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Decadal Analysis of River Flow Extremes Using Quantile-Based Approaches

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Abstract Next to the traditional analysis of trends in time series of hydro-climatological variables, analysis of decadal oscillations in these variables is of particular importance for the risk assessment of hydro-climatological disasters and risk-based decision-making. Conventional parametric and nonparametric tests, however, need implementing a set of background assumptions related to serial structure and statistical distribution of data. They neither focus on the extreme events and their probability of occurrence. In order to get rid of these limitations, we suggest a modified version of the Sen Method (SM), combined with the Quantile Perturbation Method (QPM) for examining temporal variation of extreme hydrological events. The developed method is tested for decadal analysis of monthly and annual river flows at 10 hydrometric stations in the Qazvin plain in Iran. The results show oscillatory patterns in extreme river flow quantiles, with a positive anomaly during the 1990s and a negative one during the 2000s. It is also shown that the concurrent use of the two methods allows to set a complete picture on the temporal changes in high and low extremes in historical river flow observations in different seasons.

Keywords River flow time series · Trend analysis · Extreme quantiles · Periodic fluctuations

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1 Introduction

Water resources, primarily river flows in arid and semi-arid regions, are highly sensitive to hydro-climatic changes. Eventually, a small change in hydro-climatic factors may produce a considerably large alteration in hydrological variables and may subsequently affect the regional water resources (Chen et al. 2006; Feng et al. 2011). Furthermore, the pressure on water and other natural resources in these regions is increasing as demands for water for human uses are growing rapidly because of increased population growth along with its inappropriate spatial distribution, developing industry, expanding agriculture, and urban construction (Xu et al. 2002; Masih et al. 2009; Madani 2014).

River flow is one of the main driving factors of the hydrological system and a vital water resource in water-scarce arid and semi-arid regions. River flow can change temporally in response to human activities like land use change and urbanization, or impact of climate variability for instance on precipitation and evaporation (De Roo et al. 2001; Li et al. 2007; Zhao et al. 2016; Yang et al. 2016). However, one has to be careful in attributing such change in river flow to climate change/variability as one of the primary causes, because human interventions in catchments play a crucial role in river flow change especially in developing countries (Taye et al. 2015; Bayazit 2015; Mittal et al. 2016). Whatever the driver of the changes is, it can result in profound and potentially irreversible impact on the ecosystems and society by enhancing the risk of destructive natural hazards such as hydrological droughts or fluvial floods (Pereira 2011; Bellos 2012; Tsirimpi and Dimitriou 2016).

The first step in determining the influence of the climate system on the hydrology in support of water resources management is to estimate trends (magnitude and direction) in the hydrological variables. In fact, trend analysis is a way to detect at which rate or direction a variable changes over a time period. However, a number of issues such as testing the validity of underlying assumptions for trend detection methods should be addressed to perform a meaningful hydrological trend analysis. Generally, when hydrological time series are analyzed for detecting temporal trends, the analysis is often complicated by the seasonality and serial correlations in the time series (Tabari et al. 2014) and also for the existence of extreme values (Willems 2013a). Existence of correlation between successive observations of the same variable is a common problem for trend analysis of hydrological variables which influences the results of both parametric and nonparametric methods (Tabari et al. 2012; Serinaldi and Kilsby 2016). Simulation results (Yue and Wang 2002) indicated that the power of common parametric and nonparametric trend tests depends on some restrictive assumptions such as normality and dependency. The nonparametric methods need fewer assumptions compared to their parametric counterparts and so there is an inclination towards using these methods (Zhang et al. 2015; Lu et al. 2015; Mao et al. 2016; Karandish et al. 2016; Valdes-Abellan et al. 2017; Yang et al. 2017). Nevertheless, finding a robust approach that needs fewer stringent assumptions is still a big challenge for meaningful inferences from trend results in hydrological time series.

Next to trends in hydrological time series, decadal oscillations in extreme hydrological events are of particular importance for water resources risk assessment and decision making (Taye and Willems 2012; Willems 2013b; Valdés-Pineda et al. 2017). In this context, this study proposes a method for using two statistical tests which do not depend on the above-mentioned restrictive assumption for analyzing decadal oscillations and which focus on hydrological extreme events. The two methods allow a graphical analysis of the time series for any sub-period of interest. The first method is the quantile perturbation method (QPM) to analyze periodic (e.g., decadal) variations in the extreme high river flow quantiles (values for a given frequency of occurrence or return period) on annual and seasonal time scales. The QPM, first implemented by Ntegeka and Willems (2008), initially considers two concepts including the frequency of extreme events (quantiles), and then the anomaly in terms of the relative changes in the magnitude of events based on a certain baseline. By combining the two concepts, the approach provides the possibility to analyze changes in the extremes for a particular return period (as performed by Taye and Willems 2012; Willems 2013a, b; Tabari et al. 2014). The second method is the graphical approach developed by Şen (2012) for analyzing changes in quantiles between sub-periods. This method was originally developed for long-term trend analysis. The present study modifies the method to be used for a decadal analysis. The two methods are applied for a decadal analysis of monthly and annual river flows in the Qazvin plain in Iran as a case study.

2 Methods

2.1 Quantile Perturbation Method

The QPM method determines changes in quantiles between a baseline series and a sub-series of interest (Ntegeka and Willems 2008; Willems 2013a, b). The baseline is the full time series, and the sub-series is taken from a time slice (hereinafter referred to as block period) of the entire historical period. The block period with a sliding window of one year was selected for this work. A schematic representation of the computational steps used in the QPM method is shown in Fig. 1. Once the anomalies in river flows are computed, their significance is tested using Monte Carlo simulations at the 95% confidence level (nonparametric bootstrapping method: Willems 2013a, b). The null hypothesis is that there is no trend or persistence in the time series. After calculation of the confidence intervals and anomalies, they are superimposed on the same plot, which allows a visual identification of periods with significant oscillations.

Because sliding block periods are considered in the QPM method, it is important to note that the anomalies shown are subject to temporal correlation over time spans equal to the block period length. As pointed out by Willems (2015), to avoid false conclusions to be drawn to the presence of the temporal oscillations in the time series, some checks need to be done:

1. If the time interval between consecutive oscillation highs or lows is greater than the length of block period, they are considered independent.
2. The assumption of fairly constant anomalies of higher quantiles (values higher than a certain threshold) needs to be checked. This assumption is tested from the regression slope of anomalies. If the slope is not significantly different from zero, the null hypothesis of fairly constant anomalies above the threshold is accepted.
3. If significant oscillation highs and lows are observed at several neighboring stations in the same periods, the null hypothesis of randomness would be rejected and the oscillations are considered significant.

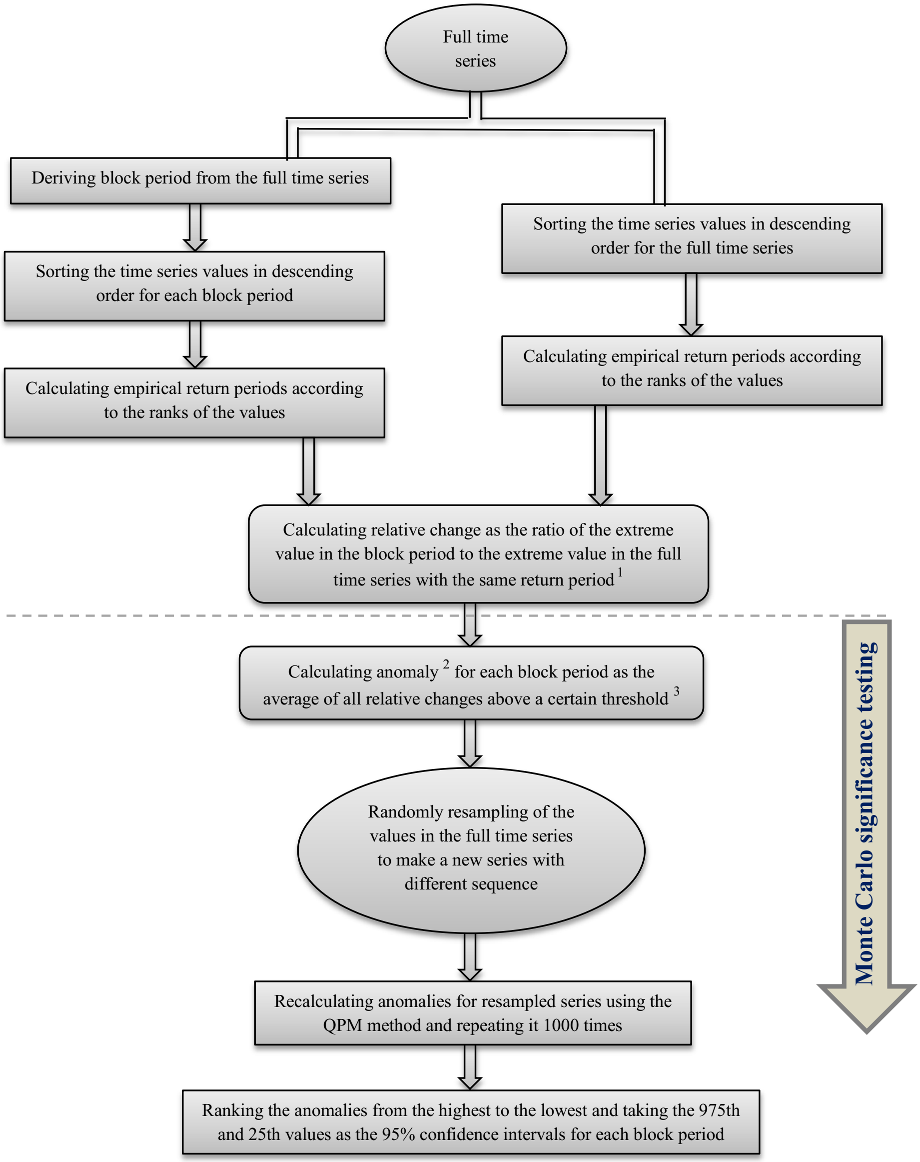

Fig. 1 Flowchart for decadal anomaly analysis using the QPM method ([1]When the empirical return period of a value in the block period does not coincide with that of the baseline period, the values can be obtained by means of a linear interpolation from the values with the closest return periods; [2]Anomaly refers to the average relative changes (as a ratio or in percent) of the most extreme observations in the selected block period; [3]Threshold applied in this study for the most extreme events will select the three highest values in each year)

2.2 Şen (2012) Method

Şen (2012) proposed a method (hereafter referred to as SM) based on quantile-quantile plots for trend analysis. In this method, the series is divided into two equal parts with regard to time and then the values in the sub-series are sorted in the ascending order to obtain quantiles. The quantiles obtained for the first and second halves of the time series are plotted as scatter points on the X- and Y-axis respectively and compared against the 1:1 (45°) line. The scatter points in the upper (lower) triangle of the square area represent increasing (decreasing) trends. There is no trend in the time series when the data are concentrated on the 1:1 line. This method does not focus on the extreme quantiles only, but allows to evaluate the changes for the full range of values (river flows in this case). In this study, the Sen method is changed in a way to be used for a decadal analysis. The study period at each station is divided into different 20-year sub-periods in which the river flow in the first half (Q_F) is compared with that in the second half (Q_S). Let us consider the period 1961–2010 as a study period. The river flow in the following decadal periods is compared: 1961–1970 vs. 1971–1980, 1971–1980 vs. 1981–1990, 1981–1990 vs. 1991–2000 and 1991–2000 vs. 2001–2010.

It is worthwhile to note that the anomaly calculated by the QPM method corresponds to the relative ratio of the quantiles if in the SM method the values for a given decadal sub-period would be plotted on the Y-axis and the values for the full series plotted on the X-axis, and after taking the difference in length between the sub-period and the full period into account. Note that both the QPM and the SM can be applied to the full range of quantiles or restricted to the extremes, i.e., quantiles above a given threshold.

3 River Flow Data

As a case study, the monthly river flow data from ten hydrometric stations located in the Qazvin plain in the northwest of the central plateau of Iran (Fig. 2) were used. The data were provided by the Qazvin Regional Water Co. For selection of the stations, the stations with fewer than 40 years of observations and with 5% or more of data gaps were excluded. Detailed information about the selected gauging stations is presented in Table 1.

In this study, changes in monthly and annual river flow time series are analyzed. For the monthly analysis, changes in each season are calculated separately. The seasons are defined according to the hydrological year in the region (from October of a given calendar year to

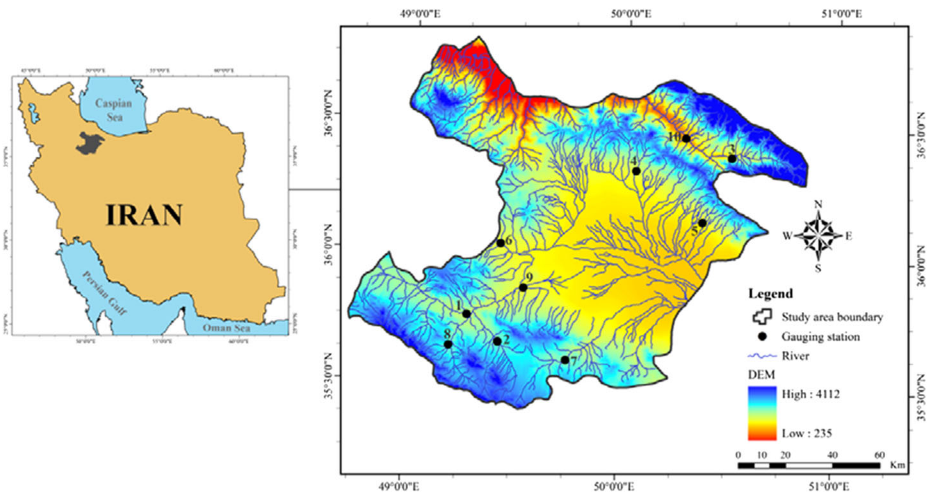

Fig. 2 Location of the study region and hydrological gauging stations

Table 1 Summary of hydrological gauging stations used in this study

Station No.	Station name	Station ID	Longitude (E)	Latitude (N)	Elevation (m a.s.l.)	River	Drainage area (km^2)	Study period		Missing data (%)
								Start year	End year	
1	Abgarm	41–067	49.28	35.76	1623	Kharrood	2416	1964–1965	2011–2012	0
2	Artesh-Abad	41–069	49.43	35.66	1750	Kalanjinchay	429	1964–1965	2011–2012	0
3	Baghkelayeh	17–039	50.50	36.39	1300	Alamootrood	695	1966–1967	2011–2012	0
4	Barajin	41–219	50.05	36.33	1480	Barajin	96	1965–1966	2011–2012	4.25
5	Behjat-Abad	41–089	50.37	36.14	1360	Bahbahrood	40	1967–1968	2011–2012	2.22
6	Gherveh	41–073	49.38	36.06	1433	Abharrood	1916	1967–1968	2011–2012	0
7	Haji-Arab	41–079	49.75	35.60	1720	Haji Arab	550	1966–1967	2011–2012	4.35
8	Pole-Arvan	41–063	49.20	35.64	1750	Arvan	101.2	1964–1965	2011–2012	0
9	Rahim-Abad	41–071	49.54	35.87	1400	Kharrood	4089	1964–1965	2011–2012	0
10	Rajaeidasht	17–201	50.28	36.46	970	Shahrood	2445	1966–1967	2011–2012	4.35

September of the next one) as follows: autumn season extending from October to December (OND), winter season extending from January to March (JFM), spring season extending from April to June (AMJ) and summer season extending from July to September (JAS). For the annual analysis, the average river flow for every hydrological year is examined.

4 Results and Discussion

Decadal analysis by the QPM method is done under the assumption of the fairly constant anomalies of larger quantiles (extreme values above a certain exceedance probability or return period). The validation of this assumption is checked prior to the analysis of decadal river flow variations to reduce the risk that the anomaly is strongly influenced by one or few high values that randomly occurred in time, as per the recommendations by Willems (2015). Figure 3 shows monthly river flow anomalies at one representative station (Abgarm) for four 10-year periods. The plot and the statistical analysis of regression slope of the anomalies approve the assumption on the fairly constant relative change for the extreme values with return period higher than 0.25 year. Higher return periods can also be selected as the threshold and the selection is rather subjective, and depends on the intended use of the results.

Selection of an appropriate block length is another important issue in application of the QPM method. Since the aim of this study is decadal analysis of river flow, a 10-year block length was selected. We performed a sensitivity analysis of river flow anomalies to different block lengths, as illustrated in Fig. 4. As the plots show, the larger the block length is, the smoother the anomaly curves will be and vice versa. Depending upon the purpose of the study and the intended use of the results, shorter block lengths for inter-annual and multi-annual analyses (e.g., a 5-year or 7-year period) or longer block lengths (e.g., a 12-year or 15-year period) for multi-decadal analyses can be selected.

Decadal variations in monthly high river flows (high extremes in monthly data) were analyzed based on the QPM method by considering all the seasons in a year using the monthly data. The results are as shown in Fig. 5. A consistent decreasing trend is common in most of the stations, while there is an indication that the 1990s had an oscillation high period with positive significant anomalies. This significant positive anomaly of around

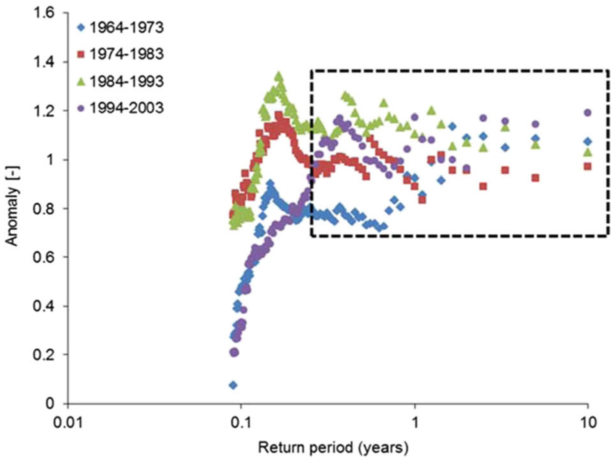

Fig. 3 Monthly river flow anomalies at Abgarm station for four 10-year periods

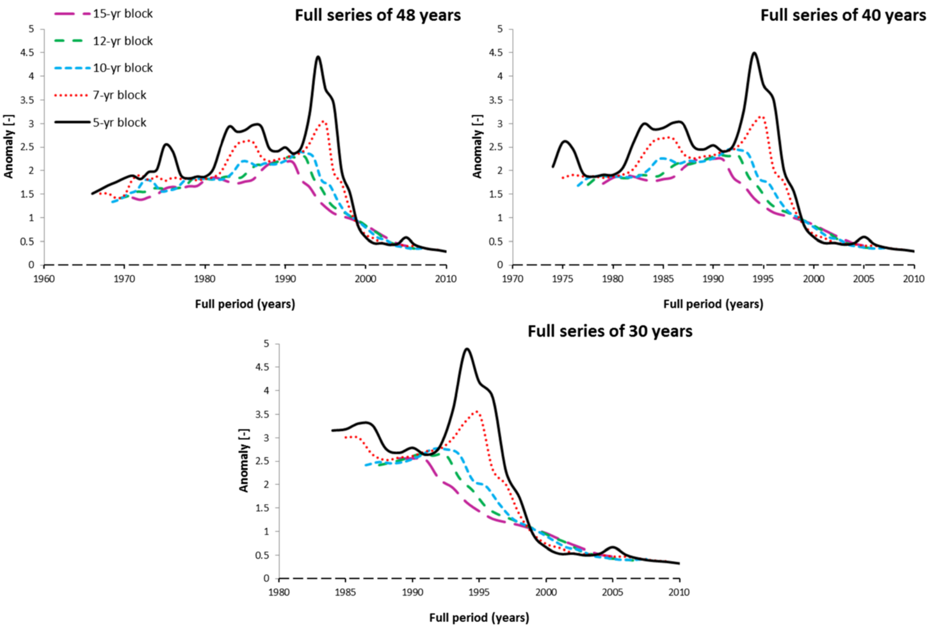

Fig. 4 River flow anomalies comparison for different lengths of block period and full series

50% (anomaly factor of 1.5) is observed at five stations. On the contrary, recent years show statistically significant negative anomalies for seven out of ten stations. At all stations, anomaly values lower than one are common from the 1990s onwards, and statistically significant negative anomalies are observed during the 2000s. The constant decreasing trend can be the result of climate oscillations or catchment changes. The rainfall within this region also shows a decreasing trend but it is not significant (Tabari and Hosseinzadeh Talaee 2011; Soltani et al. 2016). The maximum statistically significant positive anomaly value is about 72% at Artesh-Abad station during the 1970s. On the other hand, the maximum statistically significant negative anomaly value is about 75% at Rahim-Abad and Gherveh stations during the 2000s. The anomalies were also studied for the full range of river flow quantiles by the SM method, as shown in Fig. 6. In this figure, Q_1, Q_2, Q_3, Q_4 and Q_5 denote the first, second, third, fourth and fifth decades of the study period at the station respectively, while Q_F and Q_S denote the first and second halves of each 20-year sub-period, respectively. The SM plots also show an increasing trend in high river flows for the third decade (Q_3) versus the subsequent decade (Q_4) for most of the stations. The decreasing trend in high river flows in the last decade is also confirmed by the SM (i.e., Q_4 vs. Q_5 plot). In the case of low extreme values, a decreasing change is obvious for most decadal periods and the majority of the stations.

The second analysis by the QPM and the SM was done for annual river flows. While the QPM results are similar to the previous analysis with the monthly river flows, the anomaly values in the annual values are much higher (Fig. S1). A discontinuity in the anomaly pattern at Gherveh station is observed which is because of abrupt decreasing changes in the river flows. The river flows at Gherveh station at the second half of the study period are about 59% lower than those during the first half. The pattern of the annual flows by the SM is similar to that of the monthly ones (Fig. S2).

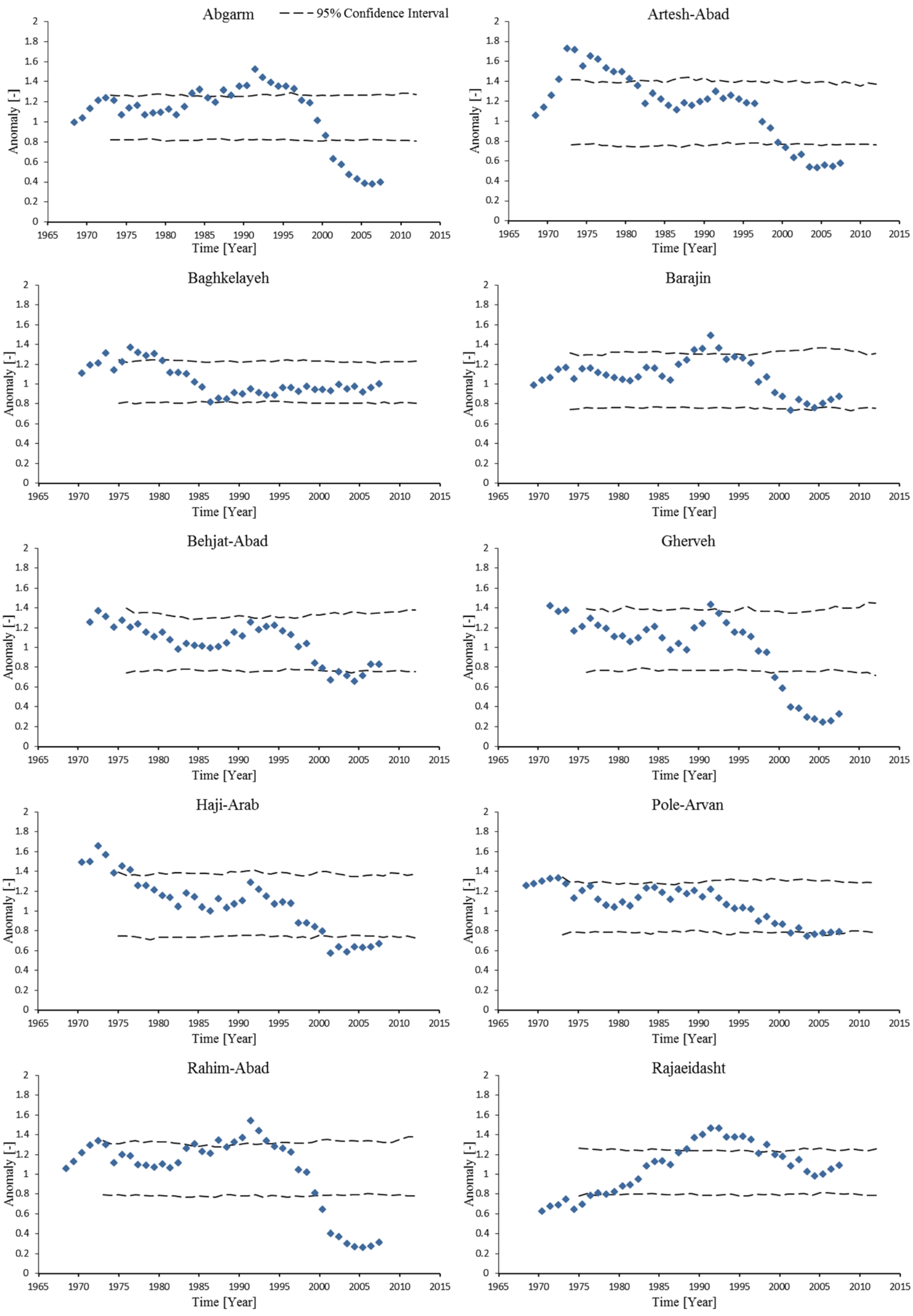

Fig. 5 Temporal variability of monthly high flows considering all seasons based on the QPM method

The monthly river flows were also analyzed for different seasons, limiting the values to the months of each season. For autumn season (OND), the significant positive anomalies are more frequent in the first decades, while increasing occurrence of the significant negative anomalies

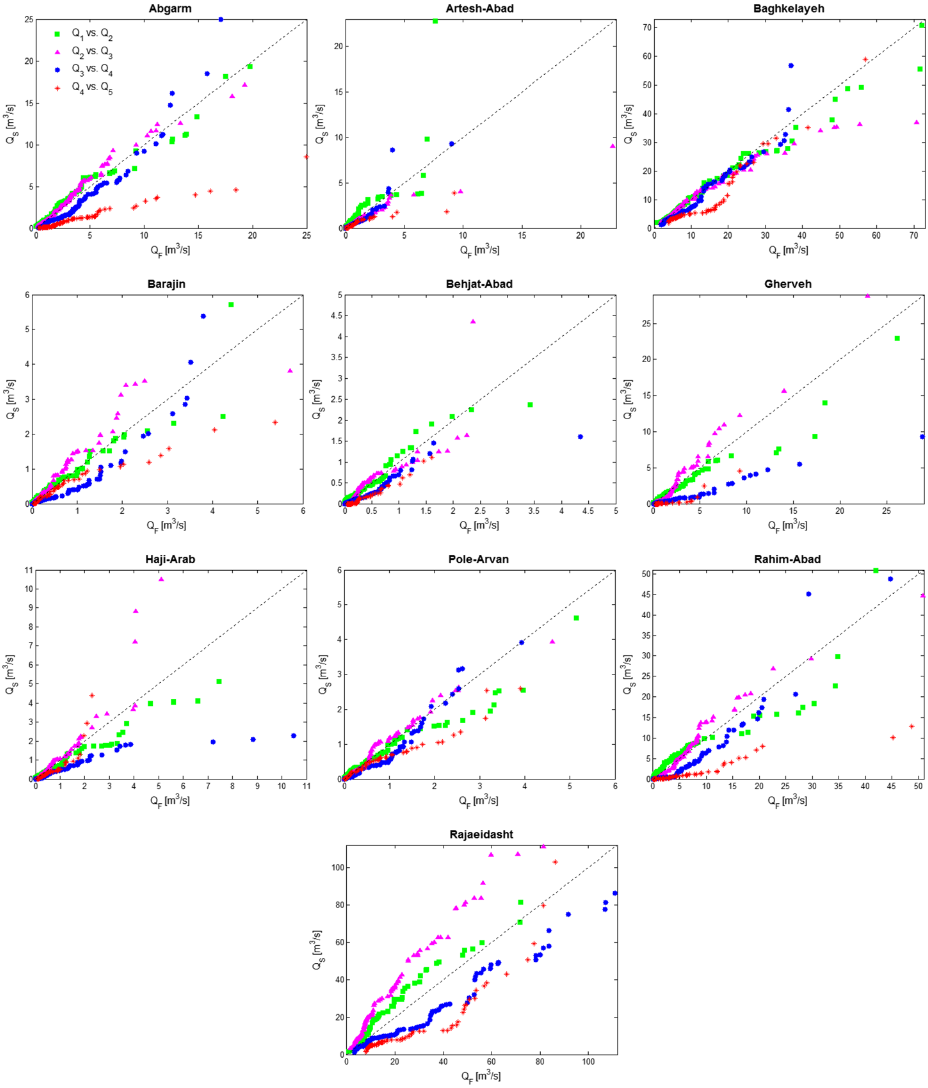

Fig. 6 Trend analysis of monthly flows considering all seasons based on the SM method

is obvious in recent decades (after the mid-1990s) (Fig. 7). The strongest positive anomalies before the 2000s are observed at Rahim-Abad, Gherveh, Haji-Arab and Abgarm stations, while the strongest negative anomalies are found at the same stations. An increasing trend in the high extreme values of autumn river flows for the first decades and a decreasing trend for the last decade are clearly seen from the SM plots (Fig. 8). A decreasing tendency in the low extreme values of autumn river flow during the recent years is also evident for most stations.

Oscillatory type patterns during winter season (JFM) are observed at three stations, Pole-Arvan, Barajin and Behjat-Abad, in which the period before the 1990s was an oscillation high period with positive anomaly values followed by an oscillation low period in the 2000s. Stations at Rahim-Abad and Gherveh show very high anomaly values in which one can see that the variability at these locations is very extreme. The oscillatory behavior of winter river

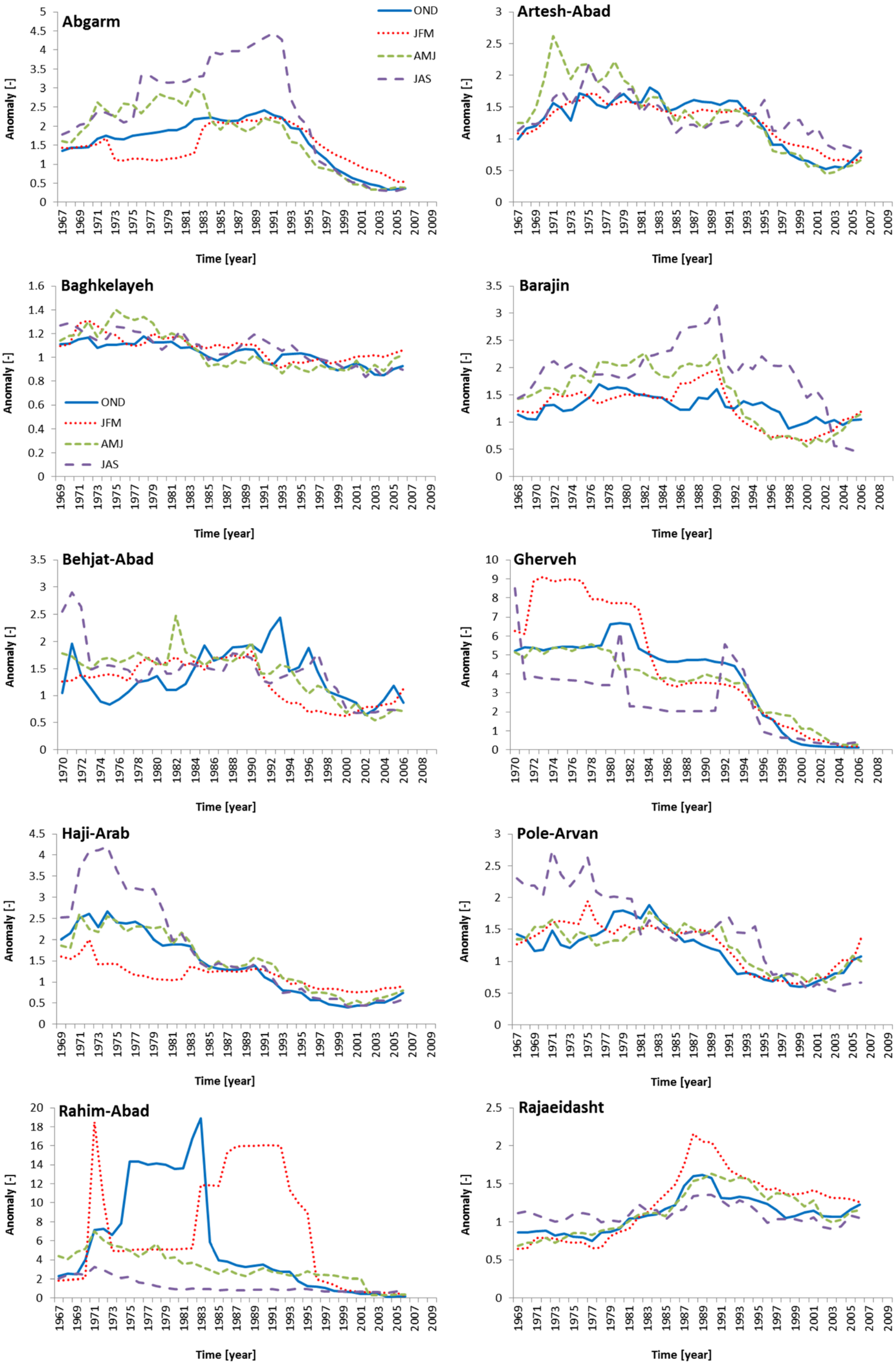

Fig. 7 Temporal variability of monthly high flows based on the QPM method during different seasons: OND: October–November-December; JFM: January–February-March; AMJ: April–May-June; JAS: July–August-September

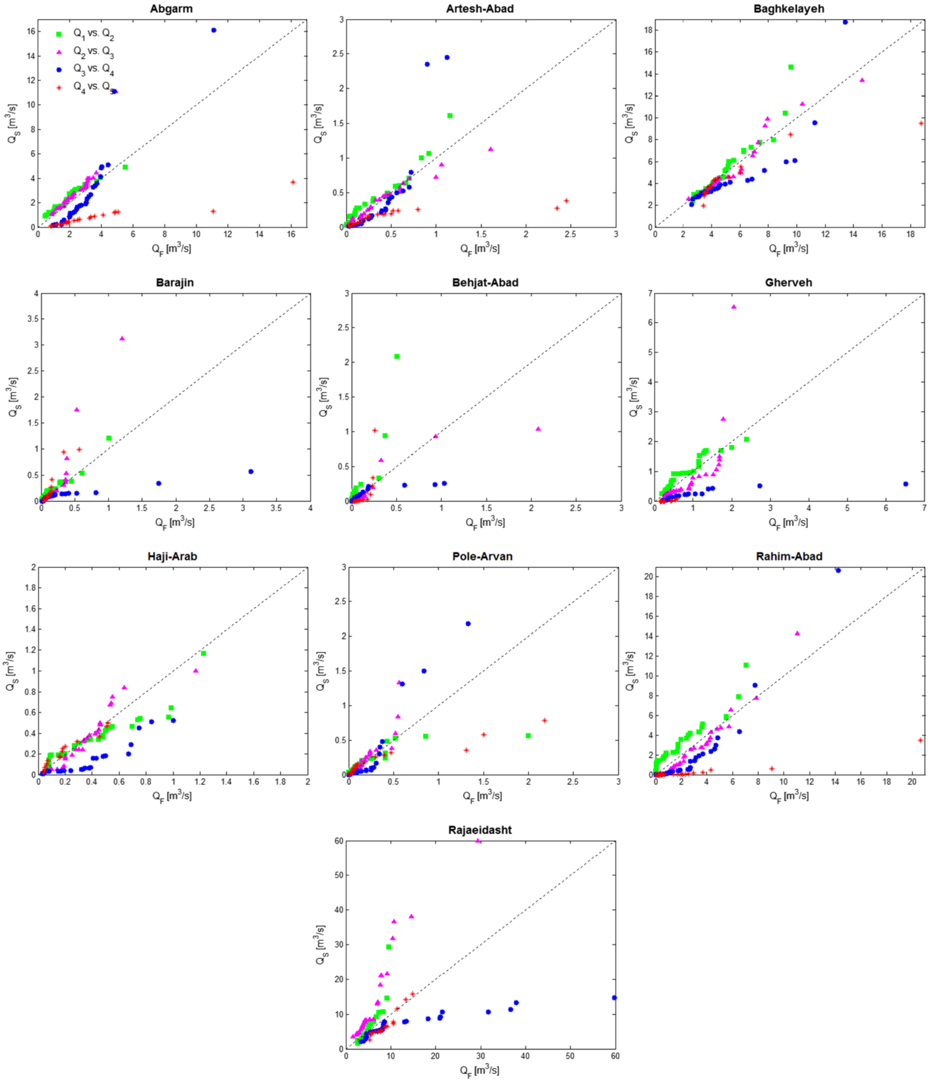

Fig. 8 Trend analysis of monthly flows in autumn (October–November-December: OND) based on the SM method

flows was also examined by the SM plots. For instance, from the SM plots it is seen that winter river flow at Rahim-Abad station has more anomalous behavior compared with Haji-Arab station at which the data are concentrated on the 1:1 line (Fig. 9). The increasing trend in high extremes in the first decade at Haji-Arab station based on the SM is in good agreement with the significant positive anomaly obtained by the QPM.

The spring season is when melting of the snow occurs in the region (Masih et al. 2011; Karimi et al. 2016). Similar result as that of all the seasons is observed for the spring season. Similar to the previous results, the dominant observation is the decreasing trend in most of the stations. The negative anomalies in the spring season (AMJ) are significant during the 2000s for eight out of ten study stations. Considering the high spring flows by the SM (Fig. 10), the

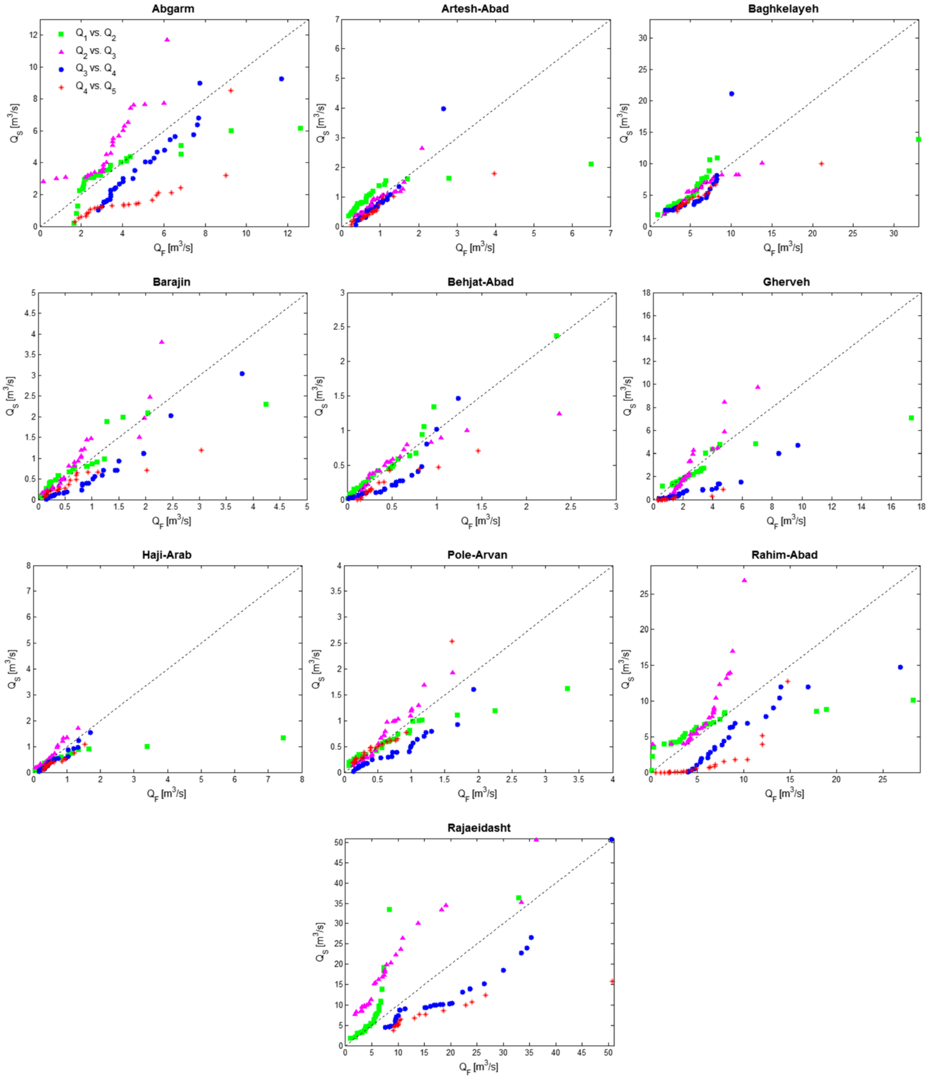

Fig. 9 Trend analysis of monthly flows in winter (January–February-March: JFM) based on the SM method

scatter points for most stations during the last decade are also located in the lower triangular area, indicating a decreasing trend. As for the low spring flows, there appears to be a decreasing trend in the recent years at most stations as well.

The decadal variability of the river flow during summer season (JAS) is common to most stations, especially those situated in the southern part of the region. Like other flow series, positive anomalies occurred more often in the summer season during the first decade, whereas the prevalence of negative anomalies is apparent in the last decades (Fig. 7). The significant positive anomaly factors go as high as 8.5 at Gherveh (the early 1970s), 4.5 at Abgarm (the early 1990s) and 4.2 at Haji-Arab (the mid-1970s) stations. On the other hand, a negative anomaly factor of 0.3 is found after the 2000s at Gherveh station. The summer patterns for high extreme values based on the SM are similar to those for the winter series at which a

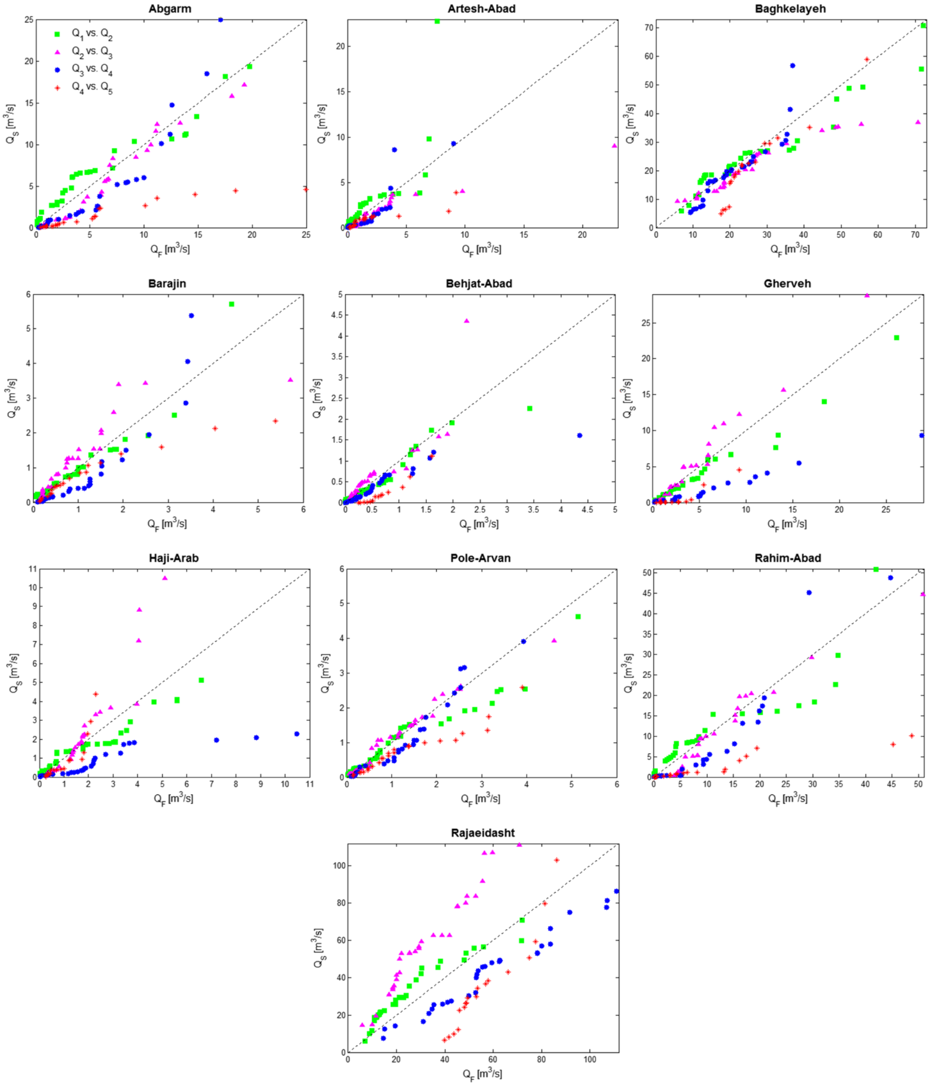

Fig. 10 Trend analysis of monthly flows in spring (April–May-June: AMJ) based on the SM method

decreasing trend is dominant (Fig. 11). A decreasing tendency can also be seen in the low extreme values of summer river flow at most stations, though the trends are weak in some cases.

5 Conclusions

This study was conducted to investigate decadal variations in river flows making combined use of two novel methods that do not need the restrictive assumptions for serial correlation and normality. The main findings of the river flow analysis are summarized as follows:

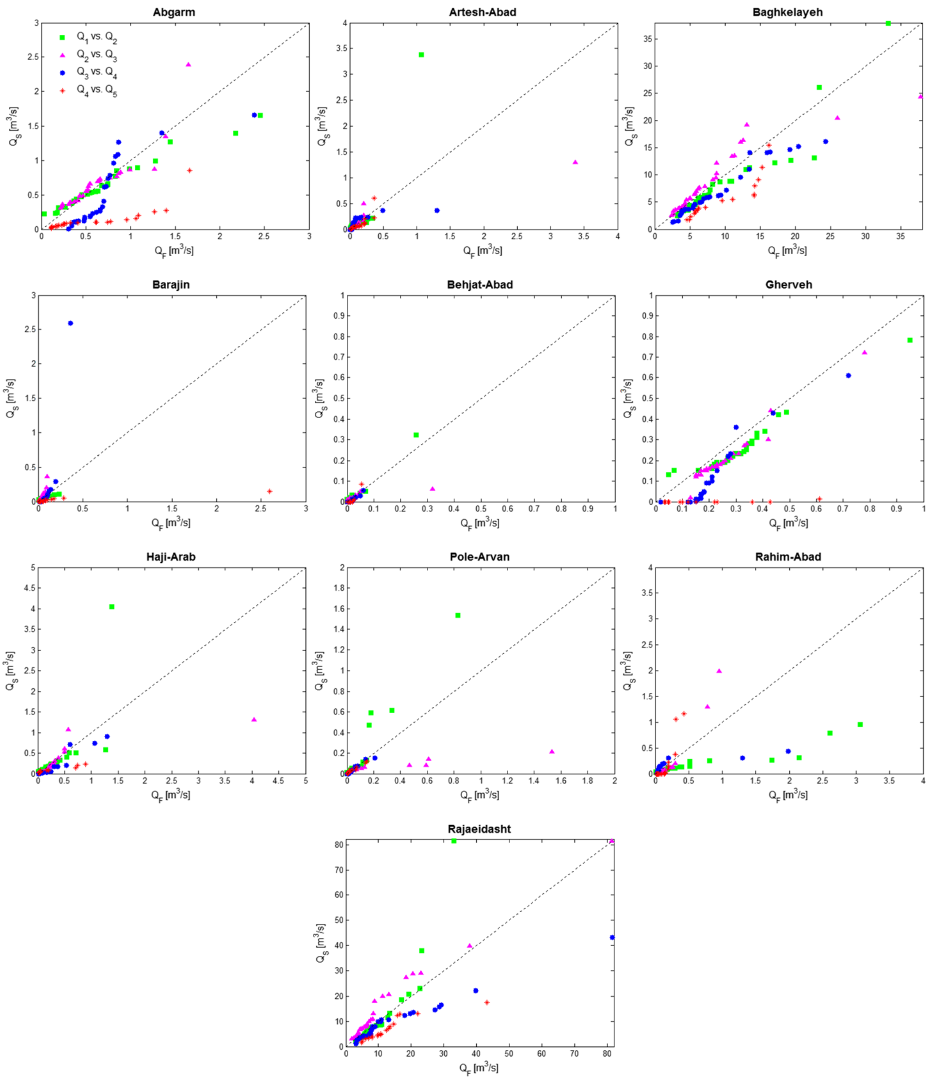

Fig. 11 Trend analysis of monthly flows in summer (July–August-September: JAS) based on the SM method

1- From the analysis considering the river flow data from all seasons, it can be concluded that the 1990s was an oscillation high period with positive anomaly values. Anomaly values less than one are common from the 1990s onwards and become significant during the 2000s. The SM method confirms the results obtained by the QPM method and also shows dominancy of a decreasing change in low extreme values for the recent years.
2- The general decreasing tendency of river flow extremes in recent years also became obvious from the seasonal analysis by both the QPM and SM methods.
3- There is a good conformity between the results of the QPM and the SM, because the anomaly calculated by the QPM method corresponds to the relative ratio of the quantiles if in the SM method the values would be plotted for the same sub-period (such as a decadal basis, which was performed in our study).

This study suggested a method for using the QPM and the SM simultaneously for hydrological trend analysis. In this study, river flow time series were analyzed on a decadal basis. Sub-decadal or multi-decadal variations in river flows can also be examined depending on the intended use of the results. The latter one also depends on the length of available time series, which is a major constraint in performing such an analysis in most developing countries. Although the existence of zero flow values in the study stations made it impossible to analyze low flows by the QPM method; however, the obtained results approve the ability of the SM and QPM methods for analyzing high and low extremes in different seasons. The findings are helpful in order to identify the temporal structure of hydrological time series that are sometimes very complex and influenced by several phenomena.

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