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Streamflow drought severity analysis by percent of normal index (PNI) in northwest Iran

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Abstract The streamflow drought is the most important type of drought due to the high dependence of many activities on surface water resources. The streamflow drought severity was identified by the percent of normal index (PNI) in the western basins of the Lake Urmia located in northwest Iran. The streamflow records were obtained from 14 hydrometric stations for the period October 1975–September 2009. The temporal trends of the streamflow drought severity were detected by the parametric Student's t test and the nonparametric Mann–Kendall and Sen's tests. The worst streamflow droughts at almost all the stations occurred in 1999–2000 and 2000–2001. The streamflow drought severity based on the PNI increased during the last 34 years. The results also indicated that the temporal dependency of time series had a dominant role in detecting trend by the parametric Student's t test.

1 Introduction

Drought is a very common phenomenon all around the world especially in those countries located in the arid and semiarid areas (Badripour 2007). Droughts are the costliest

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natural disaster of the world and affect more people than any other natural disaster (Vasiliades et al. 2011). In contrast to other natural hazards (including floods) that are typically restricted to small regions and occur over well-defined temporal intervals, drought is difficult to pinpoint in time and space because it affects wide areas over long time periods (Vicente-Serrano 2012). Four categories associated with droughts can be found in Wilhite and Glantz (1985) namely meteorological drought, agricultural drought, hydrological drought, and socioeconomic drought. 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 socioeconomic drought discusses the consequential societal impacts of drought occurrences (Tabrizi et al. 2010).

Hydrological drought is defined as a sustained and regionally extensive period of below-average natural water availability. It is a recurring and worldwide phenomenon, with spatial and temporal characteristics that vary significantly from one region to another (Tallaksen and Van Lanen 2004). The knowledge of processes causing hydrological drought and its spatial variability is essential for a sustainable management of water resources. Extreme low flows can have an impact on the ecology of a river system, especially where the river flow is used for industrial, agricultural, or domestic purposes (Stefan et al. 2004).

Zaidman et al. (2001) examined the spatial and temporal development of streamflow droughts in Europe over the last 40 years. Their results indicated that the worst and most persistent streamflow droughts occurred in southern England and northern France. Wu et al. (2008) revealed statistical characteristics on streamflow drought event parameters and

detected spatial and temporal trends in the streamflow drought in terms of frequency, duration, and severity in Nebraska. They found that droughts in the Republican watershed have become more intense; whereas the drought has become slightly alleviated in the Missouri and nearby watersheds. Shaban (2009) analyzed the hydrologic drought indices through a comparative assessment of the available data and records in Lebanon. The results showed a remarkable decrease in water quantity in different aspects and at different scales. However, this decrease varies from one index to another, but all revealed alarming status. Boughton (2009) calculated streamflow drought characteristics in eastern Australia and found that the severity of droughts increased with average recurrence interval to the limit of the generated data. Edossa et al. (2010) analyzed drought characteristics in the Awash River Basin of Ethiopia based on meteorological and hydrological variables. The results based on hydrological drought analysis showed that the severest drought events occurred in the Middle Awash Basin during May 1988 to June 1988 and April 1998 to May 1998.

Like other countries in the arid zone, Central and Southwest Asia suffer from drought. During 1998–2001, Central and Southwest Asia represent the largest region of persistent and severe drought around the globe. In parts of Iran, Afghanistan, Pakistan, and Tajikistan, the 1998–2001 drought is the worst to hit the region over the past 50–100 years (Agrawala et al. 2001). Owing to frequent dry periods and drought conditions in Iran, the increasing water demands for an ever growing population as well as for industry and economic development, including irrigation and aggravate water scarcity, makes it difficult for a rationale water management (Raziei et al. 2008). Therefore, this investigation was carried out as a part of a much larger ongoing research project to analyze streamflow drought in the western basins of the Lake Urmia. The streamflow drought severity was calculated by the percent of

normal index (PNI) using discharge records from 14 hydrometric stations located in the West Azerbaijan Province.

2 Study area and data

The West Azerbaijan Province is a mountainous area which lies in the northwest of Iran. The province covers an area of 39,487 km^2 including part of the Lake Urmia and shares a long border (805 km) with the countries such as Nakhjavan, Armenia, Azerbaijan, Turkey, and Iraq. The climate of West Azerbaijan is Mediterranean, but it is quite cold at higher altitudes and vast areas are covered with snow in winter. The region is influenced by Western air in different seasons, cold continental masses from Siberia and northern Europe enters this area. In general, this province has warm summers and hard and cold winters.

West Azerbaijan is abundant with water resources of the country's northern territory, so it has a great water potential. Fourteen major rivers and several seasonal rivers flow in the province. Most of these rivers supply water reserves is in snow, rain, and permanent springs. For this work, the monthly streamflow data were collected from 14 hydrometric stations (Table 1). Data cover the period from 1975–1976 to 2008–2009. Station maintenance and data archiving are under the supervision of the West Azerbaijan Regional Water Co. Hydrometric stations used in this study are illustrated in Fig. 1.

3 Methods of analysis

The PNI was developed for characterizing meteorological drought severity, but the PNI procedure can also be applied to other variables such as streamflow for calculating streamflow

Table 1 Details of the hydrometric stations used in the study

| No.	Station	River	Latitude (N)	Longitude (E)	Elevation (m a.s.l.)
1	Abajaloo	Nazloo-Chai	45° 08′	37° 43′	1,290
2	Chahrigh	Nazloo-Chai	44° 36′	38° 05′	1,600
3	Tapik	Nazloo-Chai	44° 54′	37° 40′	1,450
4	Babarood	Barandooz-Chai	45° 14′	37° 24′	1,285
5	Dizaj	Barandooz-Chai	45° 04′	37° 23′	1,320
6	Hashem-Abad	Barandooz-Chai	44° 54′	37° 17′	1,570
7	Band-e-Urmia	Rozeh-Chai	45° 01′	37° 30′	1,390
8	Kalhoor	Rozeh-Chai	44° 53′	37° 36′	1,500
9	Ghasemloo	Balanj-Chai	45° 09′	37° 21′	1,380
10	Marz Sero	Berdook	44° 38′	37° 43′	1,640
11	Miandoab	Simineh Rood	46° 03′	36° 57′	1,290
12	Nazar-Abad	Derik-Chai	44° 36′	38° 11′	1,620
13	Ourban	Dirali-Chai	44° 44′	38° 20′	1,640
14	Yalghouz Aghaj	Zola-Chai	44° 56′	38° 14′	1,300
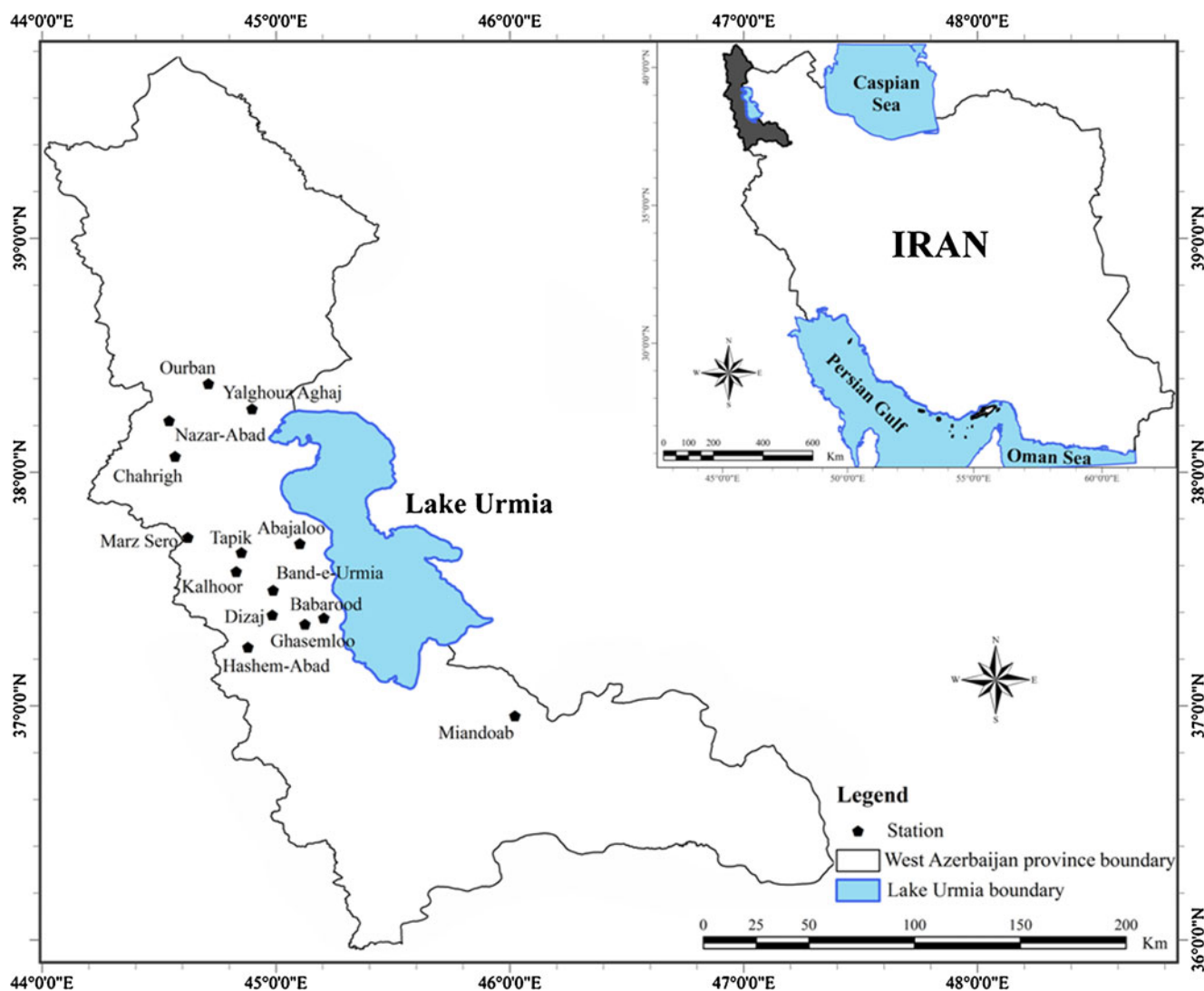
Fig. 1 Geographic location of the study area and spatial distribution of the hydrometric stations

drought severity. This index is simple, by definition, easy to calculate, and is easy understood by a general audience (Smakhtin and Hughes 2004). The index can be calculated for a variety of time scales. Usually these time scales range from a single month to a group of months representing a particular season to an annual or water year (Willeke et al. 1994). The PNI for characterizing streamflow drought severity is defined by dividing the actual streamflow (F_i) by the normal streamflow ($\overline{F}$), which is typically considered to be a mean of 30 years, and multiplying by 100 %. It is expressed by the following equation:

$$\text{PNI} = \frac{F_i}{\overline{F}} \times 100 \qquad (1)$$

One of the disadvantages of using the PNI is that the mean, or average, streamflow is often not the same as the median streamflow, which is the value exceeded by 50 % of the streamflow occurrences in a long-term climate record. The reason for this is that streamflow does not have a normal distribution. Thus, an initial transformation of the data series is usually done to make the PNI a standard normal distribution variable. The logarithmic transformation is a common transformation to remove the asymmetry in the streamflow data distribution (Cook and Jacoby 1983; Phipps 1983; Meko and Graybill 1995; Engeland and Gottschalk 2002; Morawietz et al. 2011; Moore et al. 2011). In this study, we chose log-normal probability distribution for which the normalization is simple: it suffices taking natural logarithms of streamflow (Nalbantis and Tsakiris 2009). After logarithmic transformation of the data set, the sample mean of the transformed data will be μ, then the PNI becomes

$$\text{PNI} = \frac{\ln(F_i)}{\mu} \times 100 \qquad (2)$$

Table 2 The PNI drought category classification

Criterion	Situations
PNI>80	Normal
70≥PNI<80	Slight drought
55≥PNI<70	Moderate drought
40≥SDI<55	Severe drought
SDI<40	Extreme drought

Based on the PNI, five states of hydrological drought are defined through the criteria of Table 2. After calculating the streamflow drought severity by the PNI, the temporal trends in the PNI series were detected by the parametric Student's *t* test and the nonparametric Mann–Kendall and Sen's tests.

4 Results and discussion

The skewness coefficients of the original and logarithmic streamflow are shown in Fig. 2. As shown, all of the original streamflow series had a negative skewness. Taking logarithms for the streamflow series, skewness decreased at nine out of the 14 hydrometric stations. After logarithmic transformation, skewness of the streamflow series increased at Abajaloo, Babarood, Dizaj, Band-e-Urmia, and Miandoab stations. In the cases that the skewness was removed from the streamflow series with logarithmic transformation, Eq. 2 was used while keeping Eq. 1 for the other cases. Shukla and Wood (2008) reported that the two-parameter log-normal distribution generally performed well for adjusting the streamflow data.

The PNI series at the considered stations are depicted in Fig. 3. Due to the frequent occurrence of the slight, moderate, and severe droughts, only the extreme droughts are discussed in this section. At Abajaloo, Chahrigh, and Tapik stations located along with the Nazloo-Chai River,

the extreme streamflow droughts were observed in the hydrological years of 1980–1981, 1981–1982, 1983–1984, 2004–2005, 2007–2008, and between 1997–1998 and 2000–2001. For the Barandooz-Chai River, the extreme streamflow droughts occurred in 2007–2008 and during the period from 1998–1999 to 2000–2001. The Rozeh-Chai River experienced the extreme droughts in years 1983–1984, 1998–1999, 1999–2000, 2000–2001, 2004–2005, 2007–2008, and 2008–2009. At the other stations, the extreme droughts were observed mainly during the last 12 years from 1997–1998 to 2008–2009. In general, the highest number of years (7 years) with extreme streamflow droughts in the study region was found at the Abajaloo station of the Nazloo-Chai River, the Band-e-Urmia station of the Rozeh-Chai River, the Miandoab station of the Simineh Rood River, and the Yalghouz Aghaj station of the Zola-Chai River (Table 3). In contrast, any extreme droughts were not found at the Hashem-Abad station of the Barandooz-Chai River. Urban station located along with the Dirali-Chai River faced streamflow drought conditions in 19 years   (Table 3). Furthermore, Abajaloo, Band-e-Urmia, Marz Sero, Nazar-Abad, and Yalghouz Aghaj stations experienced streamflow drought conditions in 16 years. The severity and persistence of the streamflow drought have led to a wide range of impact across the region. Agriculture, animal husbandry, water resources, and public health will be severely affected by streamflow drought throughout the region.

Most of the studied rivers discharge into the Lake Urmia and are the source of the majority of the Lake's water budget. The water level of the Lake Urmia has rapidly declined since the mid-1990s after having remained relatively stable over the 30 prior years. Since the Lake Urmia is a terminal lake with no significant water outflow, the only way water leaves the lake is by evaporation. Therefore, if the lake declines, it is either by increased evaporation or a decrease in water coming into the system (UNEP 2012). Generally, the decline is generally blamed on a combination

Fig. 2 Skewness coefficient of streamflow and its natural logarithms at the considered stations
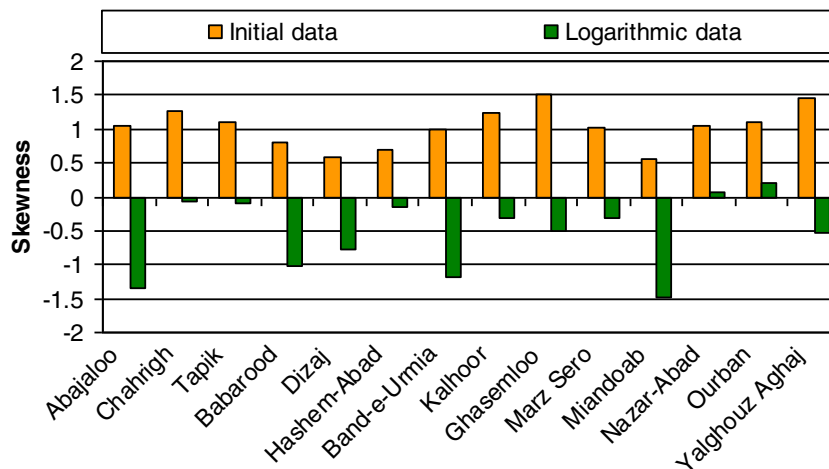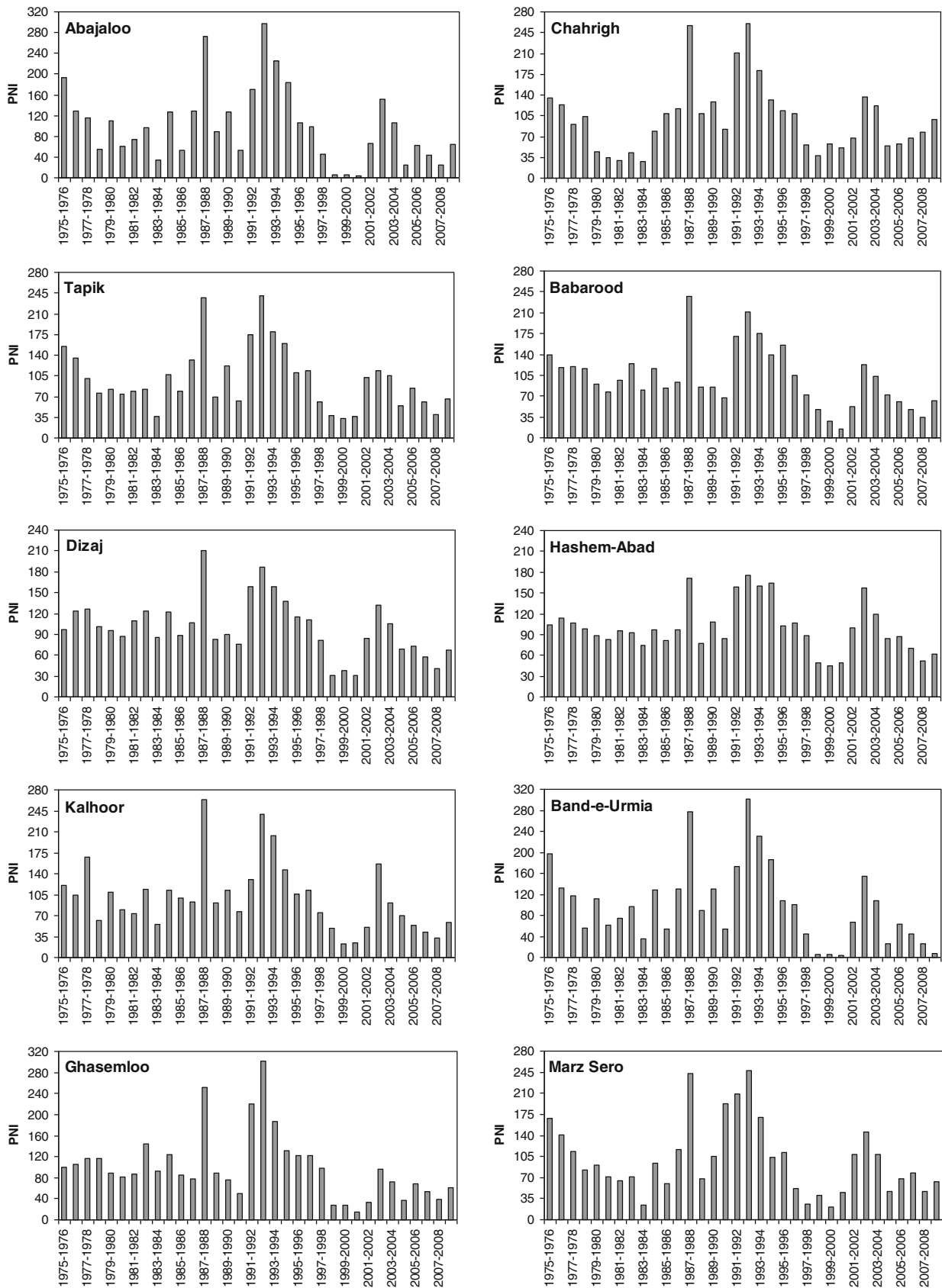
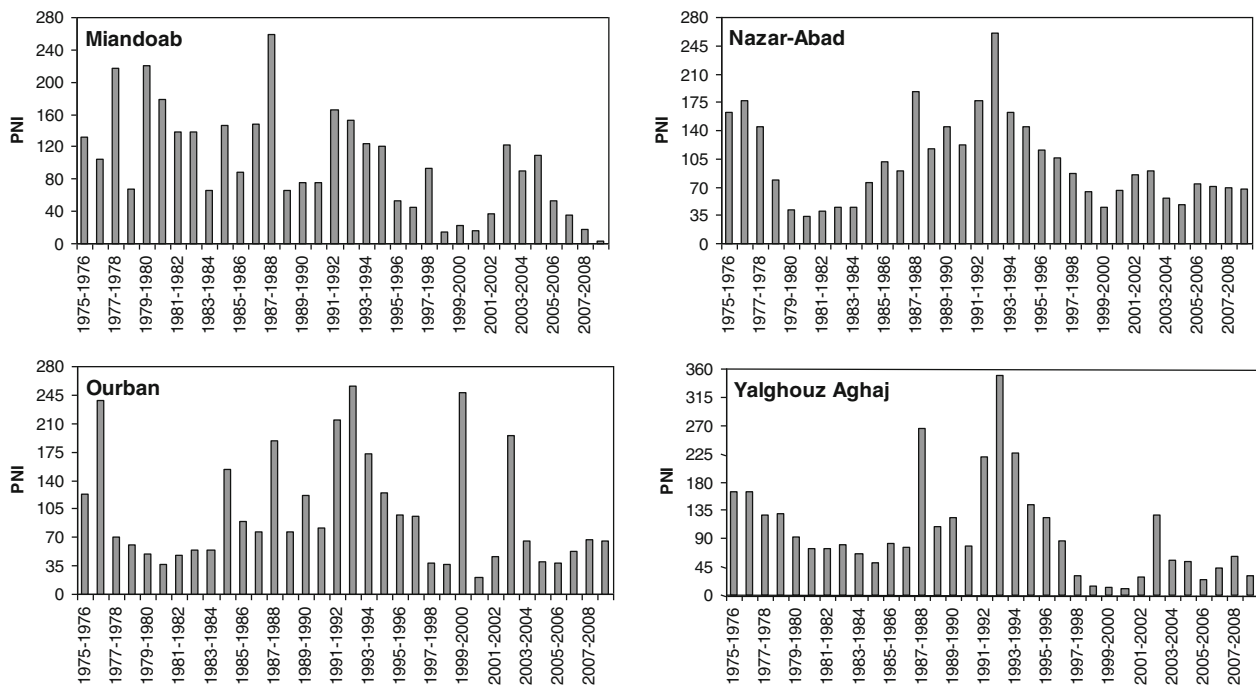**Fig. 3** PNI series at the considered stations

Fig. 3 (continued)

of drought, increased water diversion for irrigated agriculture within the lake's watershed, and mismanagement.

The results also showed that the worst streamflow droughts at almost all the stations occurred in 1999–2000 and 2000–2001. It can be inferred that the last decade was the driest period at the western basins of the Lake Urmia. Effects of the drought will likely persist for several years, even if precipitation returns to normal levels. The occurrences of several drought years in the country are a leading to

profound ecological and socioeconomic effects in this region (Shahabfar et al. 2012). Severely depleted soil moisture and water supplies will take time to recover. In addition, extremely dry soil is also prone to flash flooding with the return of rainfall. The 1998–2001 drought in Iran led to vulnerability of about 37 million people to food and water insecurity (Agrawala et al. 2001). The results of this study also showed that the wettest hydrological years during the examined period were 1992–1993 and 1987–1988.

The temporal variation of the streamflow drought severity was also analyzed by the parametric and nonparametric trend tests. Prior to the trend analysis, the serial structure of the PNI series was considered because the presence of serial correlation can complicate the identification of trends in that a positive serial correlation can increase the expected number of false-positive outcomes for the trend tests (Tabari et al. 2012b). The lag-1 serial correlation coefficients of the PNI series are shown in Fig. 4. As the results show, the PNI series at about 93 % of the stations had a significant positive serial correlation at the significance level of 0.05. The PNI series with significant serial correlation at the 0.05 level were subjected to pre-whitening procedure before applying the trend tests.

The results of the Mann–Kendall test and the Sen's slope estimator on the PNI time series are presented in Fig. 5. A downward trend was detected by the nonparametric tests in the PNI series at 12 out of the 14 considered stations. The downward trends were found to be significant at Babarood and Dizaj stations of the Barandooz-Chai River, the Kalhoor station of the Rozeh-Chai River, the Ghasemloo station of the Balanj-Chai

Table 3 The number of drought events at each hydrometric stations during the study period

| Station	Extreme drought	Severe drought	Moderate drought	Slight drought	Total
Abajaloo	7	3	5	1	16
Chahrigh	4	4	4	3	15
Tapik	5	-	4	4	13
Babarood	3	3	3	3	12
Dizaj	3	1	3	2	9
Hashem-Abad	–	4	1	3	8
Band-e-Urmia	7	4	4	1	16
Kalhoor	3	4	5	2	14
Ghasemloo	6	2	2	3	13
Marz Sero	3	5	5	3	16
Miandoab	7	3	3	2	15
Nazar-Abad	2	5	5	4	16
Ourban	5	7	4	3	19
Yalghouz Aghaj	7	3	3	3	16

Fig. 4 Lag-1 serial correlation coefficient for the PNI series at the study stations
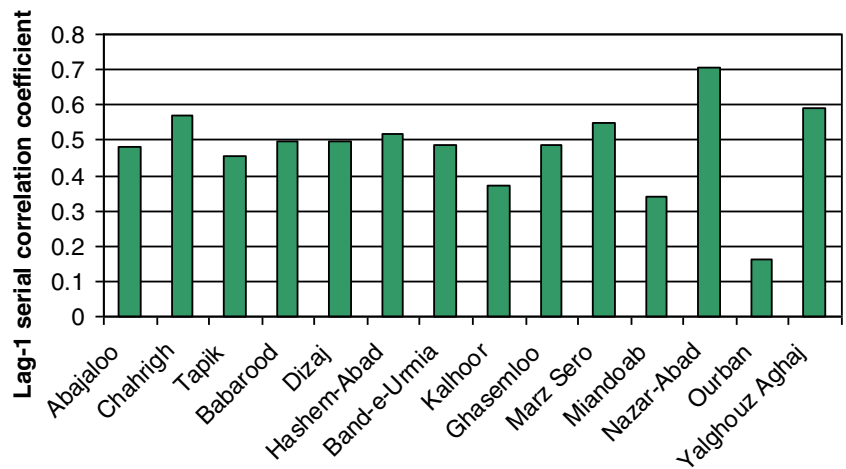
River, the Miandoab station of the Simineh Rood River and the Yalghouz Aghaj station of the Zola-Chai River. It is worthwhile to note that the downward trend of the PNI series corresponds with an increase in streamflow drought severity. In general, the streamflow drought severity in the region has increased over the time period in terms of the downward PNI trends. An increase in aridity was reported by Tabari and Aghajanloo (2012) for the northwest of Iran during 1996–2005. Climate

change and human activities, like change in precipitation record, constructions of dams, reservoirs, and irrigation canals on streams, lead to the increase of streamflow drought severity in the region (Wu et al. 2008). Tabari and Hosseinzadeh Talaee (2011) found a significant decreasing trend for annual precipitation in the northwestern regions of Iran. The arid to semiarid climate of the basin means that agriculture is largely dependent on irrigation. The decrease in precipitation along with declining

Fig. 5 Values of the statistics Z of the Mann–Kendall test and the statistics Q_{med} of the Sen's slope estimator for the PNI series
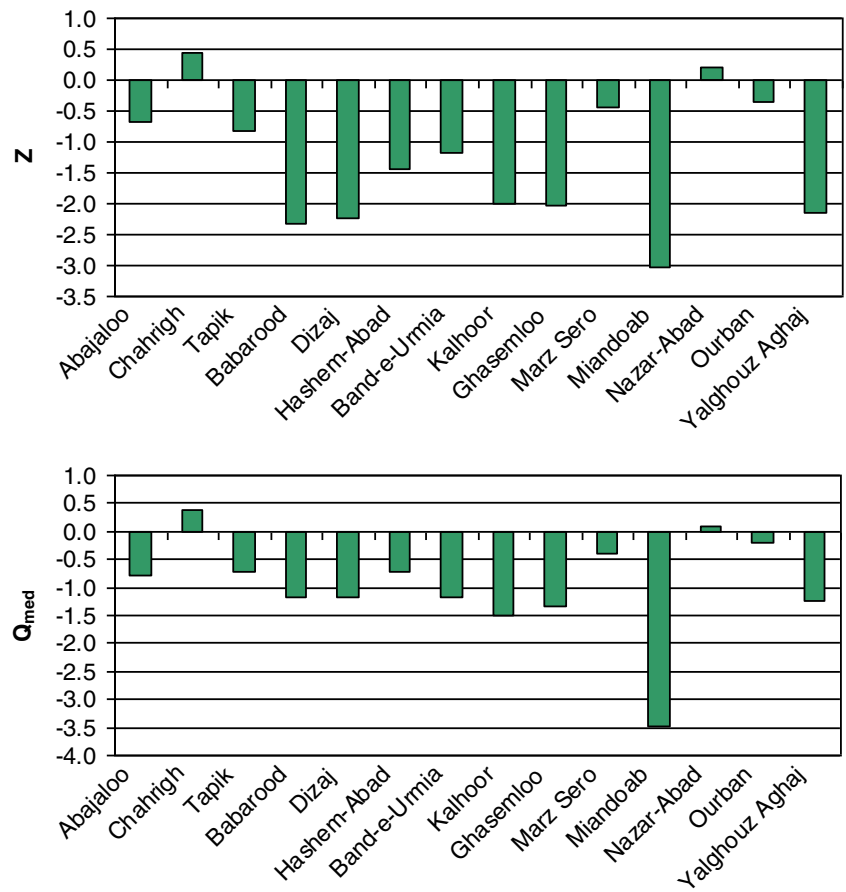
groundwater levels in this area (Wada et al. 2010; Zarghami 2011) and a growing population within the basin (SEDAC 2010) will likely exert increasing pressure to continue diverting streamflow within the basin.

There is a large body of literature for considering the effect of serial correlation on the nonparametric tests (e.g., Yue and Wang 2002; Yue et al. 2003; Khaliq et al. 2009; Tabari et al. 2011, 2012a), but the studies on the serial correlation influence on the parametric tests are very limited. Hence, the effects of serial correlation on the parametric Student's *t* test for detecting trends in the PNI series were considered in this study. The values of the slope of the linear regression and the statistics of the Student's *t* test for the original and pre-whitened PNI series are presented in Fig. 6. In all cases, the values of the statistic of the Student's *t* test decreased after eliminating the significant serial correlation from the PNI series. With decreasing of the statistic of the Student's *t* test, some of the significant trends became insignificant. For instance, the significant downward PNI trend at Yalghouz Aghaj station became insignificant after the removal of the significant lag-1 serial correlation from the time series. Similar to the nonparametric tests,

the existence of positive serial correlation increased the possibility of the parametric Student's *t* test to reject the null hypothesis of no trend while it is true. Thus, it is necessary to investigate the serial structure of the time series prior to the trend analysis by the parametric Student's *t* test.

5 Summary and conclusions

The PNI drought index was used in the present paper to assess streamflow drought conditions in the western basins of the Lake Urmia located in northwest Iran. For this purpose, the streamflow data were collected from 14 hydrometric stations for the period from 1975–1976 to 2008–2009. The extreme streamflow droughts were observed in 7 years at the Abajaloo station of the Nazloo-Chai River, the Band-e-Urmia station of the Rozeh-Chai River, the Miandoab station of the Simineh Rood River, and the Yalghouz Aghaj station of the Zola-Chai River. Almost all the stations experienced the worst streamflow droughts in 1999–2000 and 2000–2001. A significant downward trend was detected

Fig. 6 Values of the slope b of the linear regression and the statistics of the Student's *t* test for the original and pre-whitened PNI series
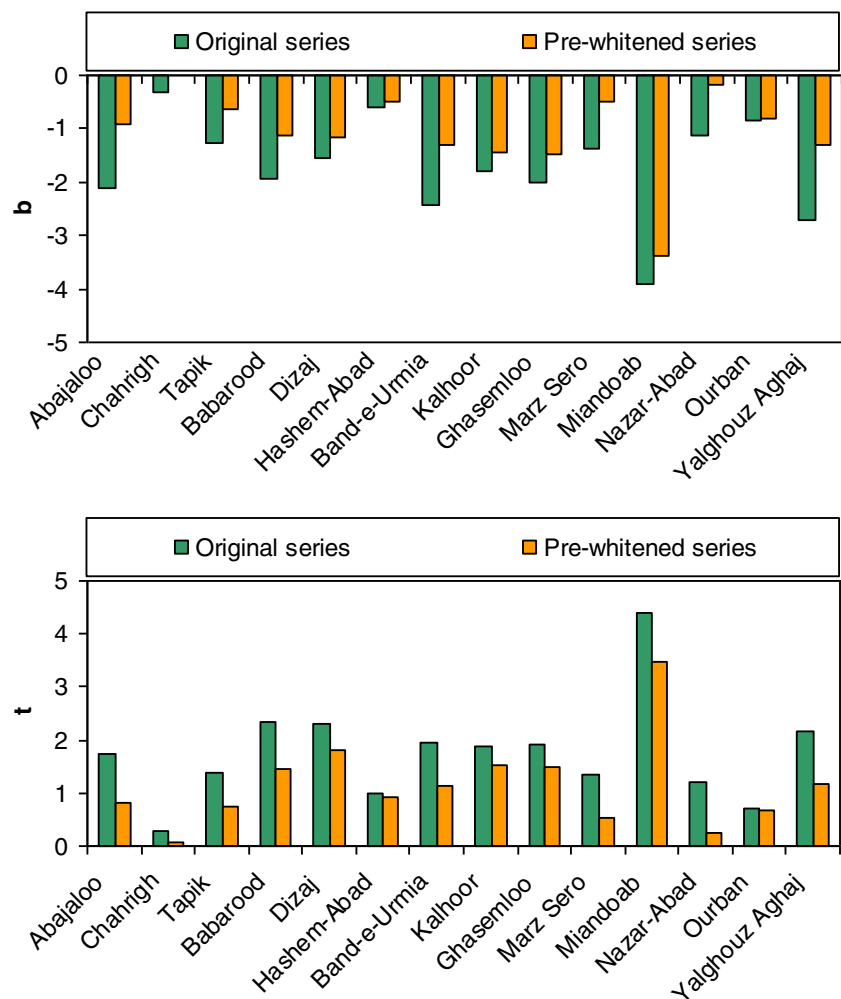
by the nonparametric tests at Babarood, Dizaj, Kalhoor, Ghasemloo, Miandoab, and Yalghouz Aghaj stations. The results also revealed that the parametric Student's *t* test is strongly affected by the serial correlation.

The findings of this study are useful for applying appropriate plans for water resources management in this region. Further studies to explain the reasons of the observed increase in streamflow drought severity are of interest for design or planning in water resources engineering. The evaluation of the other statistical indices for characterizing streamflow drought severity is recommended for further studies.

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