CrossMark

ORIGINAL PAPER

Spatio-temporal trend analysis of precipitation, temperature, and river discharge in the northeast of Iran in recent decades

Masoud Minaei[1] · **Masoud Irannezhad**[2,3]

Abstract This study analyses spatio-temporal trends in precipitation, temperature, and river discharge in the northeast of Iran during recent decades (1953–2013). The Pettitt, SNHT, Buishand, Box-Pierce, Ljung-Box, and McLeod-Li methods were applied to examine homogeneity in time series studied. The nonparametric Mann-Kendall and Sen's slope estimator tests were used to detect possible significant ($p < 0.05$) temporal trends in hydrometeorological time series and their magnitude, respectively. For time series with autocorrelation, the trend-free pre-whitening (TFPW) method was used to determine significant trends. To explore spatial distributions of trends, their magnitudes were interpolated by the inverse distance whitening (IDW) method. Trend analysis shows that for daily, monthly, and annual precipitation time series, 12.5, 19, and 12.5 % of the stations revealed significant increasing trends, respectively. For mean temperature, warming trends were found at 38, 23, and 31 % of the stations on daily, monthly, and annual timescales, in turn. Daily and monthly river discharge decreased at 80 and 40 % of the stations. Overall, these results indicate significant increases in precipitation and temperature but decreases in river discharge during recent decades. Hence, it can be concluded that decreasing trends in river discharge time series over the northeast of Iran during 1953–2013 are in response to warming
temperatures, which increase the rate of evapotranspiration. Differences between the results of our comprehensive large-scale study and those of previous researches confirm the necessity for more model-based local studies on climatic and environmental changes across the northeast of Iran.

1 Introduction

Climate change is referred to the large variation in climate averages taking place over a period of decades or even longer (Gocic and Trajkovic 2013). Due to its impacts on natural environment and human needs (e.g., agriculture, forestry, energy, and recreation), climate change is already considered as one of the foremost challenges facing humanity (Obot et al. 2010). It is broadly accepted that changes in climatic conditions, particularly precipitation and temperature, influence hydrological cycle and consequently water resource systems (e.g., IPCC 2013), which play a key role in eco-hydrological processes and natural disasters over the Earth (Buishand et al. 2013; Gocic and Trajkovic 2013; Kundzewicz and Robson 2004; Obot et al. 2010; Wang and Li 2015). To detect climate change, hence, analysis of long-term hydro-meteorological time series (e.g., precipitation, temperature, and river discharge) over different parts of the world has received a growing attention in international communities during the last decade.

Precipitation is probably the most important component of the hydrological cycle affecting water resources required for various land uses and nature conservancy, and one of the key variables for detecting regional climate change (Cannarozzo et al. 2006; McVicar et al. 2007; Obot et al. 2010). In recent years, numerous studies have analyzed spatio-temporal trends in regional precipitation to improve sustainable water resource planning and management around the world, e.g., in northern

✉ Masoud Minaei
m.minaei@um.ac.ir

[1] Department of Geography, Ferdowsi University of Mashhad, Mashhad, Iran

[2] Water Resources and Environmental Engineering Research Unit, Faculty of Technology, University of Oulu, 90014 Oulu, Finland

[3] Department of Civil and Environmental Engineering, Portland State University, Portland, OR 97201, USA

Europe (Irannezhad et al. 2014, 2015a), China (Zhang et al. 2013a), the USA (Joseph et al. 2000; Rana and Moradkhani 2016), and the Middle East (Soltani et al. 2012). For Iran, assessing precipitation records at 41 stations during the period 1966–2005, Tabari and Hosseinzadeh Talaee a found significant decreasing trends in annual precipitation at about 60 % of the stations. Abolverdi et al. (2014) identified no clear trends in precipitation over the Maharlo watershed in the south of Iran. Soltani et al. (2015) investigated climate extreme indices at 50 Iranian meteorological stations during 1975–2010 and determined significant trends at less than 15 % of the stations, which were not regionally systematic. Besides, there are other relevant studies on precipitation trends in Iran, e.g., Abghari et al. (2013), Shifteh Some'e et al. (2012), Tabari et al. (2012a), and Tabari et al. (2011).

Coupled with precipitation, temperature is one of the most important and discussed indicators of global climate change (Capparelli et al. 2013). Many policymakers and the general public believe that the effects of global warming are already being felt (Capparelli et al. 2013). Temperature changes, as a cause of alterations to precipitation patterns, are important for the management of water resources and water-related natural hazards (Zhang et al. 2013a, b). Numerous studies have focused on trends in temperature on regional and national scale over different timescales and periods, e.g., over the USA (Capparelli et al. 2013; Safeeq et al. 2013), Europe (Klein Tank et al. 2005), Finland (Irannezhad et al. 2015b), Spain (El Kenawy et al. 2012), and China (Wang et al. 2013). For Iran, Ghasemi (2015) assessed trends in maximum, minimum, and mean temperatures over the period 1961–2010 using the Mann-Kendall nonparametric test. The study found a general dominating temperature warming trends over most parts of Iran. Kousari et al. (2013) also determined significant trends in maximum air temperature during warm months (April, June, July, August, and September) throughout Iran over the period 1960–2005. Besides, Soltani et al. (2015) reported that a number of weather stations in Iran have showed statistically significant trends in most extreme temperature indices studied. Other interesting research studies on temperature changes in Iran are as follows: Saboohi et al. (2012), Tabari et al. (2011, 2012b), and Tabari and Hosseinzadeh Talaee (2011b).

Analyzing trends in hydrological time series (e.g., river discharge) is thought to be an important way to reflect, trace, and understand changes in climatic conditions, particularly precipitation and temperature (Kliment et al. 2011). In recent years, this form of analysis is also applied for hydrological risk assessments in the context of flood protection under climate and environmental change. For example, Douglas et al. (2000) assessed trends in high and low flow time series in the USA. They found significant upward trends in the incidence of low flows, but no clear changes in the flood flows. Performing trend analysis in 7-day high and low flows in Peninsular Malaysia during 1982–2006, Jha and Singh (2013) also

showed increases in the low flows. For Iran, Abghari et al. (2013) analyzed temporal trends in river discharge and precipitation time series for a 40-year period after 1969 in western parts. They reported both increasing and decreasing trends in river discharge time series and their strong relationships with annual and monthly precipitation. Moreover, there are many other studies focused on this topic around the world: Berezovskaya et al. (2004), Bormann et al. (2011), Cunderlik and Ouarda (2009), Danneberg (2012), Gebremicael et al. (2013), Hasan and Schorr (2012), Ishak et al. (2013), Kriegel et al. (2013), Li and Li (2008), Petrow and Merz (2009), Tian et al. (2010), Velpuri and Senay (2013), Wang et al. (2011), and Xu et al. (2010).

Detecting spatio-temporal trends in long-term hydro-meteorological time series on regional scale (Capparelli et al. 2013; Gocic and Trajkovic 2013; Kundzewicz and Robson 2004) plays an important role in understanding of climate change evidences and impacts across different parts of the world (Gocic and Trajkovic 2013; Kundzewicz and Robson 2004; Renard et al. 2008 Due to the necessity for more regional-, national-, and local-scale studies on climate change, a detailed and medium-scale research in order to improve our knowledge on hydro-meteorological changes in Iran is well motivated. Hence, the overall aim of the present study is to investigate spatio-temporal variability and trends in daily, monthly, and annual precipitation, temperature (maximum, minimum, and mean values), and river discharge in the northeast of Iran during 1953–2013. Specific objectives are to (1) assess and correct the quality of precipitation, temperature (maximum, minimum, and mean), and river discharge datasets at the stations studied; (2) determine statistically significant ($p < 0.05$) temporal trends in such hydro-meteorological time series; and (3) visualize the spatial distribution of such trends throughout the study area. The outcomes of this study help decision-making authorities to develop strategies for sustainable water resource planning and management in the Gorganrood watershed in northeastern Iran, where has experienced a number of disastrous flooding events during recent decades.

2 Materials and methods

2.1 Study area and data used

The main study area is located in the northeastern part of Iran and covers an area of 5500 km^2 (Fig. 1). It is located between the latitudes 36° 57′ and 37° 47′ N and the longitudes 55° 08′ and 56° 25′ E. It contains the upstream part of the Gorganrood watershed. To better understand the climatic conditions,
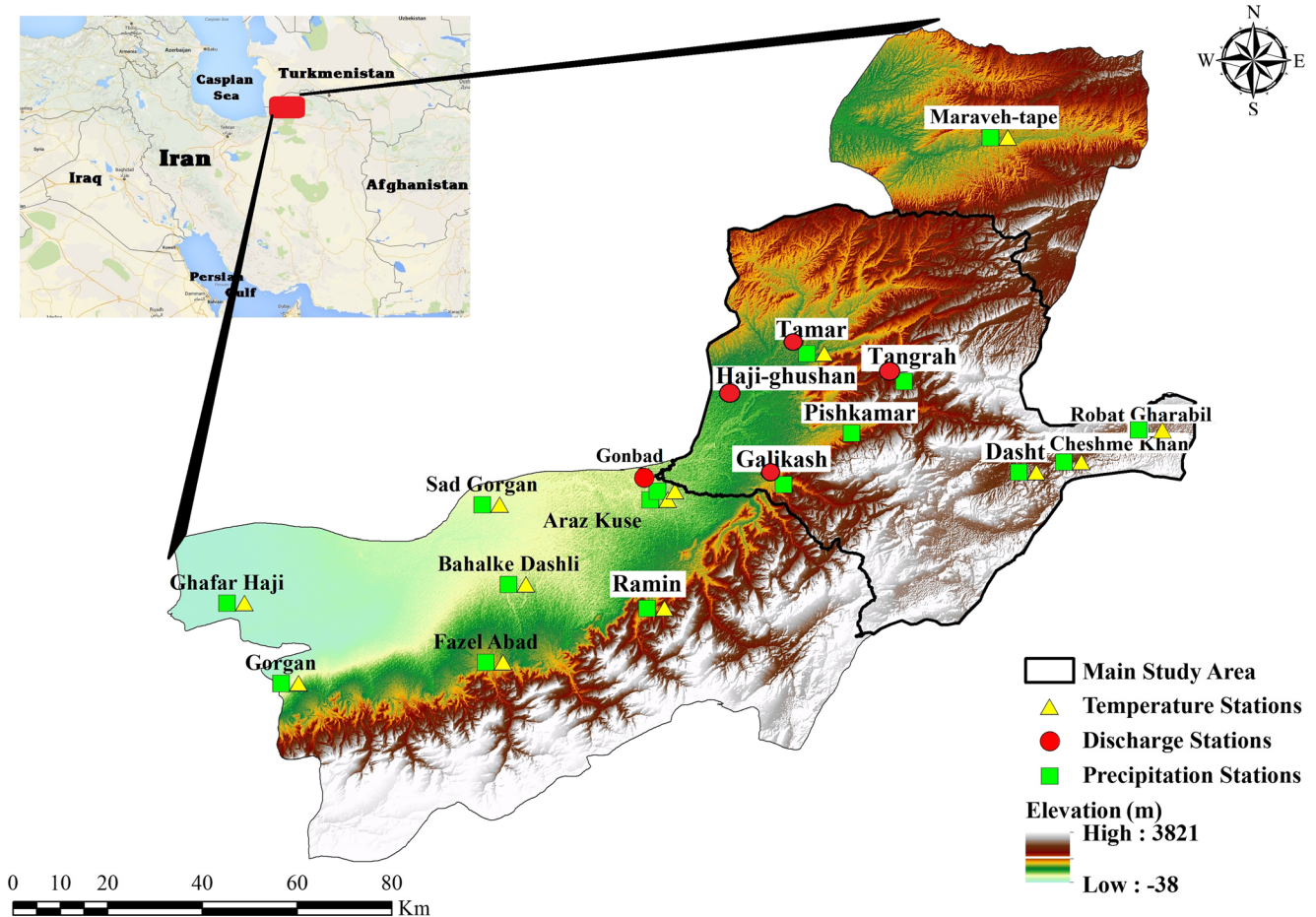
Fig. 1 Study area and the locations of hydrometeorological stations used

additional precipitation and temperature measurement stations from outside the main study area were also considered. This increased the size of study area to15,000 km^2 (Fig. 1), covering the latitudes from 36° 30′ to38° 07′ N, and longitudes from 53° 59′ to 56° 25′ E. Hence, most of the Gorganrood watershed and parts of the Atrak and Gharasoo basins are located in the study area. The altitude ranged from −30 to 3678 m above sea level. This region is very important from a number of viewpoints: first, its agricultural production activities because of valuable and fertile soils. Second, about 600,000 people live in flood prone areas within the study zone (Statistical-Center-of-Iran 2006). Third, Golestan National Park, a UNESCO heritage site, is located in this region, with (1) valuable and old forests; (2) a high level of diversity in terms of flora and fauna; and (3) a number of endangered species suffering from floods, climate change (CC), and land cover/land use change (LCLUc) (Minaei and Kainz 2016) Moreover, the study area is a geographically complex region that experiences remarkable climate variations. The plains are located in the east and center of study area, while dense forests and dry highlands in the southern parts. The northern area is semi-arid and mostly hilly in terms of its topography (Delbari et al. 2013).

2.2 Methodology

According to a definition produced by the World Meteorological Organization (WMO), analyzing data for a 30-year period is recommended because such data can provide stable and reproducible monthly means. However, in this study, some stations with less than 30 years of records were also used to improve the spatial coverage of study area. Reliable and high-quality data from 17 stations covering different hydrometeorological time series were collected from the Iran Meteorological Organization and the Ministry of Energy (Table 1; Fig. 1). The data were structured according to the hydrological year in Iran, which starts in October and ends in September. For precipitation and temperature, the longest period is between 1953 and 2013 recorded at the Gorgan station, and the shortest period is from 1992 to 2012 at the Gonbad station. For the discharge time series, the longest study period is 1955–2011 (Gonbad station) and the shortest is 1983–2011 (Haji-ghushan station). Table 1 gives summary statistics for precipitation, temperature, and discharge time series on, monthly timescale at the stations studied.

Table 1 Geographical coordinates and summary statistics for monthly hydro-meteorological time series at the stations studied

Station	Lat. (° N)	Lon. (° E)	Elev. (m)	Study period			T_{Max} (°C)	T_{Min} (°C)	T_{Mean} (°C)	Prcp. (mm)	Dis. (m^3/s)
				Precipitation	Temperature	Discharge					
Araz-kuse	37.21	55.13	34	1966–2011	1968–2011	–	25.3	10.7	17.5	37.3	–
Bahalke-dashli	37.05	54.80	24	1972–2011	1972–2011	–	24.1	10.4	17.1	36.3	–
Cheshme-khan	37.30	56.11	1250	1975–2011	1975–2011	–	19.6	3.8	11.7	19.6	–
Dasht	37.28	56.01	1000	1986–2008 (9 %)[a]	1986–2008 (9 %)[a]	–	19.8	4.2	10.8	13.5	–
Fazel-abad	36.90	54.75	210	1975–2011	1975–2011	–	23.5	10.9	17.3	56.8	–
Gonbad	37.23	55.15	37.2	1961–2013	1961–2012	1956–2011	24.3	11.4	18.0	39.4	7.1
Gorgan	36.85	54.26	13.3	1953–2013	1953–2012	–	22.8	12.6	17.7	49.3	–
Maraveh-tape	37.91	55.93	190	1970–2013	1979–2012	–	25.3	10.9	18.1	29.6	–
Ramian	37.01	55.13	200	1983–2011	1983–2011	–	22.8	10.7	16.7	72.8	–
Robat-gharabil	37.35	56.30	1450	1975–2011	1975–2011	–	21.3	3.0	12.1	15.6	–
Sad-gorgan	37.20	54.73	12	1971–2011	1971–2011	–	24.7	11.2	17.4	24.8	–
Tamar	37.50	55.50	132	1966–2011	1967–2011	1970–2011	24.6	11.0	16.7	42.3	1.5
Ghafar-haji	37.00	54.13	-22	1968–2011	1967–2011	–	22.7	11.1	16.1	37.9	–
Galikash	37.25	55.45	250	1972–2008	–	1966–2011	–	–	–	62.7	2.5
Pishkamar	37.35	55.61	976	1969–2008	–	–	–	–	–	43.7	–
Tangrah	37.45	55.73	330	1972–2008	–	1966–2011 (13 %)[a]	–	–	–	59.4	1.5
Haji-ghushan	37.40	55.35	90	–	–	1984-2011	–	–	–	–	1.9

[a] Percentage of missing data

Data are the backbone of any attempt to detect trends or other changes and should be quality-controlled before commencing any analysis of change (Kundzewicz and Robson 2004). Hence, exploratory data analysis (EDA) was used in this study to identify outliers, gaps, homogeneities, and independencies in hydro-meteorological time series. More information about EDA can be found in Kundzewicz and Robson (2004) and Cleveland (1994). All time series were firstly controlled for the outliers. To improve data quality, the small gaps (less than three missing values) were filled-in using the regression methods and also highly correlated geographically adjacent stations. Such treatments were finally resulted in less than 5 % missing data at the stations with small gaps. Besides, to avoid creating more inhomogeneity within the time series at the stations with larger gaps, the present study relied on the ability of the XLSTAT software to deal with the missing data.

Homogenous time series are often required in climate studies. Otherwise the trend analysis will be biased (Nie et al. 2012). Homogeneity and breaks cannot usually be detected by one single test in all situations (El Kenawy et al. 2013). Hence, this study used the popular Pettitt test, the Buishand and the Alexandersson's standard normal homogeneity test (SNHT) to examine homogeneity in daily, monthly, and annual hydro-meteorological time series studied (Alexandersson 1986; Bormann et al. 2011; Buishand 1982; Kang and Yusof 2012; Pettitt 1979; Wijngaard et al. 2003). Besides these homogeneity tests, the method of Santos and Fragoso (2013) was applied for determining the homogenized and inhomogenized time series.

Trend detection tests for hydro-meteorological time series can be classified as parametric or nonparametric (Chebana et al. 2013; Gocic and Trajkovic 2013; Ishak et al. 2013; Xu et al. 2010). Nonparametric tests do not need the time series to be normally distributed; hence, these tests are generally preferred to the parametric ones in scientific communities (Abghari et al. 2013; Gocic and Trajkovic 2013; López-Moreno et al. 2014). Accordingly, this study applied the Mann-Kendall (MK) nonparametric test for detecting statistically significant ($p < 0.05$) trends in the hydro-meteorological time series. The Sen's approach was used (Bormann et al. 2011) to calculate the slope of detected significant trends. The MK test is simple and robust to the missing and below a detection limit values (Shifteh Some'e et al. 2012) Furthermore, the seasonal Mann-Kendall test (12-month seasonality) is used to identify possible seasonality in the hydro-meteorological time series.

The Box-Pierce, the Ljung-Box, and the McLeod-Li tests at 95 % confidence intervals were used to determine serial correlations in the hydro-meteorological time series studies (Box and Pierce 1970; Ljung and Box 1978; McLeod and Li 1983). In the existence of such autocorrelations, the trend-free pre-whitening (TFPW) method (Yue et al. 2002) was preferred to the MK test for detecting statistically significant trends.

This method (TFPW) removes the lag-1 autocorrelation (Douglas et al. 2000; Hartmann and Andresky 2013; Irannezhad and Kløve 2015; Jha and Singh 2013; Kousari et al. 2013; Kriegel et al. 2013; Petrow and Merz 2009) and corrects the serially correlated time series using the equation $Y_t = X_t - r_1 X_{t-1}$, where X_t is the raw time series. Finally, pre-whitening approach reduces r_1 to near zero (Douglas et al. 2000; Hartmann and Andresky 2013; Yue et al. 2002).

3 Results and discussion

3.1 Daily trends

Statistically significant ($p < 0.05$) trends in daily precipitation were determined at 2 out of 16 stations (Fig. 2a). Such significant trends at both Dasht and Robat-gharabil stations were increasing (Table 2). Change point was March 1, 1999, at Dasht and March 8, 1986, at Robat-gharbil (Table 2). Significant trends were also found in daily mean temperature at 38 % of the stations (Fig. 2b). All these trends were positive (warming), with the highest rate at the Dasht station. Change points for significant increases in daily mean temperature were generally between 17 April and 29 May in the year (Table 2). Daily maximum temperature has significantly warmed at both Fazel-abadand sad-gorgan stations (Fig. 2c), but it has cooled at Maraveh-tape (Table 2). For daily minimum temperature, significant increases were identified at the Araz-kuse, Bahalke-dashli, Ramian, Robat-gharabil, Sad-gorgan, and Tamar stations. However, daily minimum temperature significantly cooled only at the Robat-gharabil station (Fig. 2d), with the change point on October 28, 2002 (Table 2). For daily river discharge, about 80 % of the stations showed significant decreasing trends (Fig. 2e), with the highest rate at the Haji-ghushan station (Table 2). Change points in such decreasing trends were in June at all Tangrah, Galikash, and Tamar stations. At the Haji-ghushan stations, the change point was on January 10, 2007 (Table 2).

The inverse distance whitening (IDW) method (Wang and Li 2015) was used to show the spatial distribution of trends in hydro-meteorological time series over the study area. Increases in daily precipitation mainly found across the mountainous region, with semi-arid climate (Fig. 2a). Warming trends in daily mean temperature were mostly observed in the wet lowland areas (Fig. 2b). Daily maximum temperature showed significant warming trends in the western lowlands, while cooling trends in the arid hilly region of northeastern area (Fig. 2c). For daily minimum temperature, significant increases were identified in the northern part of study area, while decreases in the mountainous semi-arid region (Fig. 2d). Besides, decreases in daily river discharge cover the entire of basin (Fig. 2e).

Fig. 2 Spatial distribution maps of trends in daily **a** precipitation, **b** mean temperature, **c** maximum temperature, **d** minimum temperature, and **e** river discharge in the northeast of Iran according to study period of each station given in Table 1. Triangles show stations with statistically significant (p < 0.05) trend. Size and direction of triangles describe the magnitude and direction of detected signification trend at stations, respectively. Stippling indicates where the spatial trends are statistically significant (p < 0.05)
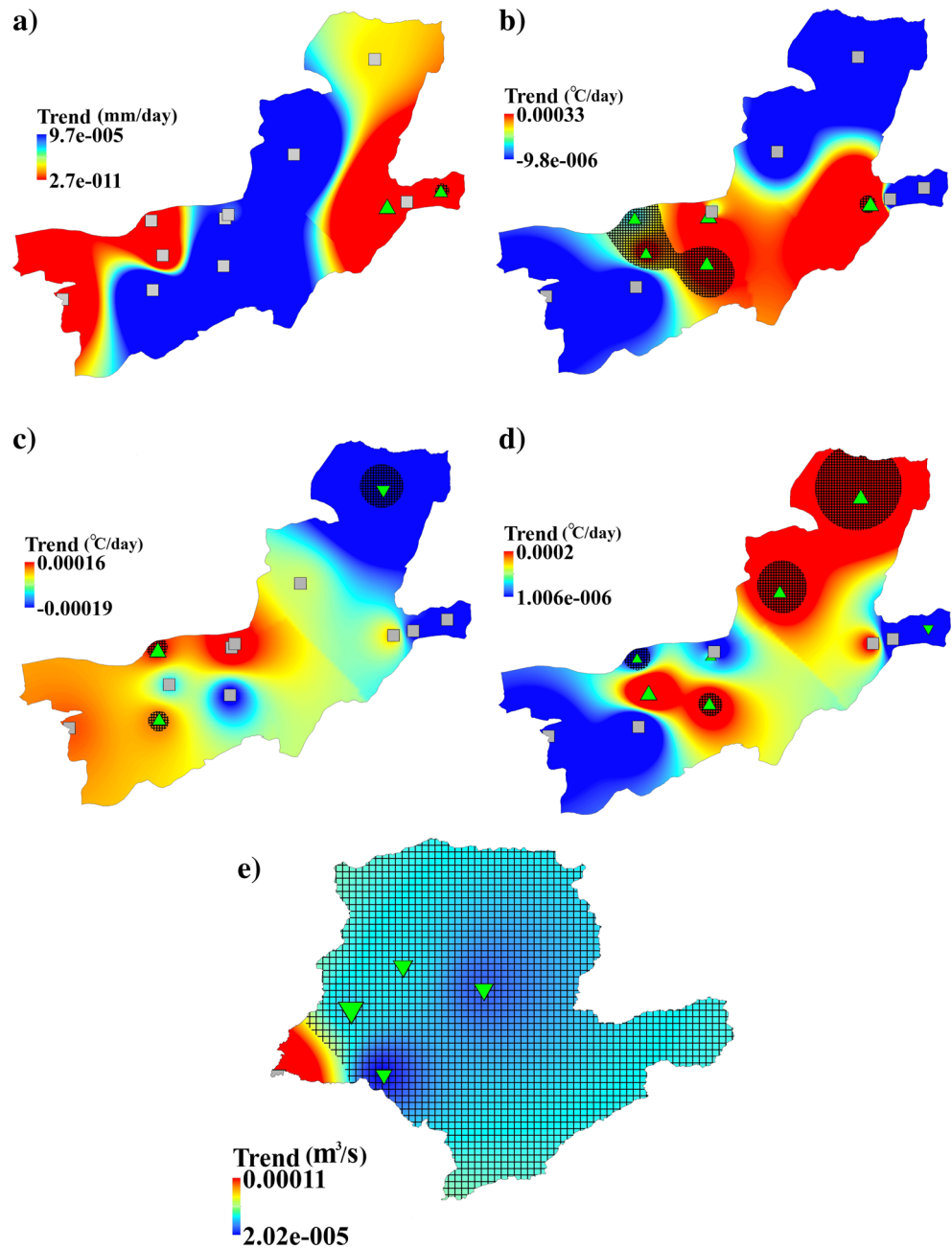
3.2 Monthly trends

Significant increases in monthly precipitation were detected at both Tamar and Dasht stations, while decreasing trend was determined at the Sad-gorgan station. Such trends were stronger than trends found in daily precipitation. With regard to seasonality in monthly precipitation time series, 37.5 % of the stations showed significant trends including Dasht, Gorgan, Robat-gharabil, Sad-gorgan, Tamar, and Tangrah. Almost 67 % of the trends at these stations were positive (Table 3). It should be noted that the Dasht station revealed the largest trend in both the daily and monthly precipitation

series. Among stations with significant trends, the break detection test identified change points at 67 % of the stations.

For monthly mean temperature, significant warming trends were found at the Araz-kuse, Tamar (highest rate), and Ghafar-haji stations (Table 3). Mean temperature at the Bahalke-dashli, Dasht, and Ramian stations showed significant trends in daily time series, but no clear changes on monthly timescale (Table 3). Seasonality analysis of monthly mean temperature determined significant trends at 61 % of the stations, all positive (Table 3). The lowest significant trend in monthly mean temperature was observed at the Fazel-abad station (0.075 °C/month) during 1975–2011, while the highest

Table 2 Statistical trends in daily hydro-meteorological time series at stations studied

Variable	Station	SC	H	Trend (/day)		Direction/CP	Section 1 (trend)	Section 2 (trend)
				Normal	PW			
Precip. (mm)	Dasht	+	−	−	*1.2E−5*	+/March 1,1999	1.4E−5	7.1E−5
	Robat-gharabil	+	−	−	*3.8E−5*	+/March 8, 1986	0	2.2E−5
T_{Mean} (°C)	Araz-kuse	+	−	−	*2.0E−4*	+/May 29, 1981	1.4E−4	8.4E−5
	Bahalke-dashli	+	−	−	*1.4E−4*	+/April 19, 1983	−1.6E−4	5.1E−5
	Dasht	+	−	−	*3.3E−4*	+/April 17, 2002	−2.3E−4	3.1E−4
	Ramian	+	−	−	*1.4E−4*	+/May 4, 1996	−9.4E−5	2.7E−5
	Sad-gorgan	+	−	−	*1.1E−4*	+/May 2, 1996	2.2E−5	−1.2E−4
T_{Max} (°C)	Fazel-abad	+	−	−	*1.1E−4*	+/April 20, 1998	2.7E−5	0
	Maraveh-tape	+	−	−	*−1.9E−4*	−/October 28, 1991	1.9E−4	0
	Sad-gorgan	+	−	−	*1.2E−4*	+/May 2, 1996	3.3E−5	−1.5E−4
T_{Min} (°C)	Araz-kuse	+	−	−	*1.2E−4*	+/May 25, 1990	−3.6E−5	0
	Bahalke-dashli	+	−	−	*2.5E−4*	+/April 22, 1983	−2.8E−4	*1.3E−4*
	Ramian	+	−	−	*1.8E−4*	+/April 21, 1997	5.5E−5	0
	Robat-gharabil	+	−	−	*6.4E−5*	−/October 28, 2002	6.7E−5	*0.002*
	Sad-gorgan	+	−	−	*6.2E−5*	+/April 21, 1997	0	−1.08E−4
	Tamar	+	−	−	*1.8E−4*	+/April 9, 1998	0	−6.5E−5
Discharge (m³/s)	Tangrah	+	−	−	*2.5E−5*	−/June 20, 1995	2.7E−5	*1.5E−4*
	Galikash	+	−	−	*2.0E−5*	−/June 14, 1997	7.7E−5	*−4.01E−5*
	Haji-ghushan	+	−	−	*3.3E−5*	−/January 10, 2007	−4.07E−5	3.8E−6
	Tamar	+	−	−	*3.4E−5*	−/June 29, 1998	7.2E−5	−1.9E−5

Sections 1 and 2 are the periods before and after CP, respectively. The "+" in the SC and H columns means that the time series need to be pre-whitened due to the existence of serial correlation and are homogeneous, respectively, while the "−" means vice versa. Statistically significant ($p < 0.05$) trends are given in italics

SC serial correlation, *H* homogeneity, *PW* pre-whitened series, *CP* change point in trend direction due to inhomogeneity

(0.325 °C/month) was found at the Ghafar-haji station during 1967–2011 (Table 3).

Monthly maximum temperature showed significant trends only at the Sad-gorgan station, which was warming (Table 3). Analyzing seasonality identified significant trends at 54 % of the stations from which 86 % being increasing. Monthly maximum temperature at the Sad-gorgan station showed the highest rate of warming trend (0.20 °C/month) during 1968–2011. Significant trends in monthly minimum temperature time series were all positive (warming), which only found at both of Bahalke-dashli and Gonbad stations (Table 3). Besides, the seasonal Mann-Kendall test revealed that monthly minimum temperature at 70 % of the stations have significantly warmed in recent decades, with Bahalke-dashli and Maraveh-tape being the most pronounced (Table 3). However, in monthly river discharge, statistically significant trends determined at the Tangrah and Haji-ghushan stations were both decreasing (Table 3).

Figure 3 demonstrates the spatial distribution maps of trends in different monthly hydro-meteorological time series studied. For monthly precipitation, stations revealing a significant trend were mainly located in the lowlands. Such trends were positive (increasing) in the east of study area, while negative (decreasing) at the Sad-gorgan station located in the west (Fig. 3a). Similar spatial pattern was identified using the seasonal Mann-Kendall test (Fig. 3b).

For monthly mean temperature, four stations in the north of study area showed warming trends (Fig. 3c). In contrast, seasonal analysis identified eight stations with significant warming trends, which geographically dispersed across the study area (Fig. 3d). Analyzing monthly maximum temperature identified a warming trend only at one station in the west of study area (Fig. 3e). However, six stations showed significant trends according to the seasonal Mann-Kendall test, which were particularly positive in the west (Fig. 3f). For monthly minimum temperature, only two stations in the lowland areas presented trends (Fig. 3g), which were both positive (warming). Based on seasonality, monthly minimum temperature time series showed similar results to the daily scale, except that the spatial distribution was larger and all the trends were positive (Fig. 3h).

Similar to daily timescale, statistically significant trends in monthly river discharge were negative (decreasing), but only found at two stations: Tangrah and Galikash (Fig. 3i). The evaluation of seasonality in monthly river discharge also identified decreasing trends at the same stations (Fig. 3j). The highest rate of decreasing trend in monthly river discharge time series was −0.002 (m³/s) found at the Galikash station during 1966–2011. Hence, among all hydrometeorological time series studied here, the most drastically decreasing trends were found in river discharge datasets.

Table 3 Statistical trends in monthly hydro-meteorological time series at stations studied

Variable	Station	SC	H	Trend (/month)		S-MK	Direction/CP	Section 1 (trend)	Section 2 (trend)
				Normal	PW				
Prcp. (mm)	Dasht	+	−	−	*0.055*	*0.29*	+/February 1999	0	0.041
	Gorgan	+	−	−	−0.014	−0.09	−/March 1982	0.03	−0.01
	Robat-gharabil	+	+	−	0.006	*0.11*	−	−	−
	Sad-gorgan	+	−	−	−0.018	−0.11	−/January 1998	0.002	0.115
	Tamar	+	−	−	*0.033*	*0.16*	+/Novemebr 1986	0.019	−0.007
	Tangrah	+	+	−	0.025	*0.08*	−	−	−
T_{Mean} (°C)	Araz-kuse	+	−	−	0.008	*0.23*	+/April 1975	0.068	0.002
	Cheshme-khan	+	+	−	0.002	*0.09*	−	−	−
	Dasht	+	−	−	0.01	*0.17*	+/June 2001	−0.006	0.02
	Fazel-abad	+	+	−	0.002	*0.07*	−	−	−
	Ramian	+	+	−	0.006	*0.13*	−	−	−
	Sad-gorgan	+	−	−	0.008	*0.20*	+/August 1975	0.1	0.003
	Tamar	+	−	−	*0.012*	*0.19*	+/January 1981	0.03	0.002
	Ghafar-haji	+	−	−	0.009	*0.32*	+/April 1974	0.02	0.002
T_{Max} (°C)	Araz-kuse	+	+	−	0.002	*0.10*	−	−	−
	Fazel-abad	+	+	−	0.005	*0.15*	−	−	−
	Gorgan	+	−	−	0.002	*0.08*	+/November 1990	-0.014	-0.023
	Maraveh-tape	+	+	−	−0.006	−0.14	−	−	−
	Sad-gorgan	+	+	−	*0.005*	*0.20*	−	−	−
	Tamar	+	+	−	0.002	*0.10*	−	−	−
	Ghafar-haji	+	+	−	0.002	*0.10*	−	−	−
T_{Min} (°C)	Araz-kuse	+	+	−	0.004	*0.17*	−	−	−
	Bahalke-dashli	+	+	−	*0.007*	*0.30*	−	−	−
	Cheshme-khan	+	+	−	0.002	*0.10*	−	−	−
	Gonbad	+	−	−	*0.005*	*0.29*	+/April 1993	0.002	0
	Maraveh-tape	+	+	−	0.008	*0.30*	−	−	−
	Ramian	+	+	−	0.006	*0.16*	−	−	−
	Sad-gorgan	+	+	−	0.003	*0.10*	−	−	−
	Tamar	+	+	−	0.006	*0.17*	−	−	−
	Ghafar-haji	+	+	−	0.005	*0.20*	−	−	−
Dis. (m³/s)	Tangrah	+	−	−	*−5.8E−4*	−0.13	−/June 1995	0.001	−4.8E−4
	Haji-ghushan	+	+	−	*−0.002*	−0.15	−	−	−

Sections 1 and 2 are the periods before and after CP, respectively. The "+" in the SC and H columns means that the time series need to be pre-whitened due to the existence of serial correlation and are homogeneous, respectively, while the "−" means vice versa. Statistically significant ($p < 0.05$) trends are given in italics

SC serial correlation, *H* homogeneity, *PW* pre-whitened series, *S-MK* seasonal Mann-Kendall test, *CP* change point in trend direction due to inhomogeneity

3.3 Annual trends

Annual precipitation showed increases only at two (Dasht and Tamar) out of 16 stations, while no significant decreasing trend (Table 4). At the Dasht and Tamar stations, change points in detected significant increasing trends were 1998 and 1987, respectively (Table 4). Such results disagree with the study by Tabari and Talaee (2011a), which identified negative trends in annual precipitation at 60 % of the stations, particularly in the northwest of Iran. Shifteh Some'e et al. (2012) also reported significant decreases in annual and seasonal precipitation in the northeast of Iran by investigating precipitation records at the Gorgan station. Such different trends identified by these studies point to the fact that trend analysis is highly dependent on location and study period.

Annual mean temperature significantly ($p < 0.05$) increased at the Araz-kuse, Sad-gorgan, Tamar, and Ghafar-

haji stations (Table 4). The highest rate of these warming trends was about 0.09 (°C/year) found at the Tamar station during 1967–2011. Such results were in agreement with the findings by Tabari et al. (2012b) reporting significant warmer climate over some parts of Iran including the northeast areas. Annual maximum temperature also showed significant trends at the Fazel-abad, Gorgan, Maraveh-tape, Sad-gorgan, and Ghafar-haji stations, all of which were warming (Table 4). However, no clear trends were found in annual maximum temperature at 61 % of all stations studied. Similar results have previously been reported by Saboohi et al. (2012). Significant trends detected in annual minimum temperature time series at the Araz-kuse, Bahalke-dashli, Gonbad, Tamar, and Ghafar-haji stations were all upward (warming). These results are consistent with previous study by Saboohi et al. (2012), which found significant increases in annual minimum temperature across Iran. However, no clear trends were
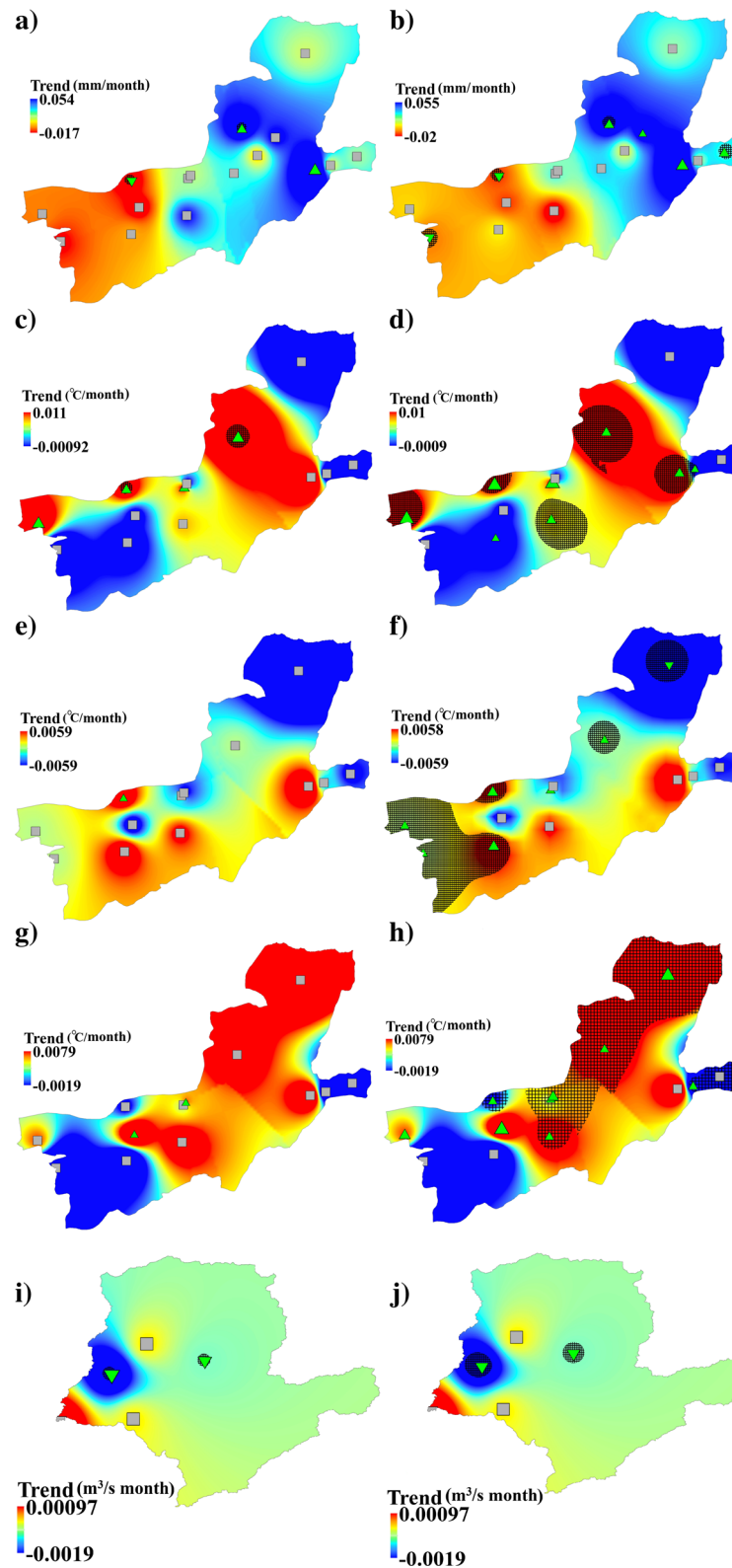
Fig. 3 Spatial distribution maps of trends in **a** monthly precipitation, **b** seasonality considered precipitation, **c** monthly mean temperature, **d** seasonality considered mean temperature, **e** monthly maximum temperature, **f** seasonality considered maximum temperature, **g** monthly minimum temperature, **h** seasonality considered minimum temperature, **i** monthly river discharge, and **j** seasonality considered river discharge in the northeast of Iran according to study period of each station given in Table 1Triangles show stations with statistically significant (p < 0.05) trend. Size and direction of triangles describe the magnitude and direction of detected signification trend at stations, respectively. Stippling indicates where the spatial trends are statistically significant (p < 0.05)

Table 4 Statistical trends in annual hydro-meteorological time series at stations studied

Variable	Station	SC	H	Trend (/year)		Direction/CP	Section 1 (trend)	Section 2 (trend)
				Normal	PW			
Prcp. (mm)	Dasht	+	−	−	*12.50*	+/1998	9.10	20.20
	Tamar	−	−	*4.90*	−	+/1987	−1.60	0.19
T_{Mean} (°C)	Araz-kuse	+	−	−	*0.05*	+/1994	0.10	0.057
	Sad-gorgan	+	−	−	*0.05*	+/1994	0.06	−0.015
	Tamar	+	−	−	*0.09*	+/1980	0.42	0.017
	Ghafar-haji	+	−	−	*0.05*	+/1991	*0.24*	0.04
T_{Max} (°C)	Fazel-abad	−	−	*0.05*	−	+/1994	0.03	*0.10*
	Gorgan	−	−	*0.019*	−	+/1996	0.01	0.02
	Maraveh-tape	−	−	*−0.079*	−	−/1991	−0.01	−0.03
	Sad-gorgan	+	−	−	*0.05*	+/1994	0.03	−0.01
	Ghafar-haji	−	−	*0.019*	−	+/1997	0.005	−0.02
T_{Min} (°C)	Araz-kuse	+	−	−	*0.07*	+/1994	0.067	0.04
	Bahalke-dashli	+	−	−	*0.06*	+/1985	0.05	0.05
	Gonbad	+	−	−	*0.04*	+/1993	−0.007	0.036
	Tamar	+	−	−	*0.14*	+/1996	*0.29*	0.008
	Ghafar-haji	+	−	−	*0.06*	+/1986	*0.59*	0.04

Sections 1 and 2 are the periods before and after CP, respectively. The "+" in the SC and H columns means that the time series need to be pre-whitened due to the existence of serial correlation and are homogeneous, respectively, while the "−" means vice versa. Statistically significant ($p < 0.05$) trends are given in italics

SC serial correlation, *H* homogeneity, *PW* pre-whitened series, *CP* change point in trend direction due to inhomogeneity

determined in annual river discharge time series. In contrast, Abghari et al. (2013) reported significant changes in annual river flows in some parts of western Iran.

Figure 4 shows the spatial distribution of trends found in annual precipitation and mean, maximum, and minimum temperatures over the study area. For annual precipitation time series, significant trends were mostly observed in the east part of study area, centered on the Dasht and Tamar stations (Fig. 4a). For annual mean temperature, the sensitive region was located in the northern margin of the basin (Fig. 4b). The stations displaying significant warming trends were mainly seen in the eastern parts, while only one station in the northeast (Fig. 4c). For annual minimum temperature, the stations with increasing trends found in the northern margin of study

Fig. 4 Spatial distribution maps of trends in annual **a** precipitation, **b** mean temperature, **c** maximum temperature, **d** minimum temperature, and **e** river discharge in the northeast of Iran according to study period of each station given in Table 1. Triangles show stations with statistically significant (p < 0.05) trend. Size and direction of triangles describe the magnitude and direction of detected signification trend at stations, respectively. Stippling indicates where the spatial trends are statistically significant (p < 0.05)
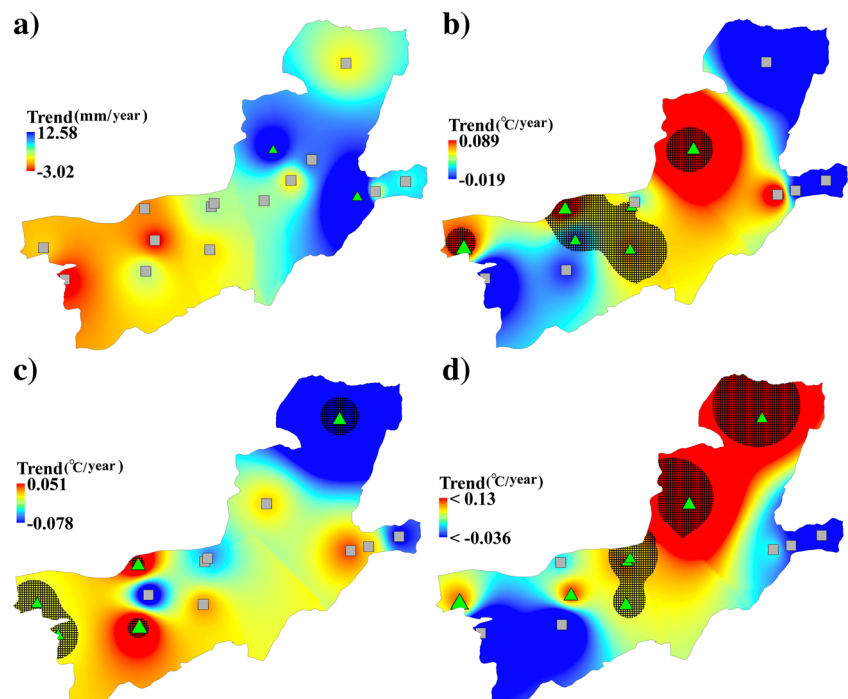
area, similar to the spatial distribution of mean temperature (Fig. 4d).

For precipitation, sensitive regions with high rates of trends were mostly located in the upstream of the Gorganrood in the highlands. For mean temperature, areas with significant trends were distributed in the northeast and northwest region with a weaker transitional zone between them. However, in maximum temperature, the west peaks shift from margin to the center. The sensitive region of minimum temperature was larger than that in the mean and maximum temperature. This suggests that a larger area tend to be less cool than before.

4 Conclusions

This study examines spatio-temporal trends in daily, monthly, and annual precipitation, temperature (in terms of mean, maximum, and minimum), and river discharge time series over the northeast of Iran during 1953–2013. Precipitation showed significant increasing trends, particularly over the main study area covering the river basins. Increasing (warming) trends were also determined in mean, maximum, and minimum temperatures, mainly at the stations located in the basins. Intensified precipitation would increase the risk of flash floods occurring in the study area. However, such risk might be decreased due to increases in the rate of evapotranspiration in response to warming trends found in temperatures. Significant declines in river discharge time series found in the study area can confirm that warmer temperature play a stronger role than precipitation abundance in controlling daily and monthly river discharge regime in the northeast of Iran. With this in mind, no trends in the annual discharge series could be associated with the flash floods that balance the conditions on annual scale. Overall, this study provides a detailed spatio-temporal picture of trends in hydrometeorological time series in northeastern Iran during recent decades, which helps environmental decision makers to improve planning and management of sustainable irrigation and water resources at district scale in Iran.

References

Abghari H, Tabari H, Hosseinzadeh Talaee P (2013) River flow trends in the west of Iran during the past 40 years: impact of precipitation variability. Glob Planet Chang 101:52–60. doi:10.1016/j.gloplacha.2012.12.003

Abolverdi J, Ferdosifar G, Khalili D, Kamgar-Haghighi AA, Haghighi MA (2014) Recent trends in regional air temperature and precipitation and links to global climate change in the Maharlo watershed. Southwestern Iran Meteorol Atmos Phys 126:177–192. doi:10.1007/s00703-014-0341-5

Alexandersson H (1986) A homogeneity test applied to precipitation data. J Climatol 6:661–675. doi:10.1002/joc.3370060607

Berezovskaya S, Yang D, Kane DL (2004) Compatibility analysis of precipitation and runoff trends over the large Siberian watersheds. Geophys Res Lett 31:L21502. doi:10.1029/2004GL021277

Bormann H, Pinter N, Elfert S (2011) Hydrological signatures of flood trends on German rivers: flood frequencies, flood heights and specific stages. J Hydrol 404:50–66. doi:10.1016/j.jhydrol.2011.04.019

Box GEP, Pierce DA (1970) Distribution of residual autocorrelations in autoregressive-integrated moving average time series models. J Am Stat Assoc 65:1509–1526. doi:10.2307/2284333

Buishand TA (1982) Some methods for testing the homogeneity of rainfall records. J Hydrol 58:11–27. doi:10.1016/0022-1694(82)90066-X

Buishand TA, De Martino G, Spreeuw JN, Brandsma T (2013) Homogeneity of precipitation series in the Netherlands and their trends in the past century. Int J Climatol 33:815–833. doi:10.1002/joc.3471

Cannarozzo M, Noto LV, Viola F (2006) Spatial distribution of rainfall trends in Sicily (1921–2000). Phys Chem Earth 31:1201–1211

Capparelli V, Franzke C, Vecchio A, Freeman MP, Watkins NW, Carbone V (2013) A spatiotemporal analysis of U.S. station temperature trends over the last century. Journal of Geophysical Research: Atmospheres 118:7427–7434. doi:10.1002/jgrd.50551

Chebana F, Ouarda TBMJ, Duong TC (2013) Testing for multivariate trends in hydrologic frequency analysis. J Hydrol 486:519–530. doi:10.1016/j.jhydrol.2013.01.007

Cleveland WS (1994) The elements of graphing data. Hobart Press, Summit, New Jersey

Cunderlik JM, Ouarda TBMJ (2009) Trends in the timing and magnitude of floods in Canada. J Hydrol 375:471–480. doi:10.1016/j.jhydrol.2009.06.050

Danneberg J (2012) Changes in runoff time series in Thuringia, Germany—Mann-Kendall trend test and extreme value analysis. Adv Geosci 31:49–56. doi:10.5194/adgeo-31-49-2012

Delbari M, Afrasiab P, Jahani S (2013) Spatial interpolation of monthly and annual rainfall in northeast of Iran. Meteorog Atmos Phys 122:103–113. doi:10.1007/s00703-013-0273-5

Douglas EM, Vogel RM, Kroll CN (2000) Trends in floods and low flows in the United States: impact of spatial correlation. J Hydrol 240:90–105. doi:10.1016/S0022-1694(00)00336-X

El Kenawy A, López-Moreno JI, Vicente-Serrano SM (2012) Trend and variability of surface air temperature in northeastern Spain (1920–2006): linkage to atmospheric circulation. Atmos Res 106:159–180. doi:10.1016/j.atmosres.2011.12.006

El Kenawy A, López-Moreno JI, Stepanek P, Vicente-Serrano SM (2013) An assessment of the role of homogenization protocol in the performance of daily temperature series and trends: application to northeastern Spain. Int J Climatol 33:87–108. doi:10.1002/joc.3410

Gebremicael TG, Mohamed YA, Betrie GD, van der Zaag P, Teferi E (2013) Trend analysis of runoff and sediment fluxes in the Upper Blue Nile basin: a combined analysis of statistical tests, physically-based models and landuse maps. J Hydrol 482:57–68. doi:10.1016/j.jhydrol.2012.12.023

Ghasemi AR (2015) Changes and trends in maximum, minimum and mean temperature series in Iran. Atmos Sci Lett 16:366–372. doi:10.1002/asl2.569

Gocic M, Trajkovic S (2013) Analysis of changes in meteorological variables using Mann-Kendall and Sen's slope estimator statistical tests in Serbia. Glob Planet Chang 100:172–182. doi:10.1016/j.gloplacha.2012.10.014

Hartmann H, Andresky L (2013) Flooding in the Indus River basin—a spatiotemporal analysis of precipitation records. Glob Planet Chang 107:25–35. doi:10.1016/j.gloplacha.2013.04.002

Hasan A, Schorr P (2012) Trend analysis of precipitation and runoff as a basis of design and operation of pumped storage water supply infrastructure in New Jersey. In: World Environmental and Water Resources Congress 2012. pp 1559–1564. doi:10.1061/9780784412312.155

IPCC (2013) Summary for policymakers. In: Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds) Climate change 2013: the physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge 28 p.

Irannezhad M, Kløve B (2015) Do atmospheric teleconnection patterns explain variations and trends in thermal growing season parameters in Finland? Int J Climatol 35(15):6419–6430

Irannezhad M, Marttila H, Kløve B (2014) Longtermvariations and trends in precipitation in Finland. Int J Climatol 34(10):3139–3153

Irannezhad M, Torabi Haghighi A, Chen D, Kløve B (2015a) Variability in dryness and wetness in Central Finland and the role of teleconnection patterns. Theor Appl Climatol 122(3):471–486

Irannezhad M, Chen D, Kløve B (2015b) Interannual variations and trends in surface air temperature in Finland in relation to atmospheric circulation patterns, 1961–2011. Int J Climatol 35(10):3078–3092

Ishak EH, Rahman A, Westra S, Sharma A, Kuczera G (2013) Evaluating the non-stationarity of Australian annual maximum flood. J Hydrol 494:134–145. doi:10.1016/j.jhydrol.2013.04.021

Jha MK, Singh AK (2013) Trend analysis of extreme runoff events in major river basins of peninsular Malaysia. International Journal of Water 7:142–158

Joseph R, Ting M, Kumar P (2000) Multiple-scale spatio–temporal variability of precipitation over the coterminous United States. J Hydrometeorol 1:373–392. doi:10.1175/1525-7541(2000)001<0373:MSSTVO>2.0.CO;2

Kang HM, Yusof F (2012) Homogeneity tests on daily rainfall series in peninsular Malaysia. Int J Contemp Math Sciences 7:14

Klein Tank AMG, Können GP, Selten FM (2005) Signals of anthropogenic influence on European warming as seen in the trends patterns of daily temperature variance. Int J Climatol 25:1–16

Kliment Z, Matouskava M, Ledvinka O, Kralovec V (2011) Trend analysis of rainfall-runoff regimes in selected headwater areas of the Czech Republic. J Hydrol Hydromech 59:14. doi:10.2478/v10098-011-0003-y

Kousari MR, Ahani H, Hendi-zadeh R (2013) Temporal and spatial trend detection of maximum air temperature in Iran during 1960–2005. Glob Planet Chang 111:97–110. doi:10.1016/j.gloplacha.2013.08.011

Kriegel D, Mayer C, Hagg W, Vorogushyn S, Duethmann D, Gafurov A, Farinotti D (2013) Changes in glacierisation, climate and runoff in the second half of the twentieth century in the Naryn basin, Central Asia. Glob Planet Chang 110(Part A):51–61. doi:10.1016/j.gloplacha.2013.05.014

Kundzewicz ZW, Robson AJ (2004) Change detection in hydrological records—a review of the methodology / Revue méthodologique de la détection de changements dans les chroniques hydrologiques. Hydrol Sci J 49:7–19. doi:10.1623/hysj.49.1.7.53993

Li ZJ, Li XB (2008) Trend and causation analysis of runoff variation in the upper reach of Chaobaihe River Basin in northern China during 1961-2005. Beijing Linye Daxue Xuebao/Journal of Beijing Forestry University 30:82–87

Ljung GM, Box GEP (1978) On a measure of lack of fit in time series models. Biometrika 65:297–303. doi:10.2307/2335207

López-Moreno JI et al (2014) Recent glacier retreat and climate trends in cordillera Huaytapallana. Peru Global Planet Change 112:1–11. doi:10.1016/j.gloplacha.2013.10.010

McLeod AI, Li WK (1983) Diagnostic checking Arma time series models using squared-residual autocorrelations. J Time Ser Anal 4:269–273. doi:10.1111/j.1467-9892.1983.tb00373.x

McVicar TR, Van Niel TG, Li LT, Hutchinson MF, Mu XM, Liu ZH (2007) Spatially distributing monthly reference evapotranspiration and pan evaporation considering topographic influences. J Hydrol 338:196–220

Minaei M, Kainz W (2016) Watershed Land Cover/Land Use Mapping Using Remote Sensing and Data Mining in Gorganrood, Iran ISPRS International Journal of Geo-Information 5:57. Doi:10.3390/ijgi5050057

Nie C et al (2012) Spatial and temporal changes in extreme temperature and extreme precipitation in Guangxi. Quat Int 263:162–171. doi:10.1016/j.quaint.2012.02.029

Obot NI, Chendo MAC, Udo SO, Ewona IO (2010) Evaluation of rainfall trends in Nigeria for 30 years (1978-2007). Int J Phys Sci 5:2217–2222

Petrow T, Merz B (2009) Trends in flood magnitude, frequency and seasonality in Germany in the period 1951–2002. J Hydrol 371:129–141. doi:10.1016/j.jhydrol.2009.03.024

Pettitt AN (1979) A non-parametric approach to the change-point problem. Appl statist 28:10

Rana A, Moradkhani H (2016) Spatial, temporal and frequency based climate change assessment in Columbia River Basin using multi downscaled-scenarios. Clim Dyn 47(1):579–600

Renard B et al (2008) Regional methods for trend detection: assessing field significance and regional consistency. Water Resour Res 44:W08419. doi:10.1029/2007WR006268

Saboohi R, Soltani S, Khodagholi M (2012) Trend analysis of temperature parameters in Iran. Theor Appl Climatol 109:529–547. doi:10.1007/s00704-012-0590-5

Safeeq M, Mair A, Fares A (2013) Temporal and spatial trends in air temperature on the Island of Oahu, Hawaii. Int J Climatol 33:2816–2835. doi:10.1002/Joc.3629

Santos M, Fragoso M (2013) Precipitation variability in Northern Portugal: data homogeneity assessment and trends in extreme precipitation indices. Atmos Res 131:34–45. doi:10.1016/j.atmosres.2013.04.008

Shifteh Some'e B, Ezani A, Tabari H (2012) Spatiotemporal trends and change point of precipitation in Iran. Atmos Res 113:1–12. doi:10.1016/j.atmosres.2012.04.016

Soltani S, Saboohi R, Yaghmaei L (2012) Rainfall and rainy days trend in Iran. Clim Chang 110:187–213. doi:10.1007/s10584-011-0146-1

Soltani M et al. (2015) Assessment of climate variations in temperature and precipitation extreme events over Iran. Theor Appl Climatol 1–21. doi:10.1007/s00704-015-1609-5

Statistical-Center-of-Iran (2006) Iranian population and housing census 1385 - Golestan Province General Results 57

Tabari H, Hosseinzadeh Talaee P (2011a) Temporal variability of precipitation over Iran: 1966–2005. J Hydrol 396:313–320. doi:10.1016/j.jhydrol.2010.11.034

Tabari H, Hosseinzadeh Talaee P (2011b) Recent trends of mean maximum and minimum air temperatures in the western half of Iran. Meteorog Atmos Phys 111:121–131. doi:10.1007/s00703-011-0125-0

Tabari H, Somee BS, Zadeh MR (2011) Testing for long-term trends in climatic variables in Iran. Atmos Res 100:132–140. doi:10.1016/j.atmosres.2011.01.005

Tabari H, Abghari H, Hosseinzadeh Talaee P (2012a) Temporal trends and spatial characteristics of drought and rainfall in arid and semi-arid regions of Iran. Hydrol Process 26:3351–3361. doi:10.1002/hyp.8460

Tabari H, Hosseinzadeh Talaee P, Ezani A, Shifteh Some'e B (2012b) Shift changes and monotonic trends in autocorrelated temperature series over Iran. Theor Appl Climatol 109:95–108. doi:10.1007/s00704-011-0568-8

Tian Y, Ma L, Lei X, Jiang Y (2010) Analysis of runoff change trend using hydrological time series method. In: Geoscience and remote sensing (IITA-GRS), 2010 Second IITA International Conference on, 28–31 Aug. 2010. pp 263–267. doi:10.1109/IITA-GRS.2010.5604096

Velpuri NM, Senay GB (2013) Analysis of long-term trends (1950–2009) in precipitation, runoff and runoff coefficient in major urban watersheds in the United States. Environ Res Lett 8:024020

Wang R, Li C (2015) Spatiotemporal analysis of precipitation trends during 1961–2010 in Hubei province, central China. Theor Appl Climatol 1–15. doi:10.1007/s00704-015-1426-x

Wang H, Zhang M, Li P, Dang X, Zhu H, Chang L (2011) Long-term trend analysis for the runoff series in Yulin. In: Water Resource and Environmental Protection (ISWREP), 2011 International Symposium on, 20–22 May 2011. pp 1062–1065. doi:10.1109/ISWREP.2011.5893197

Wang Y, Ren F, Zhang X (2013) Spatial and temporal variations of regional high temperature events in China. Int J Climatol. doi:10.1002/joc.3893

Wijngaard JB, Klein Tank AMG, Können GP (2003) Homogeneity of twentieth century European daily temperature and precipitation series. Int J Climatol 23:679–692. doi:10.1002/joc.906

Xu K, Milliman JD, Xu H (2010) Temporal trend of precipitation and runoff in major Chinese rivers since 1951. Glob Planet Chang 73: 219–232. doi:10.1016/j.gloplacha.2010.07.002

Yue S, Pilon P, Phinney B, Cavadias G (2002) The influence of autocorrelation on the ability to detect trend in hydrological series. Hydrol Process 16:1807–1829. doi:10.1002/hyp.1095

Zhang Q, Li J, Singh VP, Xu C-Y (2013a) Copula-based spatio-temporal patterns of precipitation extremes in China. Int J Climatol 33:1140–1152. doi:10.1002/joc.3499

Zhang Q, Li J, Singh VP, Xiao M (2013b) Spatio-temporal relations between temperature and precipitation regimes: implications for temperature-induced changes in the hydrological cycle. Glob Planet Chang 111:57–76. doi:10.1016/j.gloplacha.2013.08.012