Drought Analysis Based on Standardized Precipitation Index (SPI) and Streamflow Drought Index (SDI) in Chenar Rahdar River Basin, Southern Iran

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Abstract

In this research, climatologic and hydrologic droughts, as defined by Standardized Precipitation Index (SPI) and Streamflow Drought Index (SDI), were studied in Chenar Rahdar river basin, southern Iran. The basin has a total area of 178 km^2, a mean elevation of 1637m above mean sea level, and precipitation and stream flow records over the period of 1974 to 2013. SPI and SDI indices over the basin were analyzed for the 40-year record. Overlapping periods of 3, 6, 9, and 12 months were observed. Results showed that an acceptable correlation exists between SPI, as a climatological index, and SDI, as a hydrologic drought index. Analyses revealed that the basin suffered from a range of moderate to extreme droughts during the study period. From the results, one may conclude that both SPI and SDI indices are well capable of capturing the major droughts in Chenar Rahdar river basin for the past 40 years.

Keywords: Hydrological drought; Climatological drought; SDI; SPI; Chenar Rahdar river basin; Iran.

INTRODUCTION

Drought, water availability significantly below normal levels during a certain period of time, leads to significant impacts on water resources, their management, and social communities in general. As a natural occurrence, it characterizes long periods of low water accessibilities, and is spatiotemporally combined with climate variability of the area. Today, intensity and frequency of droughts are increasing, and hence impacting human life more than any other natural disaster. This may be partly attributed to the change of climatic conditions which put increased stresses on hydrological systems and water resources (Soo Jun et al. 2011). From a comprehensive view point, droughts may be associated with different groups or disciplines like meteorological drought, hydrological drought, agricultural drought, and socioeconomic drought (Yang 2010). The first three groups are defined as physical phenomenon, but the last group views drought from a supply and demand perspective. In addition, hydrological component is often seen as the most essential one, given the high dependency of many activities to surface water resources (Vasiliades et al. 2011). Hydrological droughts, primarily caused by rain shortfalls, typically have the maximum effects on reservoirs and/or lake levels within a basin (Liu et al. 2012). In fact, hydrological droughts can have significant impacts on reducing water supply, deteriorating water quality, reducing power generation, disturbing riparian habitats, limiting recreation, and even causing crop failure. One way to monitor drought conditions is to analyze drought indices that provide a quantitative index to determine the start and the end of a drought event, and level of drought severity (Tabari et al. 2012). Many researchers developed several drought indices such as Surface Water Supply Index (SWSI) (Shafer and Dezman 1982), Standardized Precipitation index (SPI) (McKee et al. 1993), Regional Deficiency Index (RDI) (Stahl 2001), Aggregate Drought Index (ADI) (Keyantash and Dracup 2004), Drought Severity Index (DSI) (Pandey et al. 2008), Standardized Runoff Index (SRI) (Shukla and Wood 2008), Streamflow Drought Index (SDI) (Nalbantis 2008), Standardized Hydrological Index (SHI) (Sharma et al. 2010), and Regional Drought Area Index (RDAI) (Fleig et al. 2010) to characterize hydrological droughts. The scope of this research is to derive SPI and SDI indices for Chenar Rahdar river basin and analyze them for the past 40 years (1974-2013) of records. Overlapping time scales of 3, 6, 9 and 12 months for SPI and SDI, and their relationship will be evaluated.

STUDY AREA

Chenar Rahdar River basin is a small undeveloped basin located in Eastern Shiraz, Fars, Iran, with an outlet elevation of 1637m from mean sea level. The river is locally used for agricultural activities and eventually pours into Maharloo Lake ~27 km southeast of Shiraz (Fig. 1). In this research, rainfall data were collected from a metrological station, and hydraulic data from Chenar Rahdar hydrometric station at the basin outlet, both managed by Fars regional water authority. In addition, data from hydrometric Shiraz station located in western Shiraz, Fars, Iran was used (Fig. 2). Overall, climate in Chenar Rahdar basin is semi-arid, with ~300 mm of annual rainfall, having a relatively hot summers (a July average high temperature of 37.8 °C) and cool winters (with average low temperatures below freezing in December and January).

Figure 1. A general map of Shiraz city in Fars, Iran

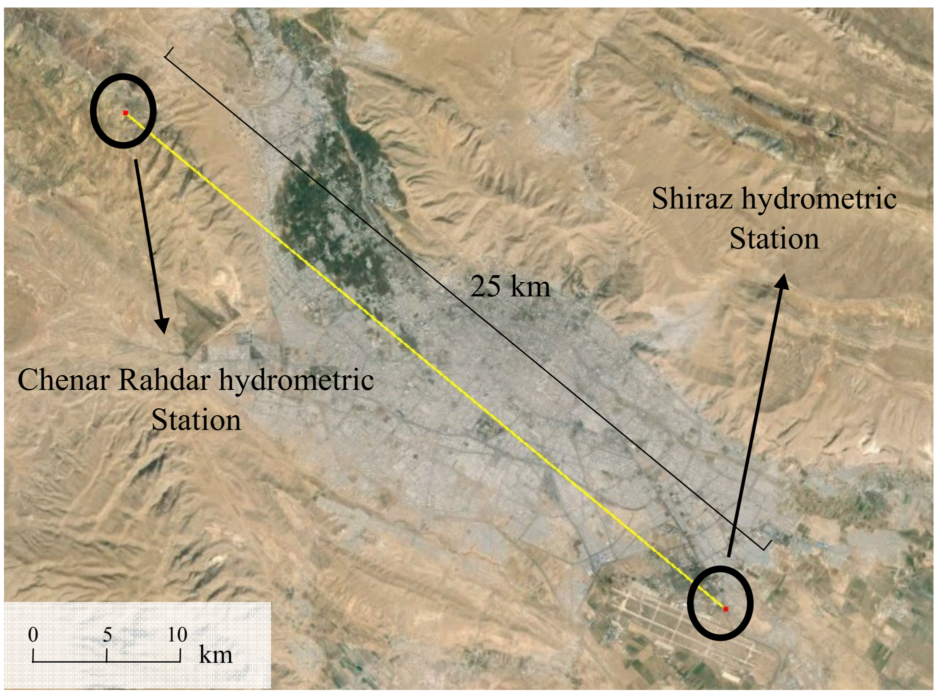

Figure 2. Locations of Shiraz and Chenar Rahdar hydrometric stations on Google Earth

METHOD AND MATERIALS

Drought analysis was performed using Standard Precipitation Index (SPI) and Streamflow Drought Index (SDI) at Chenar Rahdar river basin, Iran (McKee et al. 1993, Nalbantis 2008). Precipitation data was used for overlapping time scales of 3, 6, 9 and 12 months within each hydrological year over the recorded period of 1974 to 2013. Different statistical distributions with different P-values, the probability of observing a value at least as large as the one calculated assuming the null hypothesis is true, were investigated and the values were examined by Kolmogorov-Smirnov (K-S) test to select the most proper distribution that best fits the precipitation and streamflow data (Johnson et al. 1994, Hosking 1990 and 2000). P-values were derived based on the fact that the null hypothesis of K-S test is that the observed data has come from the proposed distribution. Around 60 statistical distributions were examined and the analyses showed that Wakeby distribution "best" suites to represent both data sets in different overlapping time scales of 3, 6, 9 and 12 months when calculating SPI and SDI. P-values for annual runoff are shown in Figure 3, as an example. As shown, many distributions have acceptable P-values of >0.90 when Wakeby is the "best" with P= 0.989. P-values for 3, 6, 9, and 12 month precipitations and runoffs are shown in Figures 4 and 5, respectively. As shown, P-values greatly improve when Wakeby distribution is fitted to the initial data.

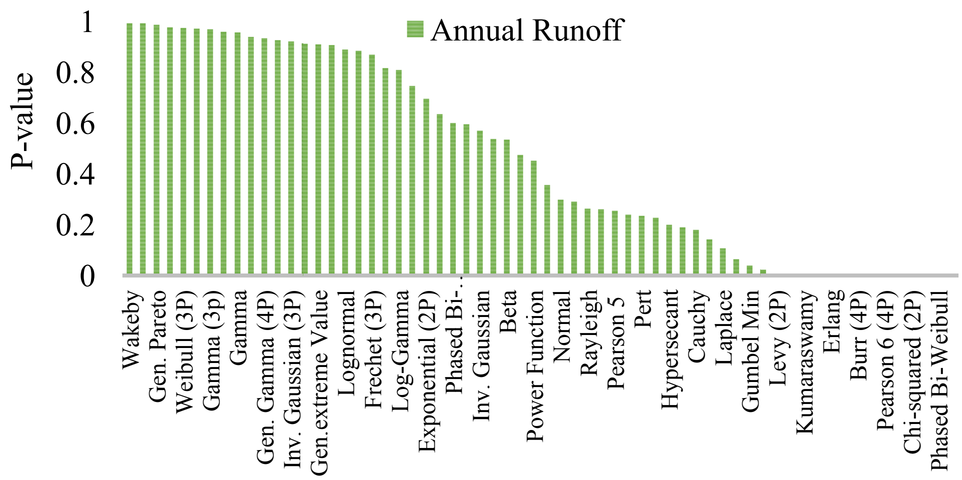

Figure 3. P-values for annual runoff at Chenar Rahdar basin outlet

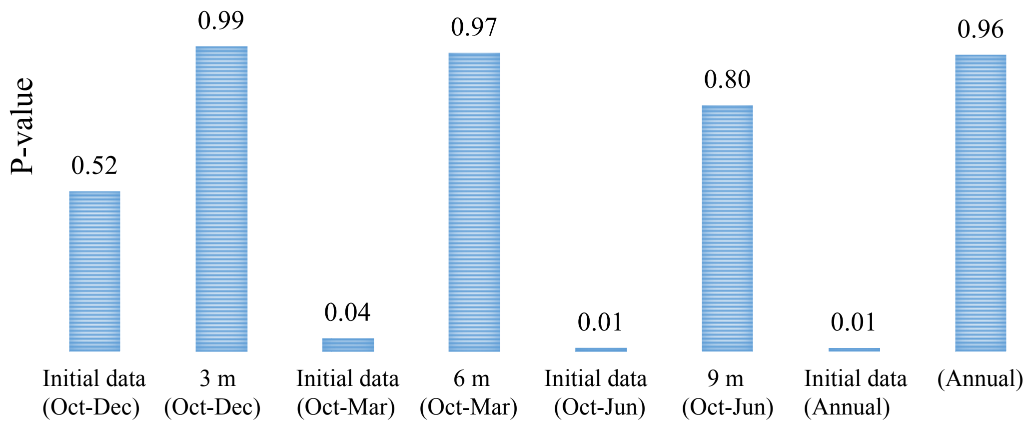

Figure 4. P-values for initial and Wakeby-fitted precipitation data for different time scales

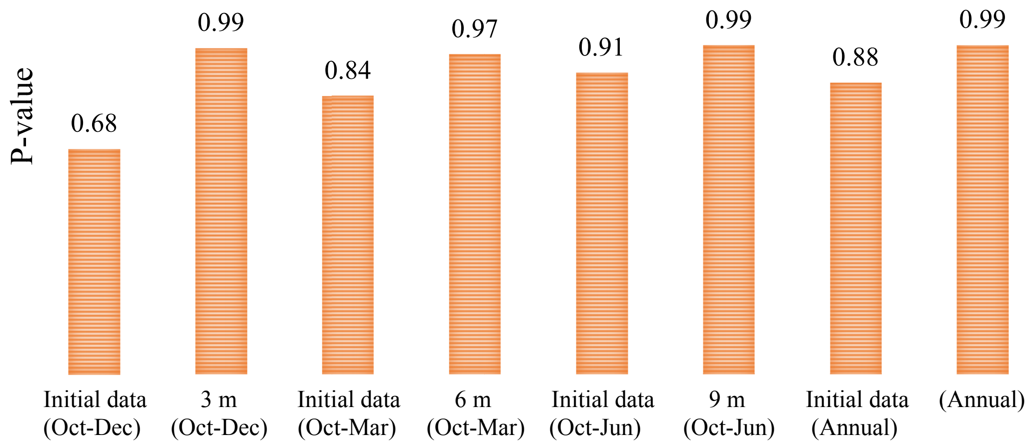

Figure 5. P-values for initial and Wakeby-fitted runoff data for different time scales

Equation 1 defines the percent point function for Wakeby distribution. Parameters β, γ, and δ are shape parameters, U is an arbitrary standard uniform random variable, and ξ and α are location parameters.

$$x(F) = \xi + \left(\frac{\alpha}{\beta}\right)\left(1-(1-U)^{\beta}\right) - \left(\frac{\gamma}{\delta}\right)\left(1-(1-U)^{-\delta}\right) \quad (1)$$

The following restrictions apply to parameters in this distribution:

$\beta + \delta \geq 0$

Either $\beta + \delta \geq 0$ or $\beta = \gamma = \delta = 0$

If $\gamma > 0$, then $\delta > 0$

$\gamma \geq 0$

$\alpha + \gamma \geq 0$

The domains in Wakeby distribution are;

ξ to ∞

if $\delta \geq 0$ and $\gamma > 0$

ξ to $\xi + (\alpha/\beta) - (\gamma/\delta)$

if $\delta < 0$ or $\gamma = 0$

It is noteworthy that with three shape parameters, Wakeby distribution may model a wide variety of shapes (Johnson et al. 1994, Hosking 1990 and 2000).

The cumulative distribution function is computed by numerically inverting the percent point function given above. The probability density function is then found by using the following relation:

$$f(x) = \frac{(1-F(x)^{\delta+1}}{\alpha t+\gamma} \qquad (2)$$

Where F is the cumulative distribution function and

$$t = (1 - F(x))^{\beta+\delta} \qquad (3)$$ (Tabari et al. 2012)

SPI may take on positive or negative values for precipitations greater or smaller than mean precipitation, respectively. Variance from the mean is a probability indication of the severity of the flood or drought that can be used for risk assessment (Morid et al. 2006). The status of hydrological droughts according to SPI values are defined in Table 1 (Edwards and McKee 1997).

Table 1. Dryness/wetness categories according to SPI values (McKee et al.1993)

State	*Category*	*SPI values*
1	Extremely wet	≥2.0
2	Severely wet	1.50 to 1.99
3	Moderately wet	1.00 to 1.49
4	Near normal	0.99 to -0.99
5	Moderately dry	-1.00 to -1.49
6	Severely dry	-1.50 to -1.99
7	Extremely dry	≤-2.0

To compute SDI, 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 (e.g. j =1 for October and j =12 for September). Based on this series, cumulative streamflow volume is computed as follows:

$$V_{i,k} = \sum_{j=1}^{3k} Q_{i,j} \qquad i=1,2,\ldots \quad j=1,2,\ldots,12 \quad k=1,2,3,4$$ (Liu et al. 2012)

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

$$SDI_{i,k} = \frac{v_{i,k} - \bar{v}}{s_k} \qquad i=1,2,\ldots \quad k=1,2,3,4$$ (Tabari et al. 2012)

Where V_k and S_k are the mean and standard deviation of cumulative streamflow volumes respectively, for reference period k as these are estimated over a long period of time. In this definition, the truncation level is set to V_k although other values could be used (Nalbantis 2008). Positive SDI values reflect wet conditions while negative ones indicate a hydrological drought. Based on the SDI, five states of hydrological drought are defined which are denoted by an integer number ranging from 0 (non-drought) to 4 (extreme drought). States of hydrological droughts according to SDI values are defined through the criteria presented in Table 2.

Table 2. Dryness/wetness categories according to SDI values (Nalbantis 2008)

State	*Description*	*values*
0	Non-Drought	SDI≥0.0
1	Mild drought	-1.0≥SDI<0.0
2	Moderate drought	-1.5≥SDI<-1.0
3	Severe Drought	-2.0≥SDI<-1.5
4	Extreme Drought	SDI<-2.0

RESULTS AND DISCUSSIONS

SDI, SPI, and their correlation were used to analyze drought in the basin. Figure 6 shows annual SDI and SPI variations over the past 40 years. The data is for Chenar Rahdar station unless SPI values for the past 14 years which are from Shiraz station due to closure of the former during this period and no data collection there. SPI's for the two stations correlated well with one another (r =0.88), justifying usage of Shiraz data for Chenar Rahdar during the past 14 years. SPI and SDI for Chenar Rahdar station (1974 to 2000) had a correlation coefficient of 0.72 while SPI for Chenar Rahdar correlated to SDI for Shiraz station (2001 to 2014) with a coefficient of 0.69. It seems that either SPI and/or SDI indices may be utilized to capture major droughts in the basin for the past 40 years.

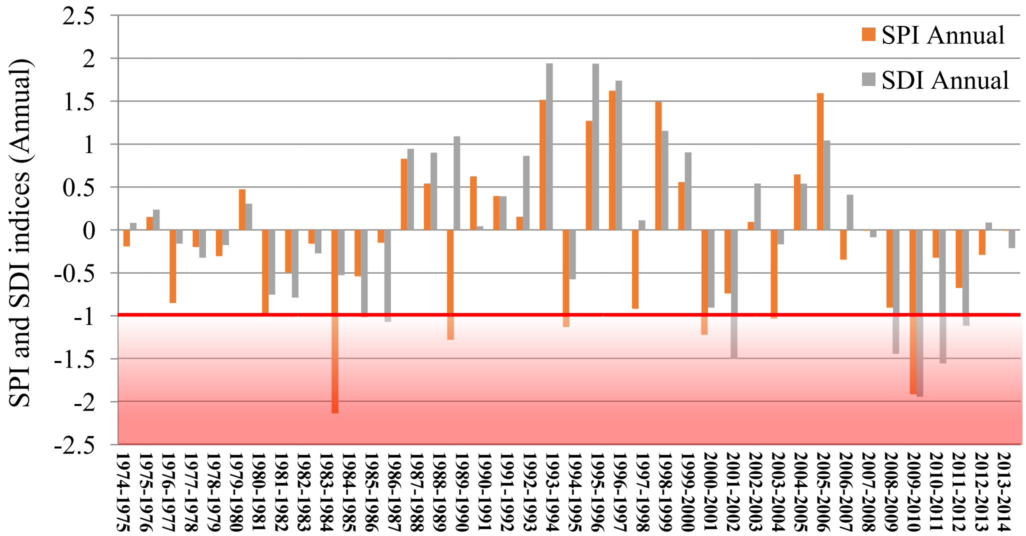

Figure 6. Annual SDI and SPI indices at the study station for the reference period

As shown, SDI indicates that during three periods (2001-2002, 2009-2010 and 2010-2011) the basin experienced severe droughts. Number of droughts is verified by SPI. However, it indicates an extreme and a severe one. While a severe drought period (2009-2010) is common between the two indices, the other one is not common. Five, more frequently occurring, moderate droughts are captured by both indices, however, they don't coincide.

Figure 7 depicts 3-month (Oct-Dec) SDI and SPI's for the same period. As shown, SDI suggests that during 2011-2012 the basin experienced an extreme drought and a severe one during 1983-1984. SPI, on the other hand, indicates these periods as droughts, however, with less severities. 6-month (Oct-March) indices indicate similar behavior, showing 2 major droughts during 1983-1984 and 2009-2010 with SPI showing less severities (Figure 8).

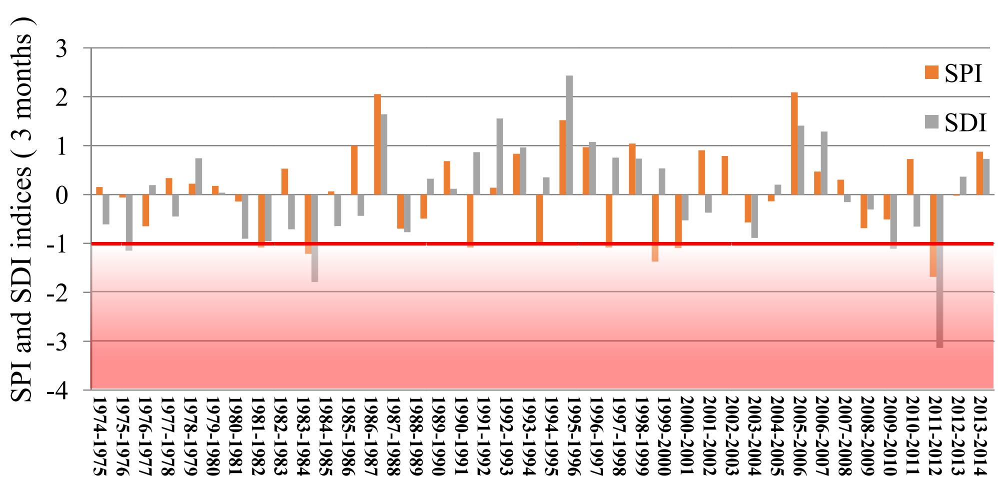

Figure 7. SDI and SPI series at the study station for reference period October–December

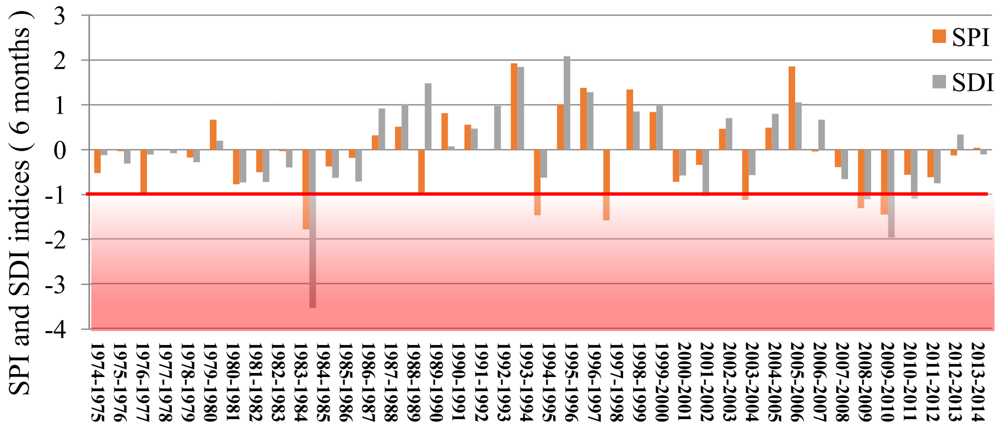

Figure 8. SDI and SPI indices at Chenar Rahdar station for the reference period, October–March

Figure 9 depicts 9-month indices for the reference period of Oct-June. As shown, SDI indicates that during 2009-2010 the basin experienced extreme droughts and during three periods of 2001-2002, 2008-2009, and 2010-2011 it experienced severe droughts. Also, SPI shows that during (1983-1984) the basin experienced extreme drought and a severe one during 2009-2010. As expected, the general trend of droughts in this figure closely follows that of Fig. 6, owing to their lengths of reference periods being close to one another.

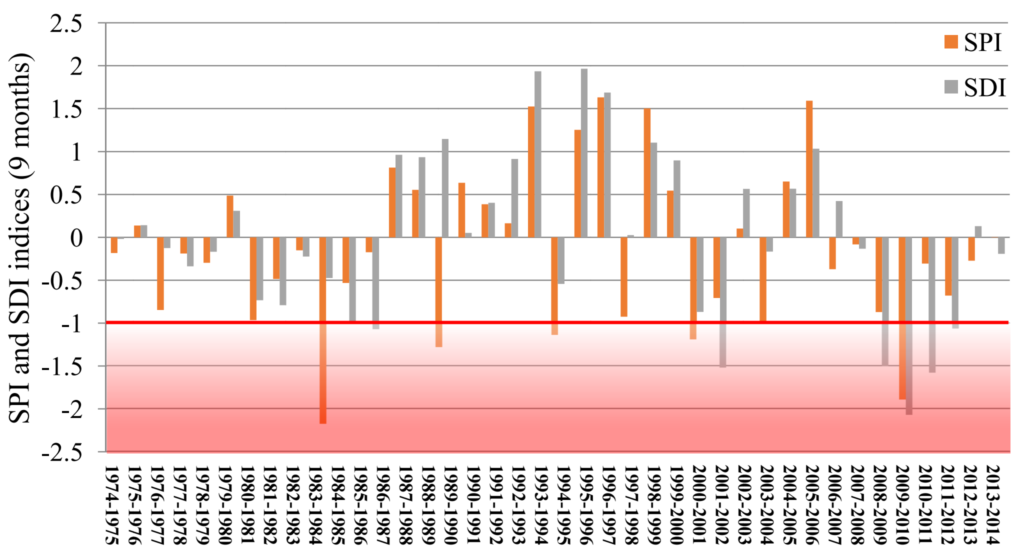

Figure 9. 9-month SDI and SPI indices at the study station for the reference period October–June

Figure 10 shows percentage of drought occurrences in the basin with different time scales based on SPI and SDI. Overall, both indices consistently indicate moderate droughts as the most occurring ones in the basin during the past 40 years, regardless of the time scales. Therefore, one may conclude that both SPI and SDI indices were well capable of capturing major droughts in Chenar Rahdar river basin.

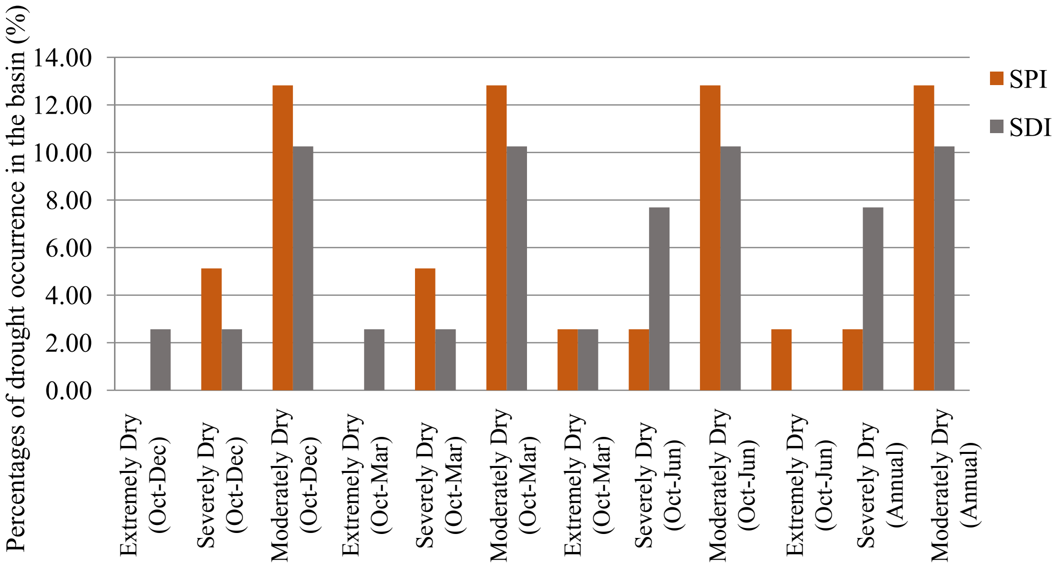

Figure 10. The percentage of drought occurrences in SDI and SPI indices

CONCLUSIONS

Climatologic and hydrologic droughts, as defined by SPI and SDI, were analyzed in Chenar Rahdar river basin, southern Iran for the past 40-year records. Overlapping periods of 3, 6, 9, and 12 months were observed. Different probability distributions were evaluated to find the one that best fits the streamflow and precipitation data. Goodness-of-fit by K-S test showed that Wakeby distribution best fits both data series. Results showed that an acceptable correlation exists between SPI, as a climatological index, and SDI, as a hydrologic drought index. Analyses revealed that the basin suffered from a range of moderate to extreme droughts during the study period, with 1981–1983 and 2007–2009 being the driest years. It was concluded that both indices are well capable of capturing the major droughts in the basin for the past 40 years.

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