nov-85
Jan-86	Mar-86	−1.8572823	3	−0.61909	−1.093601	Mar-86
Mar-87	Apr-87	−0.9619824	2	−0.48099	−0.853577	Mar-87
Nov-87	Jan-88	−1.379777	3	−0.45993	−1.072613	Dec-87
May-88	May-88	−0.0947502	1	−0.09475	−0.09475	May-88
Nov-88	May-89	−3.7874922	7	−0.54107	−1.189605	Nov-88
Mar-90	May-90	−3.2692126	3	−1.08974	−2.497838	May-90
Nov-90	Jan-91	−3.6152253	3	−1.20508	−2.13987	Nov-90
Nov-91	Nov-91	−0.7558713	1	−0.75587	−0.755871	Nov-91
Mar-92	Apr-92	−0.5690225	2	−0.28451	−0.505315	Apr-92
Nov-93	May-94	−7.3221544	7	−1.04602	−2.152491	Feb-94
Dec-95	Jan-96	−0.6104447	2	−0.30522	−0.493107	Dec-95
Nov-96	Mar-97	−5.8370723	5	−1.16741	−1.735907	Feb-97
Nov-98	Feb-99	−4.8053458	4	−1.20134	−2.005006	Dec-98
Nov-99	May-00	−7.7372002	7	−1.10531	−2.399202	May-00
Nov-00	Nov-00	−0.8124913	1	−0.81249	−0.812491	Nov-00
Jan-01	May-01	−6.0091691	5	−1.20183	−2.003284	Apr-01
Nov-01	Nov-01	−0.7670753	1	−0.76708	−0.767075	Nov-01
Mar-02	Apr-02	−0.159822	2	−0.07991	−0.138021	Mar-02
Dec-02	Jan-03	−0.5759481	2	−0.28797	−0.401649	Jan-03
Apr-04	May-04	−0.4318439	2	−0.21592	−0.231405	Apr-04
Nov-04	Nov-04	−0.8010456	1	−0.80105	−0.801046	Nov-04
Feb-05	May-05	−3.6736623	4	−0.91842	−1.477452	Apr-05

Table 3 Non-parametric tests on station pairs (SPI_{3-onth}, $SPI_{6-month}$ and SPI_{Annual} values)

Station pairs	$Z_{3-month}$	$Z_{6-month}$	Z_{Annual}
Chobkhaleh and Jamalbeik	0.056	**0.039**	0.993
Chobkhaleh and Chamriz	0.106	0.530	0.583
Chobkhaleh and Dehkade Sefid	0.424	0.883	0.231
Jamalbeik and Chamriz	0.245	0.539	0.343
Jamalbeik and Dehkade Sefid	0.561	0.864	1.289
Chamriz and Dehkade Sefid	0.345	**1.374**	0.784

Z values are for differences in SPI, which are not significantly different from zero at 5% level. Bold numbers indicate the minimum and maximum values.

meteorological drought characteristics. In most cases strong correlations exist, either at the 1% or 5% level of significance (results not shown). However, for the Jamalbeik and Chobkhaleh stations and for the case of $SPI_{3-month,}$ weak correlations were observed between $SPI_{Avg.}$ and duration. It is noted that the SPI_{Avg} is the average of monthly SPI values for a drought period. Similar result was obtained for the Dehkade Sefid station and for the case of $SPI_{6-month}$. The results show that the increase in drought magnitude seems to be associated with increased drought duration. A similar argument can also be made for the cases of increased SPI_{Avg} and increased SPI_{Min}. It is noted that absolute values of drought magnitude, SPI_{min} and SPI_{Avg} are used.

In order to evaluate the similarity of meteorological drought behavior among the corresponding stations, the non-parametric Wilcoxon–Mann–Whitney test was used to evaluate the differences in time-based SPI values among each pair of stations (Table 3). As Table 3 shows, none of the station pairs indicated significant difference between zero value and computed differences in the time-based SPI values, at 5% level.

4.3 Streamflow Drought Analysis

Streamflow drought analysis requires selection of appropriate threshold level, as a cutoff point of low flows. For this purpose, the flow duration curves (FDCs) are usually utilized. Based on the FDCs of the Chamriz and Dehkade Sefid hydrometric stations, the associated normalized FDCs were developed (Fig. 3). The normalized FDCs were calculated by dividing individual streamflow values by the mean annual streamflow value, for each hydrometric station. As Fig. 3 shows the streamflow regimes are similar for the corresponding stations, and as indicated by the slope of the FDCs, a steady-state flow system is dominant in both cases, indicating low variability with time. The streamflow regime influences the selection of discharge percentiles as threshold levels. For river systems with continuous streamflow, thresholds in the range of Q_{70} to Q_{95} would seem to be appropriate. In the present study, threshold levels of Q_{70} and Q_{90} were evaluated, which were applied to the daily time series data on streamflow.

4.3.1 Identification of Streamflow Droughts Events

Streamflow drought calculations were done by the NIZOWKA software (Jakubowski and Radczuk 2003), introduced earlier. Utilization of NIZOWKA requires parameter determination and initialization, as outlined by Tallaksen and

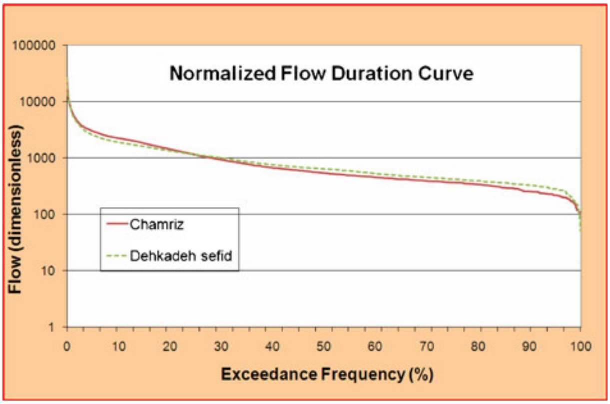

Fig. 3 Normalized flow duration curves for Chamriz and Dehkade Sefid hydrometric stations, flow is calculated by dividing individual streamflow values by the mean annual streamflow

van Lanen (2004). First, a threshold level, Q_0 is determined from the FDC. Then, minor droughts with durations smaller than critical drought duration, d_{min}, and deficit volumes smaller than minimum drought deficit volume are removed. The minimum drought deficit volume is a fraction α of maximum drought deficit volume. Next, the inter-event time criterion (IC) is used to pool dependent droughts, separated by a short period of flow above the threshold. The separation criterion, t_{min}, identifies the critical period below which the two events are pooled.

In this research considering the continuous flow regime of the study area, the Q_{70} threshold level was selected. Initially, minor droughts were included (α coefficient = 0.0, duration criterion = 1 day and separation criterion = 3 days). As shown in Tables 4 and 5, selection of the above criteria led to 63 and 71 drought

Table 4 Sensitivity analyses for drought event criteria selection (Chamriz hydrometric station)

Duration criterion	Separation criterion	Coefficient alpha	Number of droughts	Droughts < 10 days	Droughts 11–21 days	Droughts 21–30 days	Droughts < 30 days
5	3	0.005	**33**	2	3	2	26
1	3	0	**63**	28	6	3	26
1	3	0.005	**37**	6	3	2	26
2	3	0.005	**33**	2	3	2	26
3	3	0.005	**33**	2	3	2	26
4	3	0.005	**33**	2	3	2	26
5	3	0.005	33	2	3	2	26
6	3	0.005	**33**	2	3	2	26
7	3	0.005	**33**	2	3	2	26
8	3	0.005	**32**	1	3	2	26
5	1	0.005	**40**	3	7	5	25
5	2	0.005	**36**	2	4	3	27
5	3	0.005	**33**	2	3	2	26
5	4	0.005	**32**	1	3	2	26
5	5	0.005	**31**	1	2	2	26

Table 5 Sensitivity analyses for drought event criteria selection (Dehkade Sefid hydrometric station)

Duration criterion	Separation criterion	Coefficient alpha	Number of droughts	Droughts < 10 days	Droughts 11–21 days	Droughts 21–30 days	Droughts > 30 days
5	3	0.005	**44**	4	11	2	27
1	3	0	**71**	30	11	3	27
1	3	0.005	**49**	9	11	2	27
2	3	0.005	**44**	4	11	2	27
3	3	0.005	**44**	4	11	2	27
4	3	0.005	**44**	4	11	2	27
5	3	0.005	**44**	4	11	2	27
6	3	0.005	**44**	4	11	2	27
7	3	0.005	**43**	3	11	2	27
8	3	0.005	**43**	3	11	2	27
5	1	0.005	**52**	5	13	4	30
5	2	0.005	**44**	4	11	2	27
5	3	0.005	**44**	4	11	3	26
5	4	0.005	**44**	4	11	3	26
5	5	0.005	**40**	3	9	1	27

events, respectively, for the Chamriz and Dehkade Sefid hydrometric stations. As the next step for α coefficient of 0.005, sensitivity analyses were performed on different durations and separations. This selected α coefficient was also used by Tallaksen and van Lanen (2004). Then, for a 3-day separation, different durations were evaluated; and for 5-day duration, different separations were evaluated. Table 4 summarizes the results for the Chamriz hydrometric station. As Table 4 shows, if 5-day duration and 3-day separation are used, then the number of drought events converges to 33. Similarly, Table 5 shows that for Dehkade Sefid hydrometric station, 44 drought events are identified. The summary of the criteria used for pooling and elimination of minor droughts, follows:

α coefficient = 0.005,
duration criterion = 5 days,
separation criterion = 3 day.

The above selected criteria were used for streamflow drought identification for the Chamriz and Dehkade Sefid hydrometric stations. As an example, streamflow drought characteristics and related information for the Chamriz hydrometric station is given in Table 6, based on the 31-year time series data. In Table 6, deficit volume (1,000 m^3), corresponds to the sum of daily deficits calculated as the difference between the Q_{70} threshold level and the deficit streamflow value, multiplied by time (day). According to the results, for the Chamriz hydrometric station (Table 6), the worst streamflow drought occurred during year 2001, with a volume deficit of 123,950.3 (1,000 m^3), lasting for 233 day. Interestingly, the second worst drought occurred just one year earlier, during year 2000, with a volume deficit of 104,157.8 (1,000 m^3), lasting for 226 day. A rather similar behavior is also observed for the Dehkade Sefid hydrometric station (results not shown), with the worst streamflow

Table 6 Streamflow drought characteristics for Chamriz hydrometric station

Starting date	Ending date	Deficit (1000 m^3)	Drought intensity (1000 m^3/day)	Duration (day)	Minimum runoff (m^3/s)	Date of minimum runoff	Average runoff (m^3/s)
1977/06/06	1977/08/29	4,178.3	49.16	85	10.04	1977/06/17	10.71
1977/09/17	1977/10/24	1,650.24	43.43	36	8.8	1977/09/22	10.79
1979/09/29	1979/11/25	2,833.06	48.85	58	10.58	1979/10/01	10.71
1981/10/02	1981/11/03	4,409.86	133.63	33	8.9	1981/10/22	9.73
1982/09/05	1982/10/26	6,876.58	132.24	52	7.66	1982/10/06	9.75
1983/06/17	1983/11/07	27,732.67	192.59	144	7.32	1983/07/16	9.05
1984/03/07	1984/03/17	2,283.55	207.6	10	8.35	1984/03/09	8.89
1984/04/26	1984/05/06	2,155.68	195.97	11	7.32	1984/05/06	9.01
1984/05/20	1984/11/10	66,981.69	382.75	175	5.3	1984/10/22	6.85
1985/04/22	1985/11/11	84,151.87	412.51	204	5.5	1985/08/05	6.51
1986/06/17	1986/11/08	44,718.91	308.41	145	5.65	1986/10/14	7.71
1986/11/12	1986/11/18	1,077.41	153.92	7	8.56	1986/11/15	9.5
1987/06/06	1987/10/29	33,373.73	228.59	144	6.13	1987/09/20	8.68
1988/07/18	1988/11/12	9,801.22	83.06	118	9.32	1988/08/20	10.32
1989/05/17	1989/11/14	59,260.03	325.6	182	6.56	1989/05/25	7.51
1990/06/07	1990/07/05	3,124.22	107.73	29	9.04	1990/06/24	10.03
1990/07/13	1990/12/17	23,217.41	146.95	156	8.28	1990/09/15	9.59
1991/06/12	1991/10/02	14,946.34	132.27	113	8.38	1991/08/29	9.75
1991/10/14	1991/11/30	8,600.26	179.17	48	8.7	1991/10/25	9.21
1994/04/21	1994/11/06	67,535.42	337.68	199	6.14	1994/06/25	7.38
1996/10/13	1996/11/17	2,960.06	82.22	35	9.02	1996/11/07	10.33
1997/05/22	1997/11/25	61,134.91	325.19	188	5.92	1997/08/08	7.52
1998/08/13	1998/11/22	6,445.44	63.19	100	9.97	1998/08/23	10.55
1999/06/10	1999/12/10	31,394.3	170.62	180	7.82	1999/10/29	9.31
1999/12/19	2000/01/15	1,591.49	56.84	25	9.94	1999/12/31	10.83
2000/04/06	2000/11/17	104,157.8	460.88	226	3.84	2000/07/07	5.95
2000/11/22	2000/12/09	3,868.99	214.94	18	8.38	2000/11/25	8.79
2001/01/28	2001/02/10	943.49	67.39	14	10.5	2001/01/28	10.5
2001/04/12	2001/11/30	123,950.3	531.98	233	3.1	2001/06/23	5.12
2002/08/23	2002/09/29	2,393.28	62.98	35	9.7	2002/08/29	10.6
2003/06/20	2003/12/05	29,582.5	175.04	163	5.92	2003/09/14	14.26
2005/06/09	2005/07/13	3,087.94	88.23	35	9.24	2005/06/26	10.26
2005/08/03	2005/09/17	4,091.9	88.95	46	9.24	2005/08/25	10.25

drought occurring during year 2001, with a volume deficit of 36,599.9 (1,000 m^3), lasting for 236 day. Then, the second worst drought occurred during year 2000, with a volume deficit of 24,122.0 (1,000 m^3), lasting for 222 day.

In each hydrometric station, evaluation of linear correlation was conducted between pairs of drought characteristics, i.e., deficit volume, intensity, duration and minimum runoff. According to the results, strong correlation exists between most of the drought characteristics, at the 1% and 5% significance levels (results not shown). Furthermore, between the two hydrometric stations, the non-parametric Wilcoxon–Mann–Whitney test was applied to test for differences in drought intensity, duration and average runoff (results not shown). As the results, while there is no significant difference between the corresponding durations, drought intensity and average runoff values are significantly different between the two hydrometric stations.

4.4 Establishment of Time-Based Relationships

The non-parametric Wilcoxon–Mann–Whitney test was applied for an investigation of the relations between individual time-based SPI values ($SPI_{3-month}$, $SPI_{6-month}$, SPI_{Anuual}) and drought intensities from hydrometric stations. As an example, Fig. 4 (a–c) illustrate $SPI_{3-month}$, $SPI_{6-month}$ and SPI_{Anuual} values from Jamalbeik rain gauge station and drought intensities from Chamriz hydrometric station. Similar illustrations are given in Fig. 5 (a–c) for Dehkade Sefid rain gauge station and Dehkade Sefid hydrometric station. As Tables 7 and 8 show, meaningful relationships exist between time-based SPI values and streamflow drought intensities, at 5% significance level, for a majority of cases. The exceptions were the relation between Dehkade Sefid $SPI_{6-month}$ and streamflow drought intensities at Chamriz station ($Z_{6-month} = 1.646$), the one between Jamalbeik SPI_{Annual} and streamflow drought intensities at Dehkade Sefid station ($Z_{Annual} = 2.06$) and the one between Chamriz $SPI_{6-month}$ streamflow drought intensities and Dehkade Sefid station ($Z_{6-month} = 1.9$). However, the best relation is between Jamalbeik SPI_{Annual} and streamflow drought intensities at Chamriz station ($Z_{6-month} = 0.064$). This is rather interesting, since Jamalbeik is the more centrally located rain gauge station, with a mean annual rainfall value close to the average value of the rain gauges (Tables 7 and 8). Furthermore, the Chamriz hydrometric station is the drainage point of the upstream watershed, and so it is mostly representative of the watershed streamflow status. In addition, the Chamriz hydrometric station is also immediately located upstream of Doroodzan Dam (Fig. 1). Based on the results of this study, the annual moving averages of the SPI values from the Jamalbeik station (SPI_{Annual}) can be used to evaluate streamflow drought status of Chamriz station.

4.5 Comparison of Results With Documented Droughts

Comparison and verification of the results of this study requires documentation of drought events as they have occurred. Such a source of data, when available, can provide valuable information to assess applicability of the study results.

Figures 4 and 5a–c illustrate time-based meteorological and streamflow droughts for Jamalbeik rain gauge, Chamriz hydrometric stations and Dehkade Sefiid rain gauge, Dehkade Sefiid hydrometric stations, respectively. According to Figs. 4 and

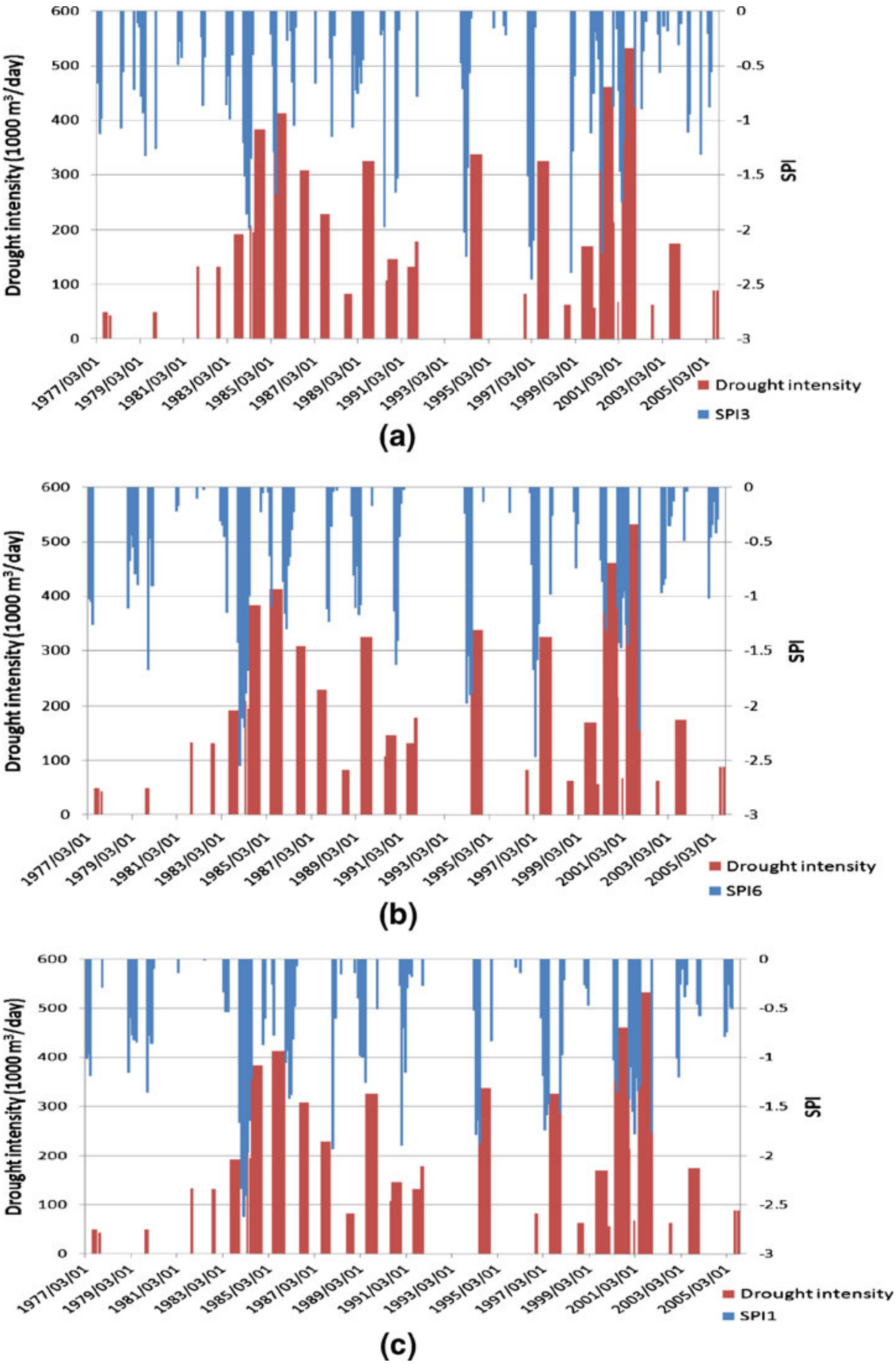

Fig. 4 **a–c** Respectively, $SPI_{3-month}$, $SPI_{6-month}$ and SPI_{Anuual} of Jamalbeik rain gauge station, versus drought intensities of Chamriz hydrometric station, top axis represents SPI values, bottom axis represents drought intensity

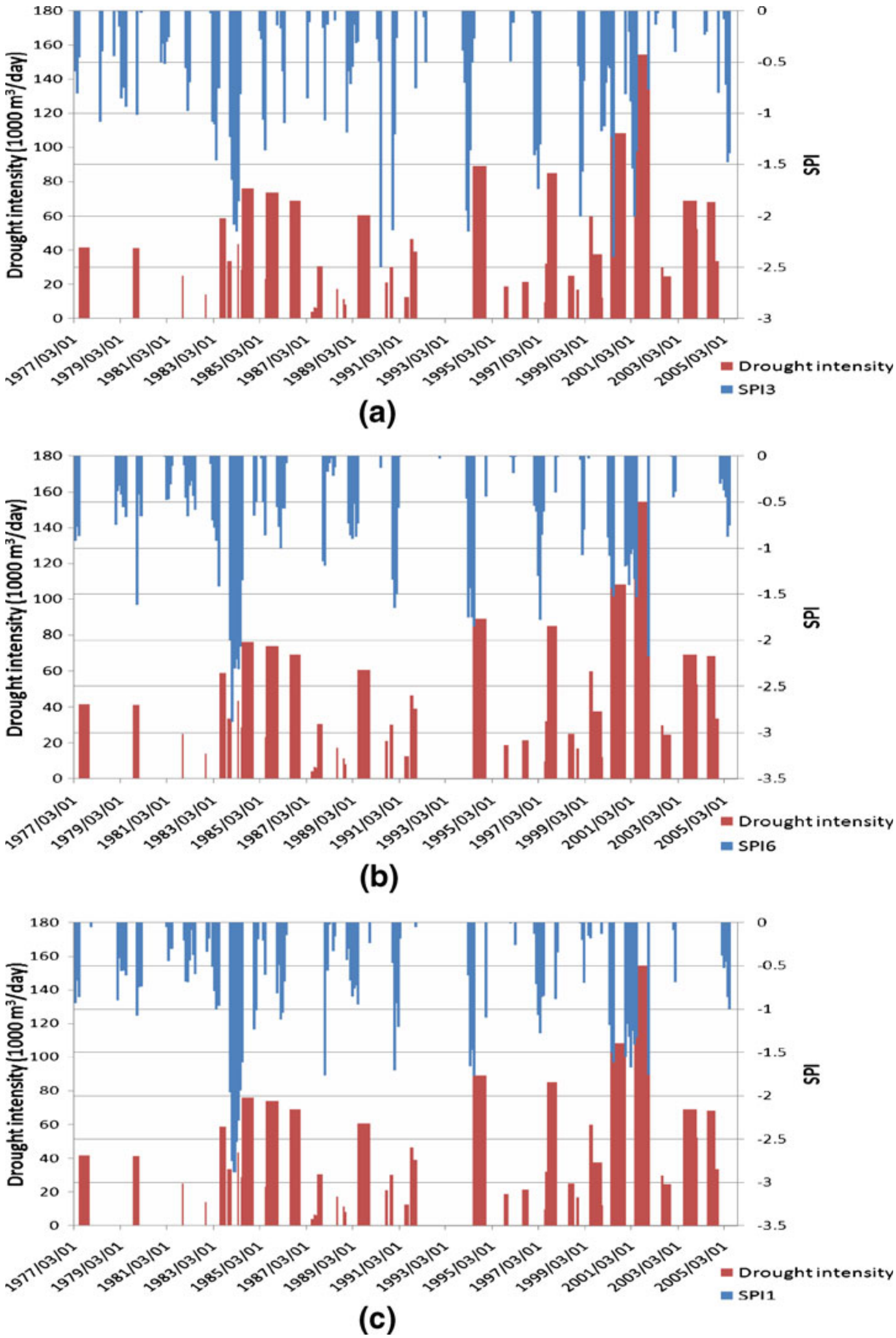

Fig. 5 **a–c** Respectively, $SPI_{3-month}$, $SPI_{6-month}$ and SPI_{Anuual} of Dehkade Sefid Rain gauge station, versus drought intensities of Dehkade Sefid hydrometric station, top axis represents *SPI* values, bottom axis represents drought intensity

Table 7 Rain gauge station time-based relation with Chamriz hydrometric station

Rain gauge stations	Average annual rainfall (mm)	$Z_{3-month}$	$Z_{6-month}$	Z_{Annual}
Chamriz	482.7	0.662	0.140	0.800
Chobkhaleh	842.8	0.522	0.579	0.557
Jamalbeik	525.6	0.564	0.360	0.064
Dehkade Sefid	477.2	0.953	**1.646**$^{+}$	1.534
Average rainfalls (mm)	582	–	–	–

Z values are compared at 5% significance level. Value in bold is significantly different at 5% level.

5a–c, several drought periods are identifiable, however, the 1998–2001 represent the most severe drought period. While there is limited history of drought documentation in the study area, several researchers have marked the 1998–2001 as one of the worst drought periods in Iran. Raziei et al. (2009) indicated that droughts of 1998–2001 impacted about half of the population, over a vast area of the country. Agrawala et al. (2001) reported that about twenty provinces experienced precipitation deficit during 2001. Yazdani and Haghsheno (2008) concluded that out of the 17 drought seasons in Iran over the last 50 years, the 1999 has been the worst. The 1999 drought was most devastating to agriculture and water resources, causing massive migration of rural people to urban areas.

Documentation of droughts for the exact location of Jamalbeik and Dehkade Sefid rain gauge stations, or Chamriz and Dehkade Sefiid hydrometric stations are not available. However, Sabetraftar and Abbaspour (2003) discussed the ecological and biological aspects as influenced by drought in the Bakhtegan region (part of the present case study). As reported, drying Bakhtegan, Arjan and Kaftar lakes and wetlands caused a drastic decrease in the wildlife population, from 14,000 species in 1997 to 56 in 2000. flamingo colonies had the worst drought impact with major disease outbreaks. To the extent possible, above studies and reports confirm the results of the present study on the occurrence of meteorological and streamflow droughts, during the 1998–2001.

Table 8 Rain gauge station time-based relation with Dehkade Sefid hydrometric station

Rain gauge station	Average annual rainfall (mm)	$Z_{3-month}$	$Z_{6-month}$	Z_{Annual}
Chamriz	482.7	1.42	1.9	1.18
Chobkhaleh	842.8	1.42	1.48	1.52
Jamalbeik	525.6	1.61	1.49	2.06[a]
Dehkade Sefid	477.2	1.09	0.21	0.49
Average rainfalls (mm)	582	–	–	–

Z values are compared at 5% significance level.

[a]Value significantly different at5% level.

5 Summary and Conclusions

In the present research time-based meteorological and streamflow drought characteristics were investigated based on data from rain gauge stations and hydrometric stations of Doroodzan Watershed and Reservoir in southwestern Iran. Central to this investigation was possible establishment of relationship between time-based meteorological drought characteristics and streamflow drought characteristics. The SPI methodologies were applied to assess meteorological drought characteristics, whereby, $SPI_{3-months}$, $SPI_{6-months}$ and SPI_{Anuual} were developed. Streamflow drought characteristics were identified by the threshold level method, whereby, Q_{70} was used to select deficits volumes and streamflow drought intensities, from data of hydrometric stations. The non-parametric Wilcoxon–Mann–Whitney test was used to investigate possible relationships between time-based SPI values ($SPI_{3-months}$, $SPI_{6-months}$, SPI_{Anuual}) and streamflow drought intensities. As indicated by the results, most time-based SPI values from the four rain gauge stations showed significant relationships (at 5% level of significance) with streamflow drought intensities from the two hydrometric stations. However, the most significant time-based relationship was between SPI_{Anuual} of Jamalbeik rain gauge station (centrally located in the study area) and streamflow drought intensity of Chamriz hydrometric station (located at the reservoir inlet). The SPI_{Anuual} is based on one-year-ahead moving average rainfalls. Then, drought occurrence triggered by SPI_{Anuual} in Jamalbeik rain gauge station can be used to investigate occurrence of streamflow droughts for Chamriz hydrometric station. This type of information can be useful for water resources management purposes since Chamriz hydrometric station is immediately located upstream of the Doroodzan Dam and Reservoir, with the responsibility of supplying water to consumers in the agricultural, domestic and industrial sectors.

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