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Changes of extreme drought and flood events in Iran

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ABSTRACT

Located in an arid and semi-arid region of the world, Iran has experienced many extreme flood and drought events in the last and current century. The present study aims to assess the changes in Iran's flood magnitude and drought severity for 1950–2010, with some time span variation in some stations. The Mann-Kendall test for monotonic trend was first applied to assess changes in flood and drought severity data. In addition, to consider the effect of serial correlation, two Pre-Whitening Trend (PWT) tests were also applied. It was observed that the number of stations with statistically significant trends has increased after applying PWT tests. Both increasing and decreasing trends were observed for drought severity and flood magnitude in different climate regions and major basins of Iran using these tests. The increase in flood magnitude and drought severity can be attributed partly to land use changes, an annual rainfall negative trend, a maximum rainfall increasing trend, and inappropriate water resources management policies. The paper indicates a critical situation related to extreme climate change in Iran and the increasing risk of environmental changes in the 21st century.

1. Introduction

There is a globally growing interest in investigating extreme climate changes during recent decades, as the human, economic and ecological impacts of these events are large and potentially serious. The global effect of climate change on climatic variables such as precipitation (Costa and Soares, 2009; Kunkel, 2003; Norrant and Douguédroit, 2006) and temperature (Frich et al., 2002; Su et al., 2006) is evident. Caprio et al. (2009) found an increasing trend in the extreme temperature indicators of northwestern of the United States. You et al. (2008) applied 12 indices for extreme climate events in the eastern and central Tibetan plateau (TP) during 1961 to 2005 and reported increasing trends in temperature and most precipitation indices in the southern and northern TP and decreasing trends in the central TP. Aguilar et al. (2009) examined extreme temperature and precipitation in western and central Africa and found that temperature was clearly increasing and total precipitation was decreasing. Zhang et al. (2009) applied the Mann-Kendall test to detect trends in the Pearl River basin, China, and found significant increasing trends in the total precipitation and frequency of extreme precipitation intensity.

The above climate extreme indices can be placed in the first group of extremes, which are based on simple climate statistics and include very low or very high values (Easterling et al., 2000). The changes in the second group, which includes more complex event-driven extremes such as floods and droughts, have not yet been adequately investigated on a global scale. From the temporal and spatial points of view, the effects of changes in climatic variables of the first group can be observed after a long time, e.g., decades or centuries, and usually on a largely global scale, while the extreme flood and drought events happen in a limited area or region and do not last long. In addition, some regions may suffer from both flood and drought events. These bipolar extreme events can increase vulnerability and risk of extremes to human populations very rapidly in a nonlinear manner and decrease the efficiency of water resources management. Therefore, it is very critical to study the extremes in both high and low directions, especially in arid and semi-arid regions of the world (Forzieri et al., 2016; Peterson et al., 2013; Singh et al., 2014).

Relatively little work has been carried out on extreme flood and drought changes on the global scale. In southern Italy, for example, the frequency of severe drought periods has changed during the last 30 years (Piccarreta et al., 2004). Sheffield et al. (2012) demonstrated that little change has occurred in global drought over the past 60 years. Across the USA, hydrologic drought trend analysis has shown a negative trend in both drought duration and severity in the eastern regions and a positive trend in the western regions of the continental United States (Andreadis and Lettenmaier, 2006). Recent studies demonstrate changes are occurring in terms of hydro-meteorological extremes (flood, low flows, and rainfall) in Canada, and further changes can be expected in future under the impact of climate change (Burn et al., 2010, 2011; Burn and Whitfield, 2015). Wang et al. (2008) found a significant positive trend for extreme streamflow variables of the Dongjiang River basin in southern China using the Mann-Kendall test. Collins (2009) investigated the trend of flood magnitude in England

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and showed a strong evidence for an increase in flood magnitudes after 1970.

The climate change and changes in the extreme climate variables of the Middle East, including some parts of Iran, have also been investigated by some studies. For Turkey, Tayanç et al. (2009) found an increasing temperature trend and a decreasing precipitation trend. The effect of rainfall change on streamflow and groundwater was investigated by Samuels et al. (2009) in the Jordan River. Evans (2010) predicted precipitation and temperature increases for western Iran using General Circulation Models (GCMs).

In recent years, the number of studies on climate change in Iran has been growing rapidly. Looking at the changes in temperature indices such as maximum and minimum temperature reveals climate warming of the country during the last half century. An increasing trend is observed for both maximum and minimum temperature over the whole country except some small areas. The warm nights and days and warm spell duration also indicate a positive trend across almost the entire country (Nasri and Modarres, 2009; Rahimzadeh et al., 2009; Zhang et al., 2005). More recently, Raziei et al. (2014) investigated trends in rainfall indices and showed positive trend for maximum daily rainfall and negative trend of below 75th rainfall quantiles.

Flood and drought trend analyses in Iran have not been investigated thoroughly, even though their impacts have been very seriously increasing. Two examples of the extreme flood and drought events in recent years are given here to illustrate the risk of extreme flood and drought events in Iran.

On Friday, 10 August 2001, a 200-year return period flash flood occurred in Golestan province, in the northern territories, with the peak flow rate of 3017 m^3/s. This catastrophe affected more than 27,000 people, rendered 10,000 homeless, and killed 247 (United National Office of the Coordination of Humanitarian Affairs, Draft interagency Mission report: Floods in Golestan, Iran, 2001, http://ochaonline.un.org). The financial loss of this destructive flood was estimated at US$ 77.25 million. Although a heavy storm was one of the main reasons for this flood, 50% deforestation and considerable land use change in northern Iran during the last 30 years were assumed as effective factors for this disaster.

In contrast, during 1997 to 2001, a severe 40-year return period drought affected half of the country's provinces, with a loss in the agricultural sector estimated at more than US$ 10 billion (National Center for Agricultural Drought Management, http://www.ncadm.ir). Most of the major rivers and lakes of the country went completely dry during this drought period (Foltz, 2002) and a Gross Domestic Product (GDP) reduction of about 4.4% was reported (Salami et al., 2009).

The more recent severe drought period (2007–2009) devastated the country on a larger scale than the previous drought period. A US$ 19 billion loss in the agricultural division has been reported during 2006 to 2008, and a 20% average reduction of rainfall has been reported for 2008 compared with a 30-year average. The drought severity was higher in the northwestern to the southwestern territories of the country than other parts of the country in 2009 and moved towards the center of Iran (National Center for Agricultural Drought Management, http://www.ncadm.ir). In spite of these drought effects, very few studies have shown drought trend in Iran. For example, Raziei et al. (2009) and Abarghouei et al. (2011) indicated changes in Standardized Precipitation Index (SPI) as a drought index for different parts of Iran. Yet, they did not consider the fact that SPI shows both wet and dry conditions rather than drought severity.

Although the occurrence of extreme events are increased in recent decades, that does not imply they are specifically caused by climate change. Since extreme droughts and floods are occurring in different parts of Iran and resulting in extensive damages in various sectors, it is important to study the changes and reasons of these natural hazard phenomena. Therefore, the aim of this paper is to investigate flood magnitude and drought severity trends in Iran during the last half and the current century to show the direction of the changes in flood and drought risks for the 21st century in Iran. The rest of the paper is organized as follows: Sections 2 and 3 give the data and methods of study. Results are presented in Section 4 and a brief conclusion is given in Section 5. Some recommendations for future studies are given in Section 6.

2. Data

Iran is a relatively large country (1,648,195 km^2) lying between approximately 25°N and 40°N and 45°E and 65°E. It consists mainly of the Iranian plateau, which features two major folded mountain belts in the northern and western regions, Elburz and Zagros mountains, respectively. Along with these mountainous regions, which block moisture from reaching the central Iran plateau, the climate of the country is driven by both large atmospheric systems (such as subtropical high pressure) and local effects (such as proximity to the sea). These local and large physical and atmospheric factors cause a large spatial and temporal variability in climatic and hydrologic characteristics over the country.

2.1. Drought variable

The drought variable in this study is based on a standardized precipitation index (SPI) calculated using monthly rainfall data collected at 150 synoptic stations launched by the Iran Meteorological Organization (IRIMO). The recorded monthly-based precipitation time series span from 1950 to 2010. Fig. 1 shows the spatial location of the synoptic stations within different climate regions of Iran. The climate regions have been identified based on rainfall statistical characteristics and frequency distribution functions (Modarres and Sarhadi, 2011). These regions are representative of different atmospheric and local rainfall systems such as subtropical high pressure in arid and semi-arid regions (G1), proximity to the sea (G4, G6 and G8) and mountainous rainfall (G2, G3, G5 and G7).

Using the 12-month SPI time series for the synoptic stations, the drought variable is calculated for trend assessment. The drought variable in this study is drought severity calculated by applying the following equation:

$$S = -\sum_{i=1}^{D} \mathrm{SPI}_i \tag{1}$$

where drought duration, D, is the number of months with consecutive negative SPI, and drought severity, S, is then the cumulative values of SPI within the duration of a drought. For convenience, drought severity is multiplied by -1 to make a positive value. In this method, the SPI $= 0$ is selected as the threshold of a drought event.

2.2. Flood variable

The flood data used in this study include the observed annual maximum flow rate or the peak flows of 462 gauged stations on the unregulated rivers, distributed over major hydrologic divisions for the period of 1950–2010. The network of the gauging stations within the major basins used in our study is shown in Fig. 2.

The hydrographic network of Iran drains the country in different regions with different densities. It is divided into six major basins (Fig. 2). The first major basin or the Kashafrud basin drains the northeastern regions of Iran. The second one is the largest basin of Iran and drains the central arid and semi-arid region of Iran into internal basins. The third major basin drains the eastern territories of Iran into Hamoon Lake in southeastern of Iran. The fourth basin covers the north and the northwestern regions and drains into the Caspian Sea. The fifth watershed drains some parts of the northwestern regions into Urmia Lake, and the sixth watershed drains water through the western and southern

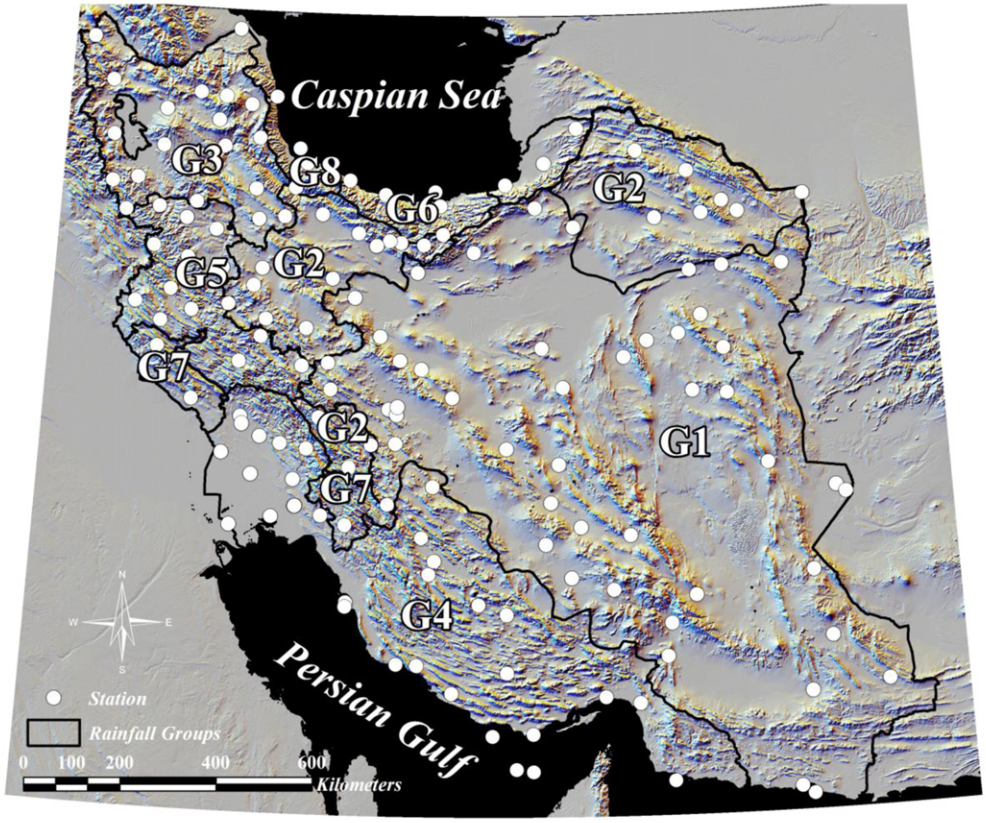

Fig. 1. Spatial distribution of synoptic stations over climate regions (G1 to G8) of Iran.

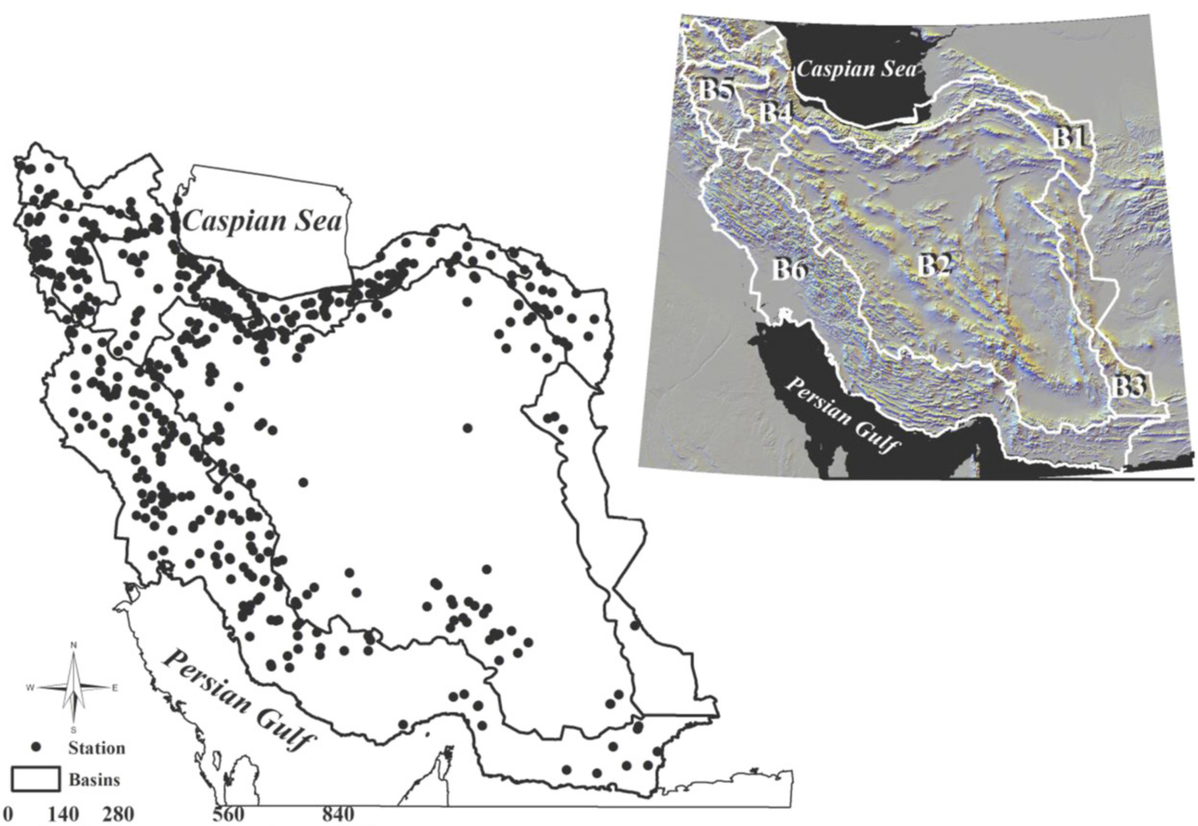

Fig. 2. Spatial distribution of a) gauging stations and b) major hydrologic basins in Iran.

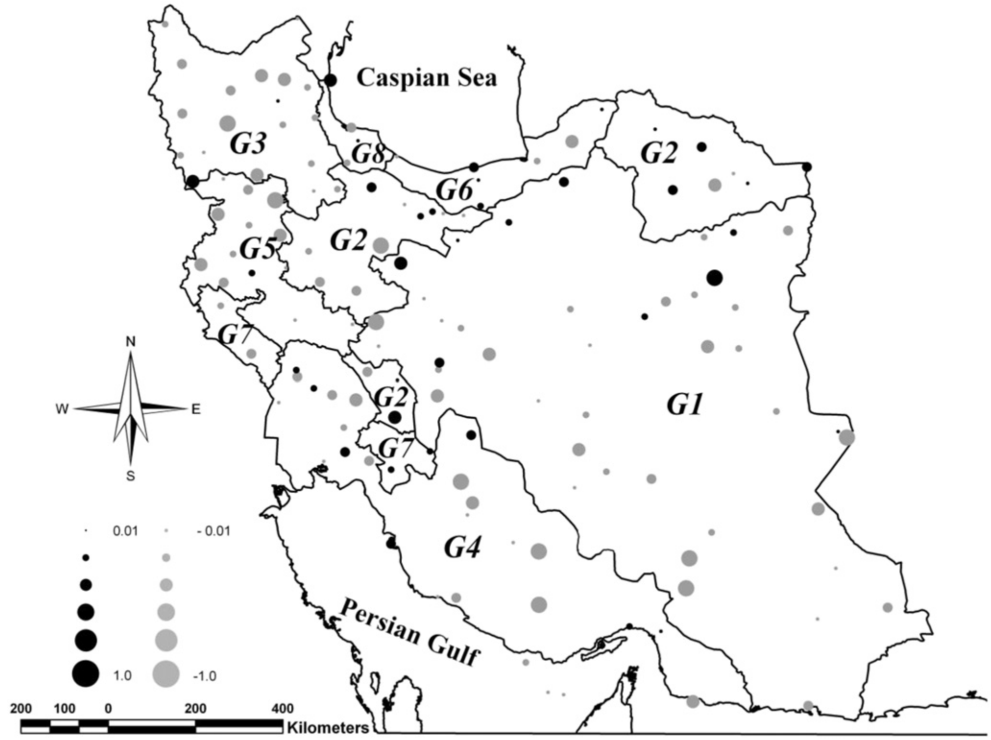

Fig. 3. Spatial pattern of Kendall's Tau for the annual rainfall at 150 synoptic sites for time period of 1950–2010. G1 to G8 show climate groups of Iran (positive trend: black circles, negative trend: gray circles).

parts of Iran into the Persian Gulf and the Sea of Oman. No major river flows into the country except the Hirmand River, which originates from Afghanistan and drains into Hamoon Lake in southeastern Iran. There are also two border rivers, Aras River in the north and Shatt-al-Arab River in the west.

Most of the streamflow depends solely on precipitation in different regions of Iran. Snowmelt is an important source of streamflow in mountainous areas. The peak floods are usually caused by rapid snowmelt and intense short rainfall events in mountainous areas with dense and steep channel networks.

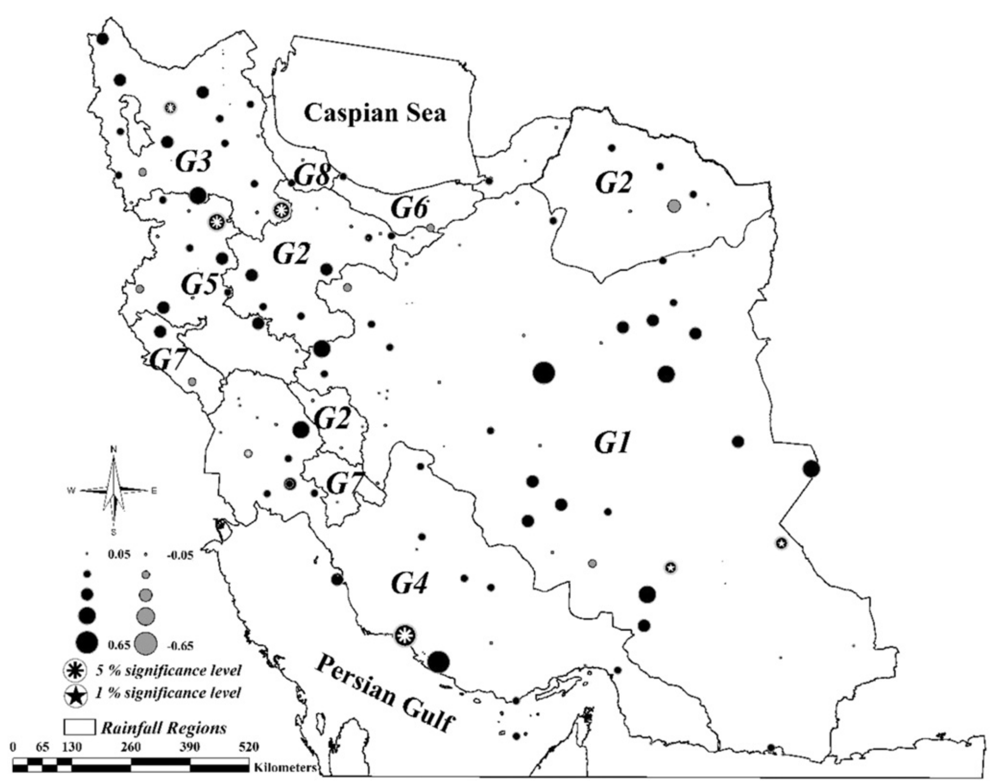

Fig. 4. Spatial pattern of Kendall's Tau statistic for drought severity at 150 synoptic sites for time period of 1950–2010.

Table 1
Correlation coefficient between rainfall and drought MK statistics.

Climate zone	G1	G2	G3	G4	G5	G6	G7	G8	Iran
Correlation coefficient	-0.53^{***}	-0.18	-0.61^{***}	0.032	-0.35	-0.16	0.005	-0.88	-0.34^{***}

*** Significant at 1% level.

3. Methodology

3.1. Mann-Kendall and pre-whitening tests

The trend assessment of flood magnitude and drought severity is applied in this study using the popular non-parametric Mann-Kendall (MK) test (Kendall, 1975; Mann, 1945). As hydro-climatic variables often exhibit autocorrelation (or serial correlation), which is believed to influence the proper identification of trend, we apply two types of pre-whitening trend techniques. The first of which was suggested by Kulkarni and Von storch (1995); Burn and Hag Elnur (2001) and Yue et al. (2002), among others, removes the first order serial correlation, Autoregressive (1) (called PWT1 hereafter). The second popular technique used to remove autocorrelation structure in the extreme time series, is presented by Zhang et al. (2000). This procedure is called PWT2 in this study. A detailed mathematical background of the Mann-Kendall and pre-whitening tests is given in Appendix A.

3.2. Sequential Mann-Kendall test for change point detection

The sequential MK test is used to detect the change point in a hydro-climatic time series. Sneyers (1991) introduced sequential values, u(t) and u'(t), from the progressive analysis of an MK test. The sequential values are standardized variables with zero mean and unit standard deviation. For the sake of brevity, the calculation of sequential values is not given here, and the interested readers are referred to Nasri and Modarres (2009).

In addition to the sequential MK test, an alternative method is also applied to perform change point detection on the study hydro-climatic variables. Using Markov Chain Monte Carlo, Erdman and Emerson (2007) provided an approximate Bayesian approach developed originally by Barry and Hartigan (1993). This algorithm is used when an unknown partition of a sequence or sequences exist(s) in continuous blocks. In this procedure, two frequentist alternatives, namely the recursive circular binary segmentation algorithm and the dynamic programming algorithm of Bai and Perron (2003) are used to estimate specific locations of change points. The Bayesian procedure offers the probability of a change point at each location in a sequence. More theoretical information about this method is presented in Barry and Hartigan (1993) and Erdman and Emerson (2007).

3.3. Regional trend assessment

3.3.1. Graphical test

The MK test is used to assess the trend of a hydro-climatic variable of a single site. To assess the regional trend, we use a quantile-quantile plot (q-q plot) of the uniform distribution of the MK test's *p*-values (Modarres and Sarhadi, 2009) for the climate regions (identified by Modarres and Sarhadi (2011)) and major hydrologic basins.

3.3.2. Nonparametric tests

The regional trend assessment is also carried out by statistical methods that compare the mean, variance and probability distribution of flood magnitude and drought severity before and after a change point determined by the sequential MK tests. Although the change

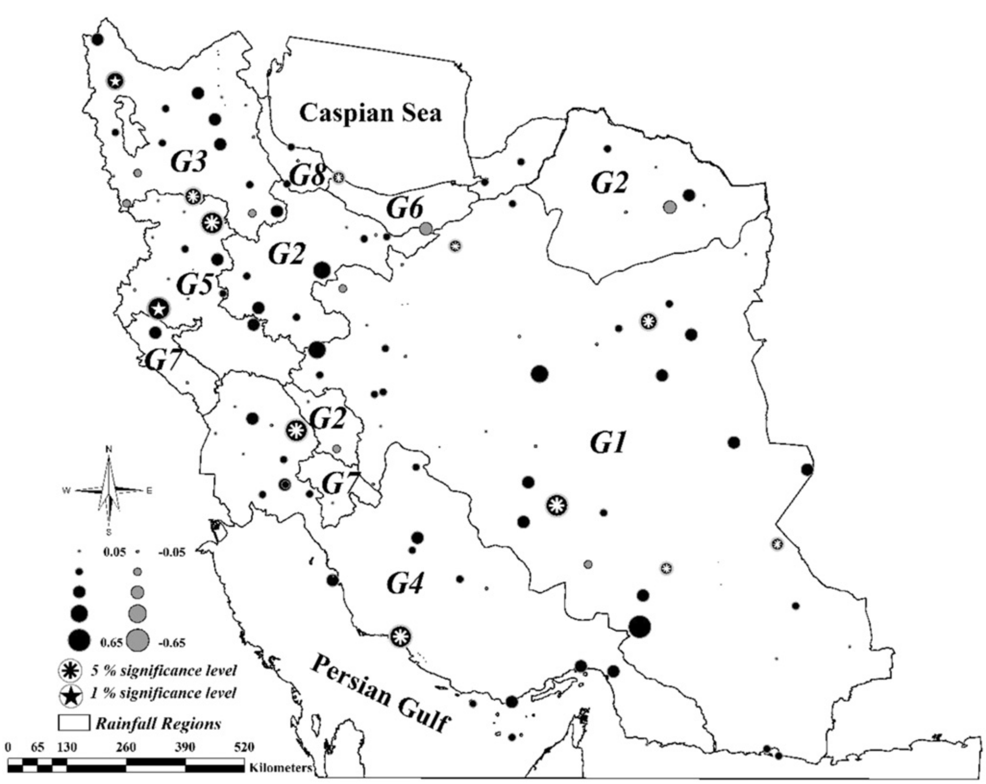

Fig. 5. Spatial pattern of PWT1-Kendall's Tau statistic for drought severity at 150 synoptic sites for time period of 1950–2010.

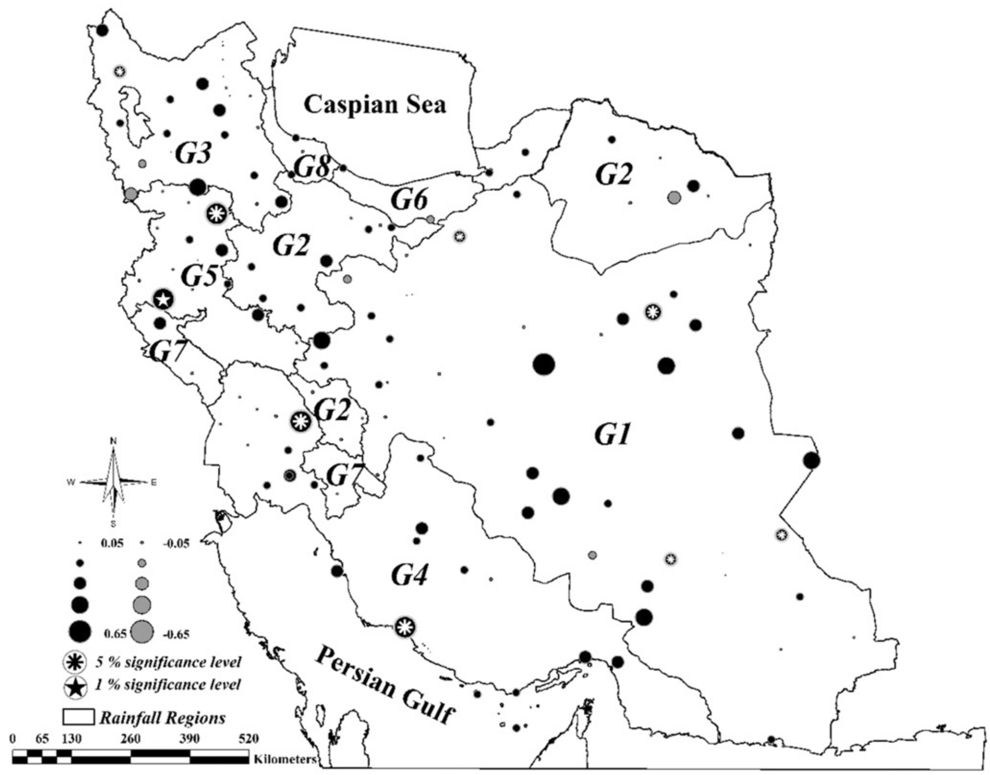

Fig. 6. Spatial pattern of PWT2-Kendall's Tau statistic for drought severity at 150 synoptic sites for time period of 1950–2010.

point is identified for a single site, the regional change point is selected based on the most frequent change point among the stations. All drought severity and flood peak observations in the climate regions and the major basins are then divided into two groups, before and after the regional detected change point. To assess flood and drought changes on a regional scale, these two groups are then compared. We then apply the following graphical test and nonparametric tests to compare the mean, variance and the cumulative distribution of the flood magnitude and drought severity before and after the change point:

- q-q plot to compare quantiles of two groups before and after the change point;
- Non-parametric Wilcoxon rank sum method to compare the difference between the means of flood magnitude and drought severity of the two groups, $\mu_1 - \mu_2$;
- Non-parametric Levene's test (Levene, 1960) to compare the equality of two population variances, $\sigma_1 = \sigma_2$;
- Non-parametric Kolmogorov-Smirnov tests for the equality of Cumulative Distribution Functions (CDFs) of two populations, $F_1(x) = F_2(x)$ for all x;

Readers interested in the details and formulations of the above tests are referred to Modarres (2009).

Table 2
Number of stations with significant trend in terms of different significance levels before and after PWT tests for drought data.

Trend test	At 5% significance level	At 1% significance level
Mann Kendall without PW	7 out of 150	2 out of 150
PWT1	12 out of 150	2 out of 150
PWT2	9 out of 150	1 out of 150

4. Results

4.1. Rainfall trend assessment

Before testing drought and flood trends, we give a brief description of rainfall trends in Iran. Rainfall variation is generally used as an indicator of climate change. A great number of research papers on rainfall trend analysis have been published. It has recently been indicated that more extreme precipitation events have been occurring globally, especially in mid and high-latitude regions (IPCC, 2007). There are some studies of rainfall trends in Iran during recent years. For example, the annual and monthly trend analysis in arid and semi-arid regions of

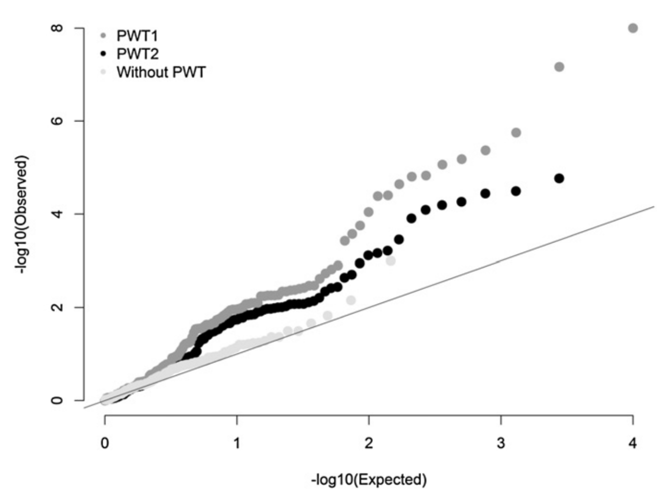

Fig. 7. Quantile-quantile plot of uniform distribution of MK p-values of drought severity data at 150 synoptic sites for time period of 1950–2010.

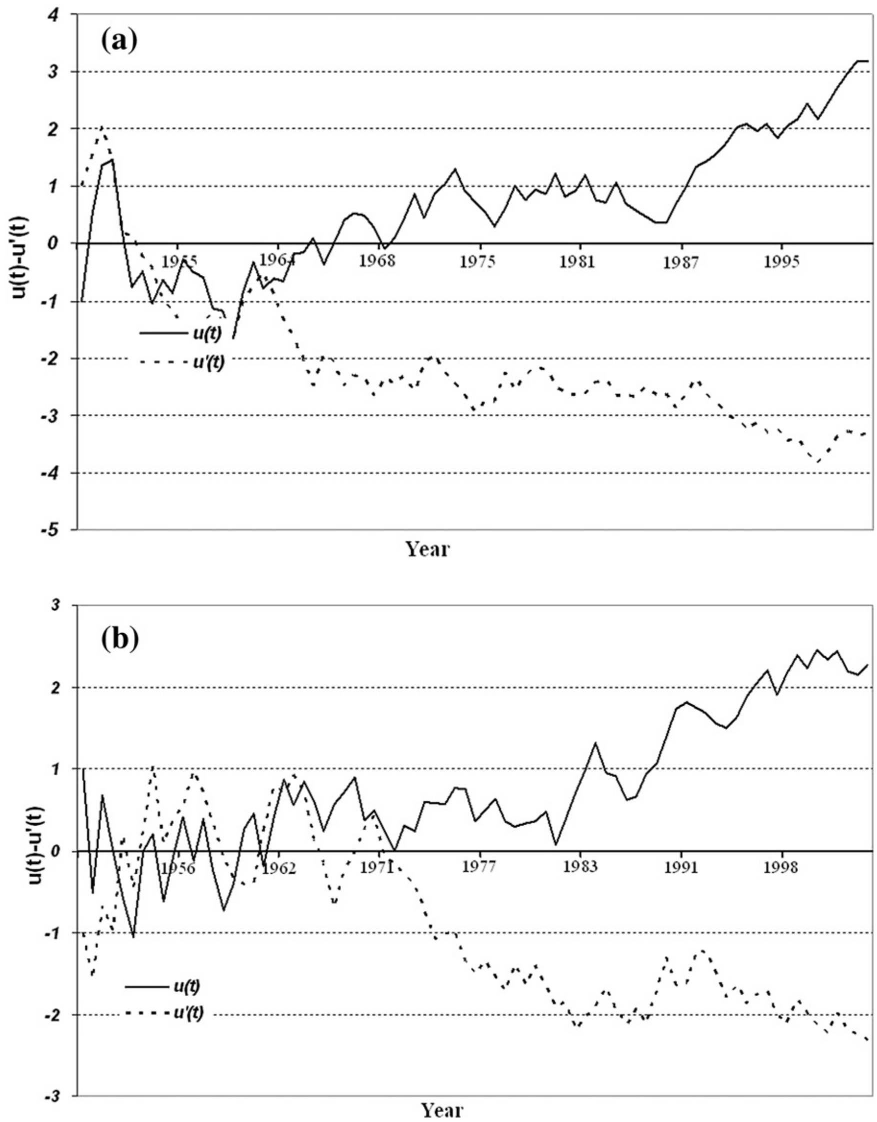

Fig. 8. Sequential values from MK test for drought severity for a) Zahedan and b) Tabriz stations.

Iran indicated significant winter and spring trends (Modarres and da Silva, 2007). While both upward and downward trends were indicated, the decreasing trends were more remarkable. On a national scale, another recent study has indicated a negative trend for annual rainfall for most of the stations in Iran (Modarres and Sarhadi, 2009). The spatial pattern of the MK's Tau statistic illustrated in Fig. 3 indicates

Table 3
Descriptive statistics of drought severity before and after 1985.

Regions	Time period	Mean	Standard deviation	Maximum	Coefficient of skewness	Coefficient of kurtosis
G1	Before 1985	2.19	2.9	23	2.75	10.6
	After 1985	2.36	2.84	22	2.09	5.27
G2	Before 1985	3.13	3.97	30	2.96	14.25
	After 1985	2.9	3.2	16	1.59	2.11
G3	Before 1985	2.8	4.11	32	3.62	19.29
	After 1985	3.52	3.52	26	1.7	3.5
G4	Before 1985	2.2	2.69	14	1.9	2.21
	After 1985	2.08	2.51	21	2.21	7.22
G5	Before 1985	2.43	2.81	13	1.49	1.9
	After 1985	2.6	3.36	23	2.35	7.14
G6	Before 1985	2.54	5.67	61	8.38	84.82
	After 1985	2.84	3.01	18	1.57	2.94
G7	Before 1985	2.02	2.25	9	1.74	2.84
	After 1985	2.7	3.07	12	1.63	2.14
G8	Before 1985	2.93	3.21	15	1.87	3.61
	After 1985	3.13	2.81	14	1.22	1.48
Iran	Before 1985	2.47	3.53	61	5.48	65.78
	After 1985	2.61	3.08	26	2	5.1

the significant negative annual rainfall trend in the northwestern and western regions of Iran. This picture of negative rainfall trends in Iran during the last half century should be cautiously considered for 21st-century water resources management and agricultural strategies for the country. The change in growing season for example, may change the cropping strategy or the crop types (Evans, 2009) in the northwest.

4.2. Drought trend assessment

A drought severity time series of the synoptic stations is used to evaluate drought trends in Iran. The spatial pattern of the Mann-Kendall's Tau statistic for drought severity is given in Fig. 4. Both increasing and decreasing trends are observed for drought severity over the country. Most of the significant positive trends are seen in the G1 and G3 climate groups.

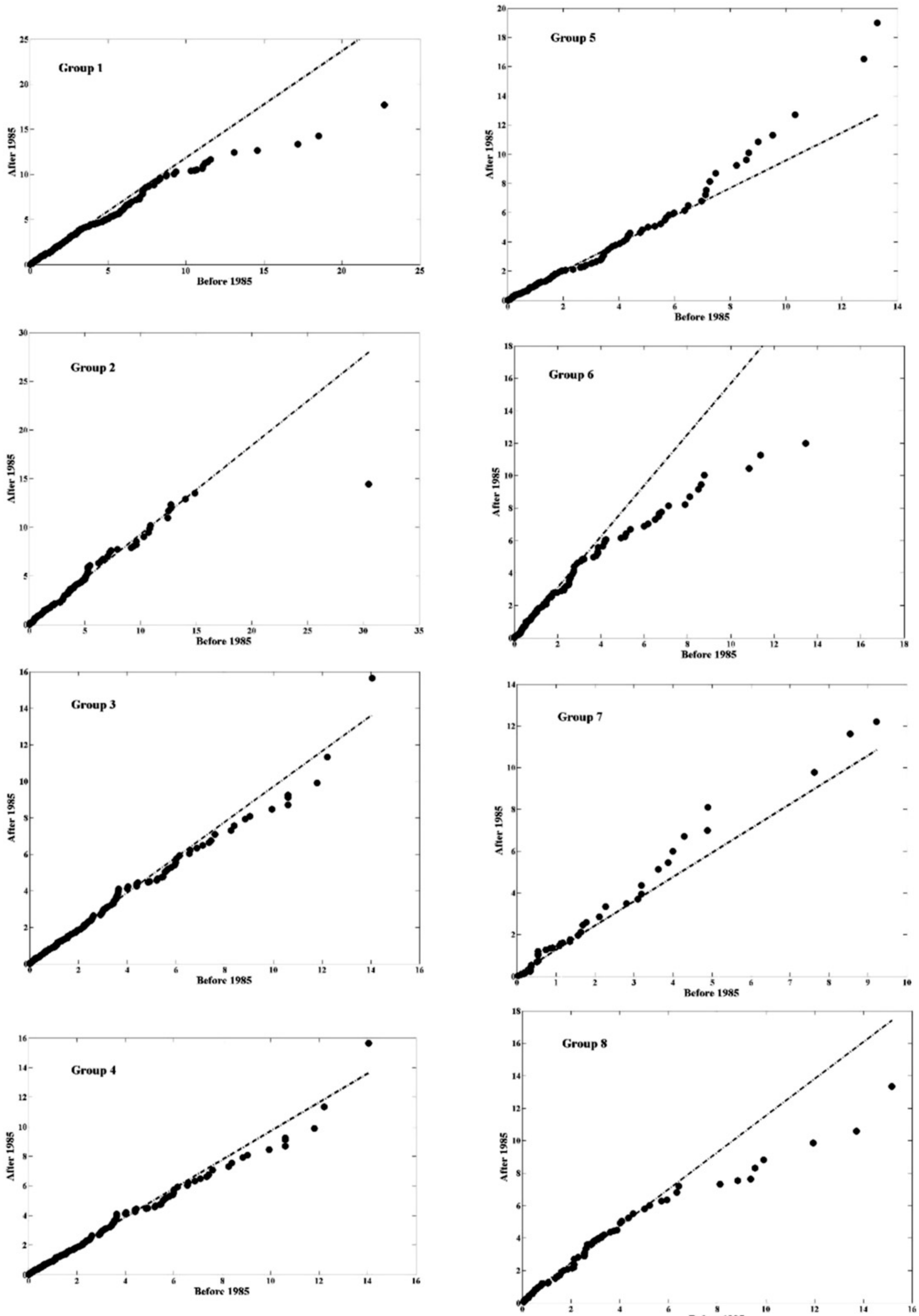

Fig. 9. Q-Q plots of drought severity of the climate groups of Iran for the periods before and after 1985 (for time period of 1950–2010).

Table 4
p-Values of non-parametric comparison of drought severity before and after 1985.

Test	G1	G2	G3	G4	G5	G6	G7	G8	Iran
Wilcoxon	0.08	0.96	0.03**	0.84	0.97	0.02**	0.47	0.22	0.01***
Levene	0.46	0.19	0.14	0.3	0.51	0.67	0.1	0.89	0.54
K-S	0.28	0.77	0.04**	0.95	0.96	0.07	0.6	0.07	0.02**

*** Significant at 1% level.
** Significant at 5% level.

To check the consistency of rainfall and drought trends for the entire country and the climate regions, the correlation coefficients between rainfall and drought Kendall's statistics for all stations in each climate group are given in Table 1. This table indicates a significant relationship between decreasing rainfall and increasing drought severity for the entire country. It suggests that the rainfall reduction could be a significant factor in drought severity increasing across the country. It can also be seen in Figs. 3 and 4 that the number of stations with "negative rainfall's Kendall's statistics" and "positive drought's Kendall's Tau" is higher than other stations. The correlation between rainfall reduction and drought severity increase is also significant for groups G1 and G3, which cover arid and semi-arid central and northwestern regions, respectively.

It is important to note that arid and semi-arid regions have high sensitivity to drought events. In other words, the same changes in drought severity have more impacts and consequences in arid regions than humid regions. The arid region of Iran (G1 group) covers 13 out of 28 provinces and includes two major capital cities, Isfahan and Shiraz, and many other big cities and population centers such as Kerman, Yazd and Zahedan cities in the central and the southeastern territories. Critical water scarcity is predicted for this region in the current century, according to the observed increasing trend of drought severity.

In order to take into account the effect of serial correlation on the significance of MK test, two PWT procedures are applied and their statistics for selected stations are shown in Figs. 5 and 6 for drought time series using PWT1 and PWT2, respectively. At first glance, one can see a good agreement between the results of the MK and PWT1 and PWT2 outputs, regarding the MK (positive or negative) sign. There are some stations for which the significant level of the MK statistics has changed and is also different between two the PWT procedures. The number of stations with different significance level is presented in Table 2 for drought time series. It is seen that the number of stations with 5% significant level has increased after employing the PWT tests while the number of stations at 1% significance level does not show a remarkable change.

To evaluate whether drought severity shows a significant regional trend, the q-q plot of the uniform distribution for *p*-values of the MK tests for the entire country is given in Fig. 7. The departure of observed *p*-values for MK's statistics from linearity is not strong, and we cannot reject the null hypothesis of no regional drought severity trend for the entire country. For the PWT results, however, the departure is significant and the regional change of drought seems to be significant.

The regional drought trend results are consistent with the regional annual rainfall trend analysis for the climate groups and the entire country (Modarres and Sarhadi, 2009) and also Table 2.

To find the change point of drought severity based on the sequential MK test, two examples among the stations with a significant trend in drought severity, Zahedan station in the southeastern of Iran and Tabriz station in the northwestern of the country, are given in Fig. 8. For Zahedan station, this figure demonstrates the divergence between u(t) and u′(t) during both the 1960s and 1980s. The u(t) and u′(t) lines remain almost parallel after 1960 and begin a clear divergence during the 1980s. The same condition can be seen for the Tabriz station during the 1970s and 1980s. The rainfall analysis of these two stations shows the divergence in the 1970s (Modarres and Sarhadi, 2009). This almost 10-year lag time between drought and rainfall change, for these two stations, is not a new phenomenon in hydrology and climate science, but is the first time reported for Iran.

Analyzing the sequential MK test for stations with significant drought severity trends shows that a clear divergence between u(t) and u′(t) usually happens within the 1980s. Therefore, we select the

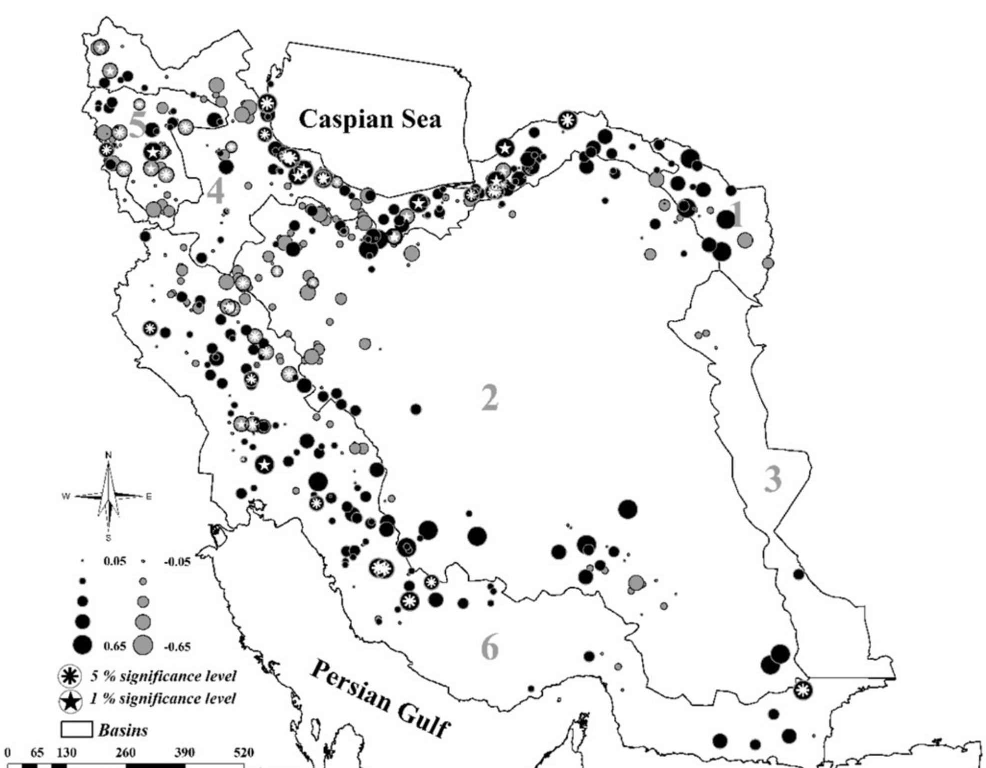

Fig. 10. Spatial pattern of Kendall's Tau statistics for the flood magnitudes of 462 gauged stations spanning 1950–2010 within major hydrologic basins.

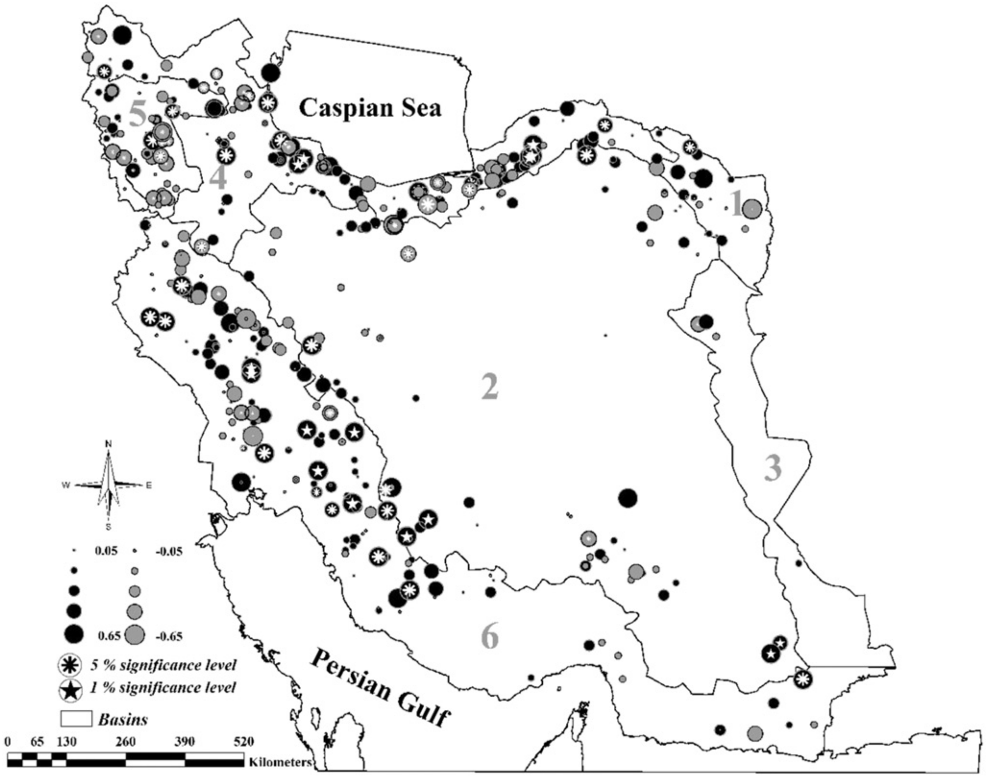

Fig. 11. Spatial pattern of PWT1-Kendall's Tau statistic for flood magnitudes of 462 gauged stations spanning from 1950 to 2010 within major hydrologic basins.

1980s (typically 1985) as the changing point for drought severity on the regional scale because the divergence between u(t) and u′(t) is more frequent and significant during 1980s and keeps diverting afterwards.

The nonparametric tests are then applied to investigate the difference between the statistical characteristics of drought severity before and after 1985. The descriptive statistics of drought severity are given

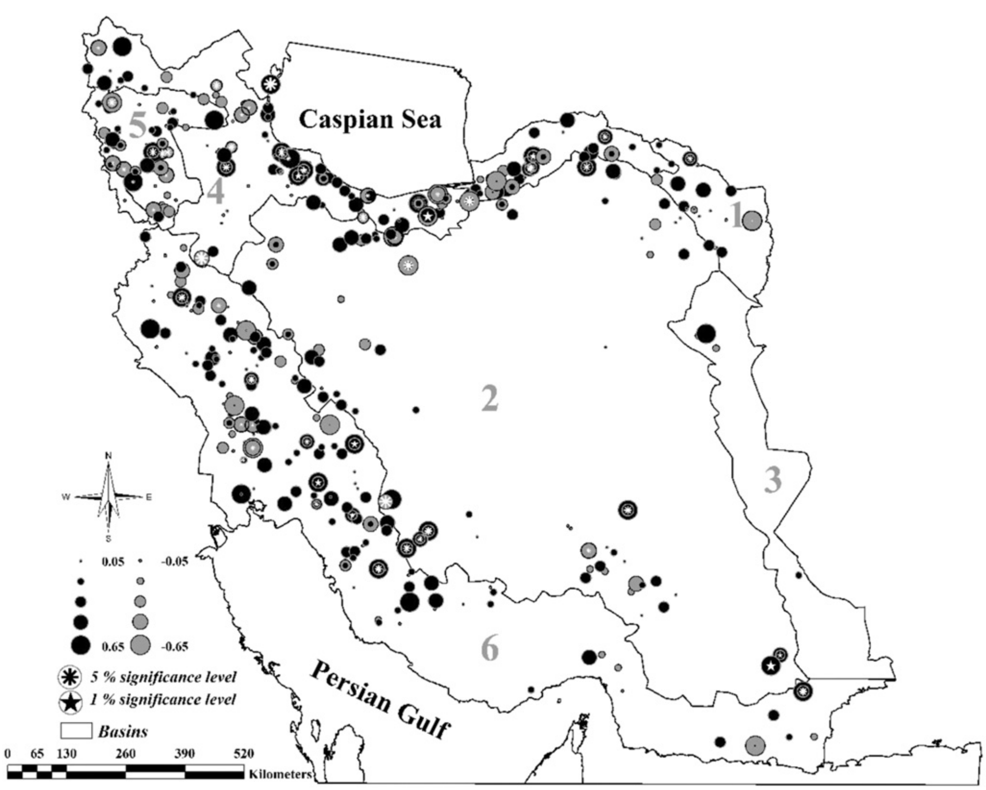

Fig. 12. Spatial pattern of PWT2-Kendall's Tau statistic for flood magnitudes of 462 gauged stations spanning from 1950 to 2010 within major hydrologic basins.

in Table 3 for different climate regions as well as the entire country. It is clear that the average drought severity before and after 1985 does not differ markedly for the climate regions, while the maximum drought severity differs considerably for the G2, G4, G5 and G6 regions. The difference between maximum severities also influences the skewness and the kurtosis of drought severity. The coefficients of the skewness and kurtosis of random observations, such as drought severity, are representative for their frequency distribution functions. The change in statistical moments of drought probability function may indicate a change in the probability of drought occurrence after 1985 or the existence of large values of drought severity after 1985.

An easy way to support one of these hypotheses is drawing the q-q plot, which shows the quantiles of the first dataset, drought severity before 1985) against the quantiles of the second dataset, drought severity after 1985. If the two datasets have the same distribution function, the points should fall approximately along the 45-degree reference line. The greater the departure from the reference line, the greater the evidence that the two datasets have different distribution functions (Wang et al., 2008). The q-q plots of drought severity for each group, before and after 1985, are given in Fig. 9. The upper tail of quantile function of drought severity departs from the 45-degree reference line for most of the regions, but the change in lower parts (quantiles) is not significant. In other words, the probability of severe (extreme) drought events that have more destructive consequences on water and environmental resources shows more changes than the usual, more frequent drought conditions that happen over the country. In other words, the q-q plots support the hypothesis that more extreme drought events have occurred after 1985, which make substantial change in higher statistical moments such as skewness and kurtosis coefficients (see Table 3).

These q-q-plots show no drought severity change in groups G2, G3 and G4, a decrease in drought severity in G1, G6 and G8 and an increase in groups G5 and G7. The insignificant changes in low quantiles neutralize the change in high quantiles, and therefore, the K-S goodness-of-fit test of the *p*-values of the MK test statistics does not reject the null hypothesis of no change of drought severity. We follow the q-q plots by non-parametric tests to verify these results. The results of non-parametric test comparing drought severity before and after 1985 are given in Table 4.

The Wilcoxon test shows that the change in the mean of drought severity is only significant for G3 and G6 groups at a 5% significance level, for G1 group at 10% significance level (a weak change) and for the entire country at 1% significance level. However, the change in standard deviation is not significant. In other words, there is no significant difference between drought severity variation around the mean before and after 1985. It is also clear that the frequency distribution of drought severity has not changed after 1985, except G3 region and the entire country at a 5% significance level. Two weak changes of distribution function at a 10% significance level are also observed for the G6 and G8 groups.

4.3. Flood trend assessment

For flood trend analysis in Iran, we first consider the MK test without pre-whitening analysis for the selected stations. Fig. 10 shows the MK test statistics for the annual flood peaks, with an increasing trend for most of the stations in the northern, northeastern, southeastern and southwestern regions and a negative trend in the northwestern territories. Comparing the rainfall and flood trend maps demonstrates that the spatial pattern of annual and maximum daily rainfall trend (Modarres and Sarhadi, 2009) is not consistent with the spatial pattern of flood magnitude trend, except the northwestern Iran.

The spatial pattern of the MK statistics after pre-whitening is illustrated in Figs. 11 and 12. One can see a good agreement in sign between the MK test with and without pre-whitening. Table 5 reveals that the number of locations showing significant flood trend is increased after removing autocorrelation structure in the extreme flow time series.

Table 5
Number of stations with significant trend in terms of different significance levels before and after PWT tests for peak floods.

Trend test	At 5% significance level	At 1% significance level
Mann Kendall without PW	55 out of 462	18 out of 462
PWT1	65 out of 462	26 out of 462
PWT2	57 out of 462	17 out of 462

The coastal regions along the Caspian Sea and the northern slopes of the Alborz Mountains covered by natural forests, have encountered intense land use changes in the last decades. A recent study (Saghafian et al., 2008) in the eastern side of the coastal regions, the Golestan Watershed in Golestan province, demonstrated a 13.2% increase in agricultural lands and decrease in forest lands during 1967–1996 and indicates a 23% increase of peak floods according to the land use change. Many flood events have occurred in the north of Iran in the last decades, among which the 2001 flood was the most destructive one as explained above. According to experts, official and unofficial reports, land use change is the major factor with respect to increasing flood magnitude in the north of Iran, as well as the entire country. However, very few valid reports and studies have taken this assumption into account. The negative trend of flood peak, and therefore mean annual streamflow, in the northwestern regions may be the result of rainfall reduction during the last decades (Modarres and Sarhadi, 2009). However, this statement needs more careful and detailed studies in the future.

The regional trend analysis of flood magnitude is applied by drawing a q-q plot of the uniform distribution fitted to the *p*-values of the MK tests (Fig. 13). The results of the K-S testing for the uniform distribution (not shown here) show that the null hypothesis of no regional trend is not rejected for B1 and B3 major basins, whereas other major basins as well as the entire country show a significant departure from the uniform distribution. These results indicate the existence of a significant regional flood magnitude trend for most of the major hydrologic basins and the entire country.

The sequential MK tests are checked for the stations with significant flood trends to determine change point of flood magnitude. One station is selected for each hydrologic basin to illustrate the sequential MK test (Fig. 14). The change point of the annual flood peak, where u(t) and u′(t) begin to diverge, is roughly observed during the 1980s (typically 1985). The industrial development during the 1970s and the population growth and intense pressure on natural rangelands and forests, overgrazing, rangeland degradation and deforestation, especially in the central arid and semi-arid regions, can be considered as major factors on runoff and flood changes on a national scale.

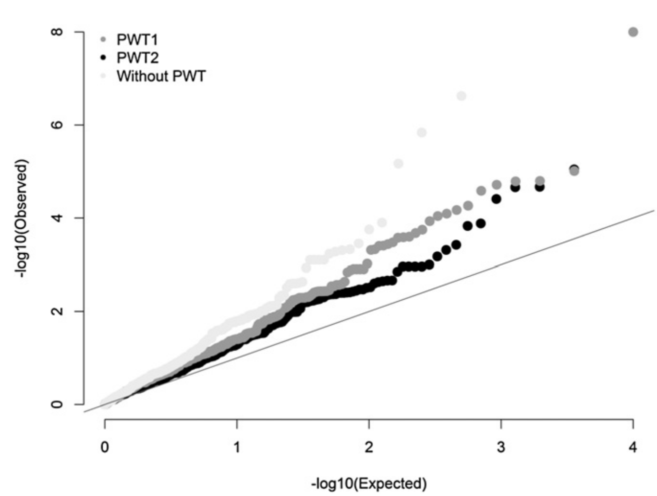

Fig. 13. Quantile-quantile plot of uniform distribution of MK *p*-values of flood magnitude data at 462 gauged stations spanning from 1950 to 2010.

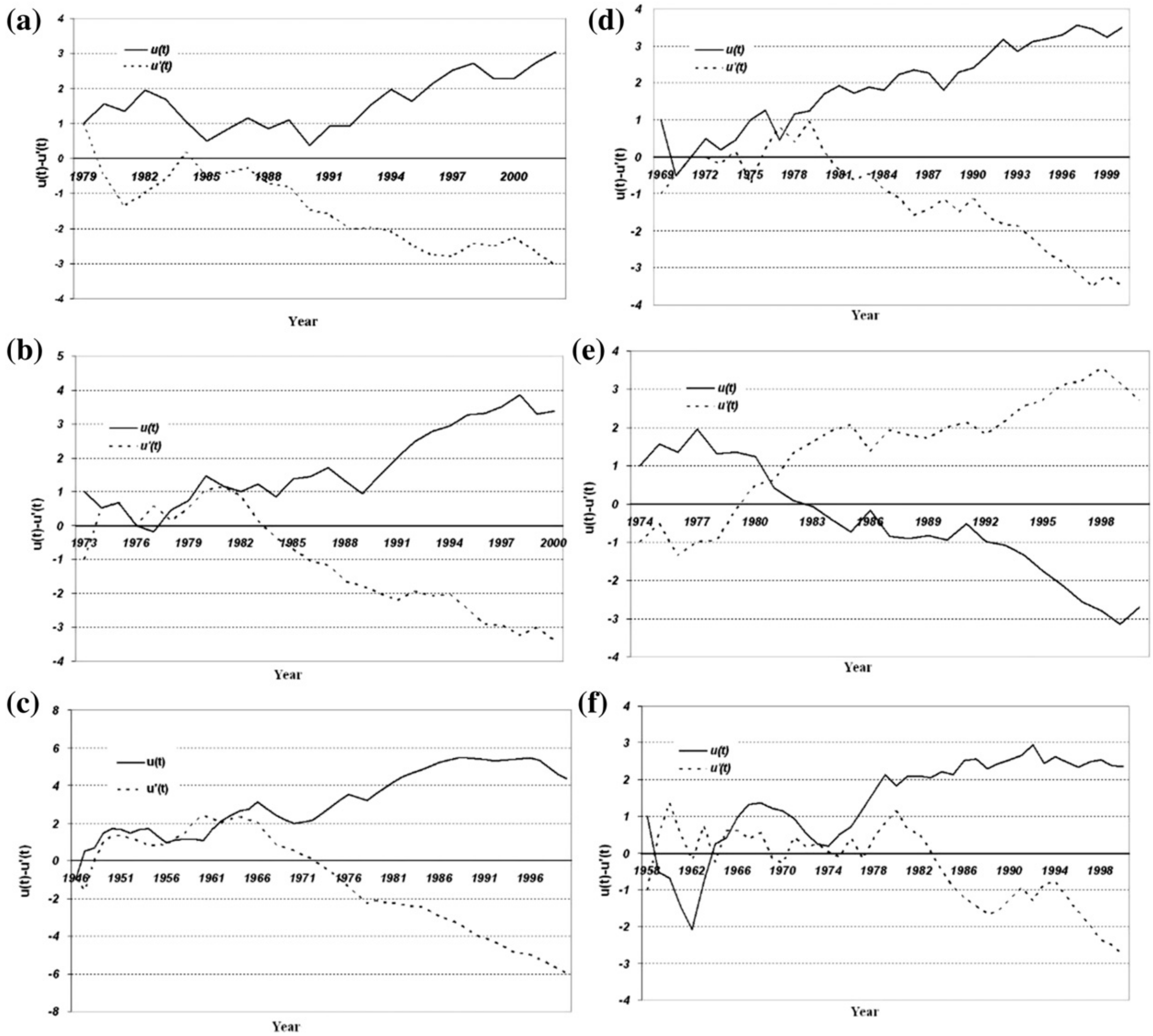

Fig. 14. Sequential values from MK test for flood magnitude for one typical station in major basins (B1 to B6), a) Hatam, b) Goldar, c) Ladiz, d) Poonel, e) Ghabghab, f) Kahir.

On the regional scale, comparison of flood characteristics before and after 1985 is also carried out. The descriptive statistics for all flood observations in each major basin are given in Table 6. This table shows an increase in almost all flood statistical parameters, such as the mean and the higher statistical moments for the major basins as well as the entire country after 1985. The change in skewness and kurtosis coefficients could be an indicator of the change in flood distribution after 1985. In other words, the frequency of extreme flood occurrence has changed, and more extreme events are usually observed after 1985. Due to the intense deforestation and forest and rangeland degradation in many areas of Iran, one of the main reason for increasing flood magnitude or the increasing frequency of extreme flood events is considered to be land use changes over the country in recent decades. In addition to the land use changes, the trend of rainfall intensity, which may

Table 6
Descriptive statistics of drought severity before and after 1985.

Regions	Time period	Mean (m^3/s)	Standard Deviation (m^3/s)	Maximum (m^3/s)	Coefficient of skewness	Coefficient of kurtosis
B1	Before 1985	89.22	130.56	625.0	2.14	4.48
	After 1985	77.51	142.8	1293.0	5.35	36.32
B2	Before 1985	103.7	234.0	2060.0	4.96	30.44
	After 1985	119.3	269.97	3960.0	6.4	59.59
B3	Before 1985	92.34	122.0	355.2	1.44	1.70
	After 1985	43.78	60.35	250.0	1.98	3.32
B4	Before 1985	161.30	318.77	3398.0	4.35	25.06
	After 1985	154.61	374.27	5004.0	6.47	54.19
B5	Before 1985	95.46	198.35	3620.0	10.64	168.03
	After 1985	96.88	191.79	1380.0	4.94	28.14
B6	Before 1985	612.26	947.95	7796.0	2.74	9.39
	After 1985	609.65	1069.86	11,284.0	3.47	16.65
Iran	Before 1985	312.38	667.90	7796.0	4.24	23.39
	After 1985	299.52	723.85	11,284.0	5.32	39.79

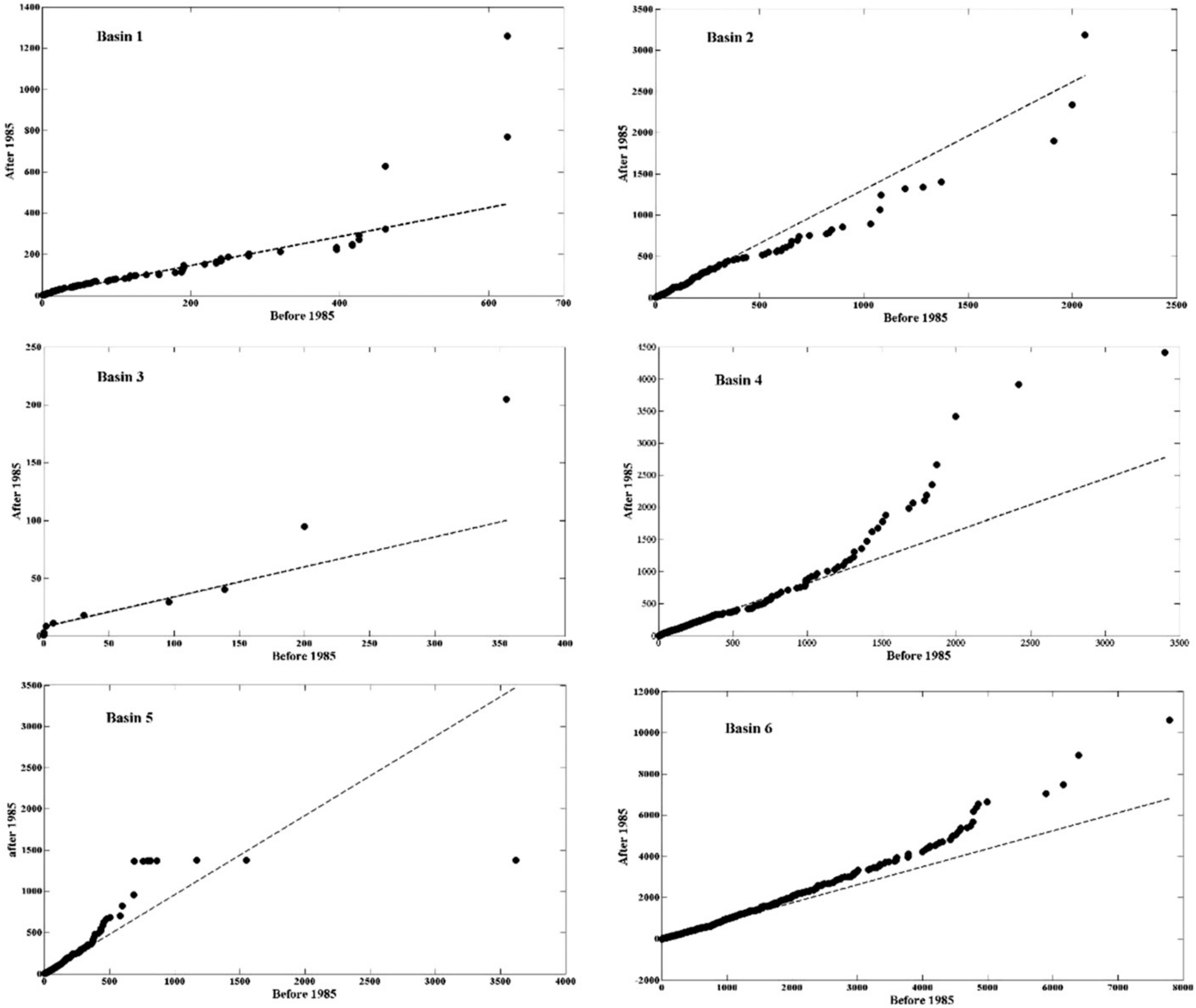

Fig. 15. Q-Q plots of flood peaks of Iran for the periods before and after 1985 at 462 gauged stations spanning from 1950 to 2010.

influence flood magnitudes, should also be investigated in different basins of the country.

The change in flood magnitude can also be investigated by plotting flood quantiles before and after 1985 against each other. The q-q plots of flood magnitudes are given in Fig. 15. The significant departure from linearity is obvious for flood peaks in most hydrologic basins after 1985, except B2 basin. The changes are evident for extreme high flood peaks (high quantiles) and may be the main reason for significant changes in the descriptive statistics of flood peaks after 1985. In other words, the flood high quantiles have increased after 1985, while the low quantiles seem to remain unchanged after 1985. This implies the increase of flood risk consequences after 1985 in most of the hydrologic basins.

The results of non-parametric tests to check changes in the mean, standard deviation and frequency distribution of flood magnitude after 1985 are presented in Table 7. The results indicate significant changes of the mean, standard deviation, and the probability distribution of flood peak magnitude for most of the basins and the entire country. It is important to note the significant changes in all the statistical characteristics, i.e. mean, standard deviation, and the probability, of flood peaks after 1985 for the entire country. According to the above analyses, the changes in the probability of flood occurrence and the increase of flood magnitude, especially in high extreme quantiles are evident in the most parts of Iran. If these upward trends continue in the 21st century, one would expect higher flood risks and adverse consequences arising in the different regions of the country.

Table 7
p-Values of non-parametric comparison of flood magnitude before and after 1985.

Test	B1	B2	B3	B4	B5	B6	Iran
Wilcoxon	0.415	0.257	0.057**	0.666	0.884	0.074**	0.002***
Levene	0.10	0.227	0.003***	0.641	0.278	0.198	0.001***
K-S	0.322	0.048**	0.554	0.254	0.066**	0.010***	0.006***

*** Significant at 1% level.
** Significant at 5% level.

5. Discussion and conclusion

This study deals with trends in drought severity and flood magnitude between 1950 and 2010 in Iran. According to the results obtained from different trend assessment methods before and after considering serial correlation, it can be concluded that drought severity in Iran shows a monotonic change in different climate regions. Most of the changes are observed as changes in extreme drought events.

The trend in rainfall shows a relationship with trends in drought severity on a local scale, but on the regional scale, there is no evidence to conclude that the decreasing rainfall trend is the only factor contributing to increased severe drought events, at least for the selected dataset. Other local or regional factors related to rainfall reduction may cause changes in drought severity. These factors, including anthropogenic activities and temperature rising, should be investigated in future studies.

The change in flood magnitude, especially high quantiles, shows a significant increasing trend in most hydrologic basins and national scale. One can expect that the hazard and risk of the extreme flood events over Iran are rapidly and exponentially increasing based on the obtained results of this study. For most of the climate and hydrologic regions of Iran, an increasing trend of flood magnitude was observed for both the PWT tests and the common MK test. The change is usually observed in extreme flood events (those with low probability or high return periods of occurrence), which have higher risks than low return period-flood events. The land use changes in most parts of the country, reported officially and unofficially, may intensify the flood hazard in the 21st century. Consequently, more people may suffer from flash flood hazards on a larger and more harmful scale than those during the last decades.

The effects of rainfall reduction and temperature rise, flood magnitude aggravation, and drought severity changes can be intensified by man-made impacts. The anthropogenic influences may include growing population, unsustainable exploitation of water resources, inappropriate policies in water consuming sectors (specifically economical reliance on agriculture sector), large dam constructions, environmental and ecosystem degradation, soil and water pollution, deforestation and biodiversity reduction, soil and water erosion, and desertification and dust storm hazards (which are not mentioned in this paper but are informed in official and unofficial scientific and media reports as current man-made destructive elements). This study demonstrates an ongoing and future critical situation for the country in terms of extreme hydro-climatic phenomena. Therefore, it is of crucial importance to water resources authorities in Iran to act immediately and follow practical and effective strategies in terms of water resources management. By following integrated long-term development polices for the country's water resources, water managers will be able to mitigate adverse consequences of current and future water crisis arising from extreme hydro-climatic disasters.

6. Future studies

Climate change and its impacts on Iran's hydrology and water resources have not been thoroughly investigated. The spatial and temporal correlation between different hydrologic and climatic variables and its impacts on trend assessment is still unknown. The use of new techniques in multivariate trend assessment is strongly recommended to study multi-dimensional aspects of the hydro-climatic phenomena in future work. It would also be interesting to apply downscaling and regional climate models to predict climate change impacts on extreme drought and flood events in Iran. Future studies could also focus on local and regional hydrologic responses due to land use change and its interaction with climate change. The change in probability of extreme events occurrence under the impact of climate change would be another interesting research idea for future works.

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Appendix A*A.1. Mann-Kendall test for monotonic trends*

For a sample of size n, x_1, …, x_n, and the null hypothesis that the sample is independent and identically distributed, the alternative hypothesis of a two-sided test is that the distribution of x_i and x_j are not identical. The MK test statistic is therefore written as:

$$S=\sum_{i=1}^{n}\sum_{j=1}^{i-1} sign(x_1-x_j) \tag{A1}$$

The mean and the variance of S is given as follows:

$$\mathrm{E}[\mathrm{S}]=0 \tag{A2}$$

$$\mathrm{var}[S]=\frac{n(n-1)(2n+5)-\sum_{p}^{q} t_p(t_p-1)(2t_p+5)}{18} \tag{A3}$$

where t_p is the number of ties for the pth value and q is the number for tied values. The standardized test statistic (Z_{MK}) is computed by:

$$Z_{MK}=\begin{cases}\frac{S-1}{\sqrt{Var(s)}} & S>0\\ 0 & S=0\\ \frac{S+1}{\sqrt{Var(s)}} & S<0\end{cases} \tag{A4}$$

A positive Z_{MK} indicates an increasing trend while a negative Z_{MK} shows a negative trend.

A.2. Pre-whitening trend tests

In the PWT1 method based on Yue et al. (2002), the first order serial correlation, Autoregressive (1) is removed from time series by the following equation:

$$Y_t=X_t-r_1X_{t-1} \tag{A5}$$

where X_t is the observation at time step t,X_{t-1} is the observation at $t-1$ time step and r_1 is the $lag-1$correlation coefficient. The new time series, Y_t, is then considered for trend assessment.

Another popular approach is presented by Zhang et al. (2000). Suppose that we have a time series, X_t with the following three components:

$$X_t=\mu-T_t+\vartheta_t \tag{A6}$$

where μ is a constant term, T_t is a trend and ϑ_t is the noise at time t. Zhang et al. (2000) rewrote the above equation considering a linear trend and an AR(1) process in the noise:

$$X_t=\mu+\beta_t+\varphi X_{t-1}+\varepsilon_t \tag{A7}$$

This new equation is then considered for trend assessment.

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