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ORIGINAL PAPER

Quantitatively evaluating the effects of climate factors on runoff change for Aksu River in northwestern China

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Abstract Much attention has recently been focused on the effects that precipitation and potential evapotranspiration (PET) have had on runoff change; however, the influence of temperature on runoff needs to be further studied. We attempted to employ the improved elasticity method to evaluate the effects of climate factors (CF, especially temperature) on runoff change for Aksu River in the arid region of northwest China. Data from Aksu River in the arid region of northwest China were analyzed to investigate changes in annual runoff and CF during the period of 1960–2010. The key findings of this study indicated that the annual runoff had a significant ($P<0.01$) increasing trend with a rate of 3.78×10^{8} m^3/decade, and the temperature and precipitation also exhibited significant rising trends, at a rate of 0.28 °C/decade ($P<0.01$) and 15.11 mm/decade ($P<0.05$), respectively, while PET showed a decreasing trend (22.66 mm/decade, $P<0.01$). Step change point in runoff occurred in the year 1993. Thus, we employed the mean runoff and climate factors during the period 1960–1993 as the benchmark value to measure the change. In 1994–2010, mean runoff increased by 22 %. Results also revealed that temperature rising was the most important factor that increased runoff with contribution of 45 %, while precipitation and PET were responsible for 22 and 27 % of the runoff change, respectively, indicating that the runoff of increasing percentage only accounted for 6 % owing to human activities and other factors, and showed that climate variability was the main reason for the runoff change in Aksu River.

1 Introduction

Climate variation has made the global water cycle remarkably change (Milly et al. 2005; Chen et al. 2013; Chen and Chen 2014). With a worsening of the water shortage problem and increasing of global average temperature, much attention has recently been focused on the effects of climate variation on hydrological cycle (IPCC 2007). As a particular case, the air temperature in the arid region of northwest China has been increasing by a rate of 0.33–0.39 °C/decade in recent 50 years (Zhang et al. 2010; Li et al. 2012a, 2013a), higher than the average of China (0.25 °C/decade) (Ren et al. 2005) and that of the entire globe (0.13 °C/decade) (IPCC 2007) for the same period. This further exacerbated the vulnerability and uncertainty of water resources system that is mainly recharged by mountain glacier and snow melt water (Xu et al. 2011). Therefore, quantitatively evaluating these effects is important for regional water resources assessment and management.

Recently, some new approaches have been proposed to explore the effects of climate change and human activities on runoff (Ma et al. 2008a; Liu et al. 2010; Zhang et al. 2012; Meng and Mo 2012; Jiang et al. 2012; Li et al. 2014a). For example, Jiang et al. (2011) have identified the climate variability and human activities on runoff from the Laohahe Basin by using double cumulative curve method. Zheng et al. (2009) attempted to analyze the responses of streamflow to precipitation, potential evapotranspiration (PET), and land surface change in the headwaters of the Yellow River Basin. Meanwhile, hydrologic sensitivity analysis method has been employed to probe into the effects of precipitation and PET on runoff for Kaidu River Basin in arid region of northwest China

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(Chen et al. 2013) and to quantitatively assess the impacts of climate variability and human activities on runoff changes in Haihe River Basin (Wang et al. 2013). Zang et al. (2013) illustrated the impacts of human activities and climate variability on green and blue water flows in the Heihe River Basin in northwest China. Ye et al. (2009, 2013) distinguished the relative impacts of climate change and human activities on variation of streamflow in the Poyang Lake catchment in China by using a coupled water and energy budgets analysis. Li et al. (2014b) utilized statistical methods to separate the impacts of climate variation and human activities on runoff in the Songhua River Basin of northeast China. Zeng et al. (2014) investigated the impacts of climate on runoff changes at annual, seasonal, and monthly time scales in the Zhang River Basin of north China-based hydrological modeling and sensitivity method. It can be seen that more research focus in humid and semi-humid regions, but less study has been done on special hydrological processes in arid areas. Moreover, several selected methods, such as gray correlation analysis method (Yang et al. 2005), linear regression method (Jiang et al. 2011), the double mass curve method (Jiang et al. 2012), water balance method, hydrological sensitivity analysis (Chen et al. 2013; Ye et al. 2009, 2013; Li et al. 2014b; Zeng et al. 2014), hydrological model (Zhang et al. 2012; Zang et al. 2013; Li et al. 2014a), slope change ratio of accumulative quantity method (Wang et al. 2012), etc., were applied to quantitatively differentiate the effects of climate change and human activities on runoff. Hydrological model method has a strong physical basis, but there is still obvious uncertainty (Song et al. 2013). Statistical analysis method can be easily used and demand detailed long-term period observation hydrologic and meteorological data for the basin. These methods can be adopted to quantitatively indicate the impacts of precipitation and PET on runoff (Ye et al. 2009, 2013; Li et al. 2014b); moreover, the effect of temperature on runoff can be only reflected by PET (Zheng et al. 2009; Chen et al. 2013; Wang et al. 2013; Ye et al. 2013; Chen and Chen 2014). However, with the intensifying global warming, the influence of temperature change on water resources gradually strengthened, especially the surface runoff recharges mainly from glacier and snow melt water in arid region rivers, which cannot be reflected accurately the impact of climate change on runoff only by PET. Therefore, these methods are so limited that it is difficult to calculate runoff change directly generated by temperature rising (Chen et al. 2013; Chen and Chen 2014). Thus, it is important to understand the hydrological process responses to different climate factor (temperature, precipitation, and PET) changes in order to develop sustainable basin management strategies.

Aksu River is the main tributary of the Tarim River, and its upper reaches are in the Kunlun Mountains, nearly half of the water from the mountains of glacier and snow melt water in the Tarim Basin. Some scholars have conducted research on the correlation between Aksu River runoff and regional climate change in recent years. Jiang et al. (2005) analyzed both intra-annual distribution law and variation characteristics over years of different supply sources runoff and come to conclusion that annual runoff discharge from glacier and snow smelt water has been increasing since 1990 in mountain area and the rise of temperature has a huge effect on runoff increase than that of precipitation in Aksu River. Li et al. (2008) investigated the relationship between North Atlantic Oscillation and Aksu River runoff by using the methods of wavelet transform and cross wavelet transform and indicated the atmospheric circulation variations caused by NAO has an impact on the climate of the Aksu River Basin; meanwhile, the runoff of the Aksu River is affected. Chen et al. (2009) pointed out that the increase of temperature in the tributaries of the Aksu River is higher than that in the tributaries of the Yarkand River and Hotan River in the Tarim Basin. Yu et al. (2011) checked the nonlinear characteristics of annual runoff processes from 1957 to 2008 and illustrated that the annual runoff in Aksu River will show an increasing trend in the future. Xu et al. (2011) found that there was a close relationship between variations in the annual runoff of the Aksu River and regional climate change. Li et al. (2012b) found that if runoff recharge proportion from glacier and snow smelt water is very large, the correlation between runoff and temperature is significantly positive in typical river area. Predecessors' research results show that annual runoff discharge from glacier and snow smelt water is about 42 % (Jiang et al. 2005); thus, we guess that the influence of temperature on runoff is very important in the Aksu River. These studies analyzed qualitatively the influence of climate on Aksu River runoff but did not explore quantitatively the effect of climate factors on runoff.

In this study, firstly, we make an attempt to improve elasticity method based on the principle of elasticity theory; secondly, we further quantitatively evaluate the impact of temperature, precipitation, and PET on annual runoff change for Aksu River in the arid region of northwest China by using the improved elasticity method.

2 Materials and methods

2.1 Study area

Located on the south slope of the Tianshan Mountains and the northwest edge of the Tarim Basin, Aksu River is the largest runoff of the rivers and is enclosed between latitudes 40° 17′–42°27′ N and longitudes 75° 35′–80° 59′ E (Fig. 1) with a basin area of 5.14×10^4 km^2 (Xu et al. 2011). The topography descends gradually from north to south and from west to east, featured by unique terrain from high to low, low-middle mountain and hill, group of piedmont pluvial fans, tilted

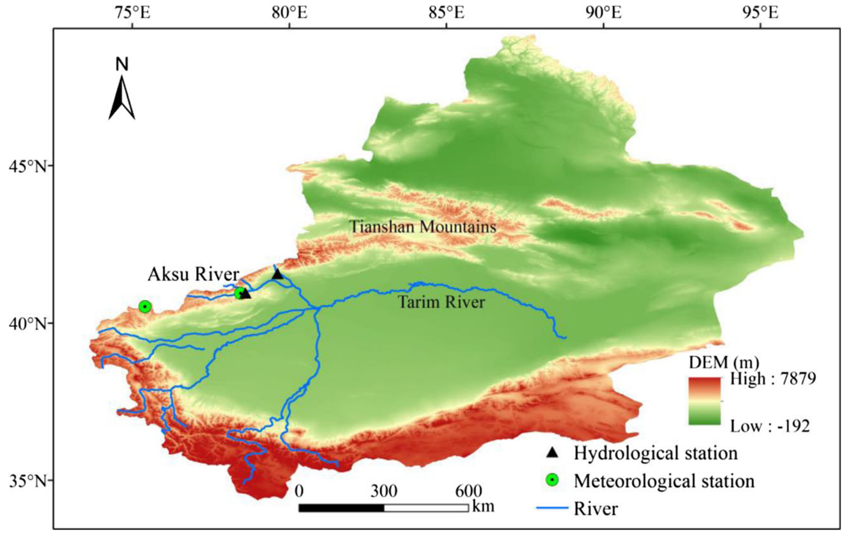

Fig. 1 Location of the Aksu River and the distribution of meteorological station and hydrological station

alluvial-proluvial plain, and alluvial plain (elevation of 1000–1500 m) in turn. The Aksu River belongs to temperate continental arid climate, which is characterized by drought, lack of rainfall, intensity evaporation, and large temperature difference between days and years, because of the distinct geographical position and far away from sea; the drainage's average annual temperature, precipitation, and PET are 9.2–11.5 °C, 64 mm, and 1890 mm, respectively (Xu et al. 2011); annual extreme maximum and minimum temperatures are 40.2 and −27.6 °C, respectively, and the mean annual sunshine duration is 2850 h. The Kumalak and Toxkan River, as two main tributaries, join at Kaladuwei before flowing into the Aksu River. Mountainous areas are the major areas of runoff generation for the Aksu River, and the complex climatic condition and hydrological environment causes the runoff fluctuation.

2.2 Data

Monthly runoff data from the Xiehela and Shaliguilake hydrological station in the mountains-pass, which was available for the period from 1960 to 2010, were used in this study. To reflect the effect of mountain climate on runoff, we selected the meteorological station (Aheqi and Toergate) to represent climate variations of mountains area (average elevation of 2746 m). Daily relative humidity, maximum and minimum air temperature, wind speed, and sunshine hours from meteorological station during the period of 1960–2010 were utilized to calculate potential evapotranspiration by the Penman-Monteith equation recommended by FAO (Allen et al. 1998).

All meteorological station data selected for this study had been maintained following the standard methods of the National Meteorological Administration of China, having strict high-quality data control (including extreme inspection and time consistency checks) before releasing these data. The runoff data in each river were obtained from local Hydrology Bureaus. Meanwhile, using the RClimDex software package (available at the ETCCDI website, http://cccma.seos.uvic.ca/ETCCDI/ software.shtml) attained data quality control and homogeneity assessment (You et al. 2011).

2.3 Method

2.3.1 Elasticity theory method

The concept of elasticity theory could be used to detect the effect of an independent variable on the dependent variable (Jin and Wu 2002). To quantitatively evaluate the impacts of climate factors on the runoff change, we first assume that the attributions of runoff change to climate factors (CF) and non-CF-related change (such as human activities and other factors) can be approximated as follows:

$$\Delta Q = f'_C \Delta C + \Delta f'_N \Delta N \tag{1}$$

$$f'_C \Delta C = f'_T \Delta T + f'_P \Delta P + f'_E \Delta E \tag{2}$$

where ΔQ, ΔC, and ΔN are changes in runoff, CF (including ΔT, ΔP, and ΔE are changes in temperature, precipitation, and potential evapotranspiration, respectively) and non-CF, respectively, with $f'_T = \partial Q / \partial T$, $f'_P = \partial Q / \partial P$, $f'_E = \partial Q / \partial E$, and $f'_N = \partial Q / \partial N$. If we assume that the every factor is independent of other change factors, Eqs. (1) and (2) can be written as the following:

$$\Delta Q = \Delta Q_T + \Delta Q_P + \Delta Q_E + \Delta Q_N \tag{3}$$

$$\Delta Q_T = f'_T \Delta T \tag{4}$$

$$\Delta Q_P = f'_P \Delta P \tag{5}$$

$$\Delta Q_E = f'_E \Delta E \tag{6}$$

$$\Delta Q_N = f'_N \Delta N \tag{7}$$

where ΔQ_T, ΔQ_P, ΔQ_E, and ΔQ_N change in runoff due to temperature, precipitation, potential evapotranspiration, and non-CF, respectively. This framework is used to separate the effects of CF and non-CF factors on runoff.

Following the method (Schaake 1990), this study defines the climate factor (C_i) elasticity regarding runoff (ε_i) as the ratio of the proportional change of runoff to the proportional change of the factor:

$$\varepsilon_i = \frac{dQ/Q}{dC_i/C_i} \tag{8}$$

$$i\in\{\text{temperature, precipitation, potential evapotranspiration}\}$$

The physical meaning of ε_i is that 1 % of a factor change may lead to ε_i% of runoff change. Based on Eq. (8), we rewrite Eq. (4–6) as

$$\Delta Q_i = (\varepsilon_i \Delta C_i / C_i) \cdot Q \tag{9}$$

$$i\in\{\text{temperature, precipitation, potential evapotranspiration}\}$$

From Eq. (8) we also see

$$\varepsilon_i = \frac{dQ\,C_i}{dC_i\,Q} = f'_{Ci} C_i / Q \tag{10}$$

$$i\in\{\text{temperature, precipitation, potential evapotranspiration}\}$$

If the relationship between runoff and CF is known, the CF elasticity can be derived mathematically.

Following the literature (Schaake 1990; Sankarasubramanian et al. 2001; Zheng et al. 2009), we utilize a nonparametric estimator to deserve the relationship between runoff and CF directly based on observation values:

$$\left(Q_j - Q_b\right)/Q_b = \varepsilon_i \left(C_{ij} - C_{ib}\right)/C_{ib} \tag{11}$$

where ε_i is elasticity of runoff with respect to CF; Q_j and C_{ij} are yearly runoff and the factor values, with j=1960, 1961, … 2010; Q_b and C_{ib} are the benchmark value for the runoff and CF, respectively. Therefore, ε_i can be regarded as the linear regression coefficient between $(Q_j - Q_b)/Q_b$ and $(C_{ij} - C_{ib})/C_{ib}$.

To quantitatively identify runoff change caused by CF change in the past 50 years, the following formula is used to calculate the change rate of runoff:

$$\varphi_i = 100\% \times \left(\varepsilon_i \cdot \frac{\Delta C_i}{C_{ib}} \cdot Q_b\right) / \Delta Q \tag{12}$$

where ΔC_i and ΔQ are the changes of CF and runoff during the period 1960–2010, respectively. Thus, φ_i is the importance of the CF variation in runoff change in recent 50 years.

A vast number of climate elastic analysis methods exist; however, the elastic analysis based on nonparametric method has higher effectiveness and stability (Sankarasubramanian et al. 2001). To verify the result of this paper, we adopt the nonparametric elastic analysis method proposed by Zheng et al. (2009) to explore the sensitivity of annual runoff to the CF. The method is widely utilized to present the sensitivity of hydrological elements to changes in meteorological elements in the process of the effect of climate change on hydrological system (Zheng et al. 2009; Chen et al. 2012; Li et al. 2013b). The formula is as follows (Zheng et al. 2009):

$$\varepsilon = \frac{\overline{X}}{\overline{Q}} \frac{\sum \left(X_i - \overline{X}\right)\left(Q_i - \overline{Q}\right)}{\sum \left(X_i - \overline{X}\right)^2} \tag{13}$$

where X_i denotes the meteorological element, Q_i denotes the annual runoff, ε is the sensitivity coefficient, and $\overline{X}$ and $\overline{Q}$ are mean values of runoff and meteorological element in many years, respectively.

2.3.2 Trend test

We employed the Mann-Kendall (MK) statistical test (Mann 1945; Kendall 1975) to test the significance of trends in the annual runoff, temperature, and PET in the study area. The nonparametric Mann-Kendall statistical test has been commonly adopted to assess the significance of monotonic trends in meteorological and hydrologic series (Chen and Xu 2005; Zhang et al. 2011). For a time series $X=\{x_1, x_2, \ldots, x_n\}$, when $n>10$, the standard normal statistic Z is estimated as follows:

$$Z = \begin{cases} (S-1)/\sqrt{\operatorname{var}(S)} & S > 0 \\ 0 & 0 \\ (S+1)/\sqrt{\operatorname{var}(S)} & S < 0 \end{cases} \tag{14}$$

where

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \operatorname{sgn}\left(x_j - x_i\right) \tag{15}$$

$$\mathrm{sgn}(\theta) = \begin{cases} +1, & \theta > 0 \\ 0, & \theta = 0 \\ -1, & \theta < 0 \end{cases} \qquad (16)$$

$$\mathrm{var}(S) = \left[n(n-1)(2n+5) - \sum_t t(t-1)(2t+5) \right] / 18 \qquad (17)$$

where t is the extent of any given tie, and Σ_t denotes the summation of all ties.

2.3.3 Step change point analysis

The nonparametric Mann-Kendall-Sneyers test (Mann 1945; Kendall 1975; Sneyers 1975) was applied in this study for determining the occurrence of step change points of climate factor and runoff. $x_1, \ldots, x_n$ represent the data points. The numbers m_i of elements x_j preceding it ($j < i$) such that $x_j < x_i$ are computed for each element x_i. Under the null hypothesis (no step change point), the normally distributed statistic t_k can be described as follows:

$$t_k = \sum_{i=1}^{k} m_i \qquad (2 \le k \le n) \qquad (18)$$

t_k as mean and variance of the normally distributed statistic can be calculated as follows:

$$\bar{t}_k = E(t_k) = k(k-1)/4 \qquad (19)$$

$$\mathrm{var}(t_k) = k(k-1)(2k+5)/72 \qquad (20)$$

u_k as the normalized variable statistic is given in following formula:

$$u_k = \left(t_k - \bar{t}_k\right) / \sqrt{\mathrm{var}(t_k)} \qquad (21)$$

3 Results

3.1 Trend of CF and runoff

Figure 2 shows long-term variations in annual runoff, temperature, precipitation, and potential evapotranspiration (PET) for Aksu River from 1960 to 2010. Mann-Kendall statistical test reveals that the runoff and temperature exhibits an increasing trend at $P<0.01$ significant level, with the rate of 3.78×10^8 m^3/decade and 0.28 °C/decade, respectively. Precipitation shows significant upward trend ($P<0.05$) with the rate of 15.11 mm/decade. However, the PET has a significant decreasing trend ($P<0.01$) at a rate of 22.66 mm/decade.

The Mann-Kendall-Sneyers test was applied to detect the step change point of the annual runoff during 1960 to 2010. Figure 3 shows the computed probability series of the step change point years for runoff. The intersection of the curves indicates that there is a step change point in 1993 (at $P<0.05$ significance level) for the runoff. The value is consistent with the results from previous research (Li et al. 2008). To investigate the effect of CF on runoff, we also carried out the test for annual temperature, precipitation, and PET. The results reveal that abrupt changes in temperature (1993), precipitation (1992 and 1994), and PET (1990) basically occurred in the early 1990s. That is to say, from 1994 to 2010, runoff had significant change caused by climate and other factors. In this study, we used the mean runoff and CF of 1960–1993 as the benchmark value to measure the change. Concurrently, annual runoff, temperature, and precipitation in 1994–2010 was more about 22, 60, and 23 %, respectively, than that of the period 1960–1993, while annual PET was less 5 %.

3.2 CF elasticity of runoff

Figure 4 shows the linear regression relationships between the proportional change in temperature, precipitation, PET, and that in runoff. Regression equation reveals that between the temperature, precipitation and runoff during 1960–2010 exhibited significant positive correlation (Fig. 4a, b), while there was a significant negative correlation between PET and runoff (Fig. 4c). In addition, F test and correlation significance test are conducted on 51 (or 50) samples in temperature, PET (or precipitation), and runoff. Confidence is taken as 99 % and $P<0.01$. The 1 % significance level of the statistical test is passed, indicating that the linear regression coefficient can well display their relationship.

Based on Eq. (11) and Fig. 4, the elasticity of runoff in relation to temperature (ε_T) and precipitation (ε_P) are 0.1656 and 0.2078, respectively, which means that 10 % increase in temperature and precipitation will result in a 1.656 and 2.078 % increase in runoff. Meanwhile, the PET elasticity of runoff is estimated to be −1.1865 (ε_{PET}), which means that 1 % reduction in PET will lead to a 1.1865 % increase in runoff.

3.3 Impacts of CF on runoff

Based on CF change rates and elasticity of runoff in relation to precipitation, temperature, and PET, using Eq. (12), we can quantitatively evaluate the effects of climate factors on runoff change (Table 1). The results show that temperature change

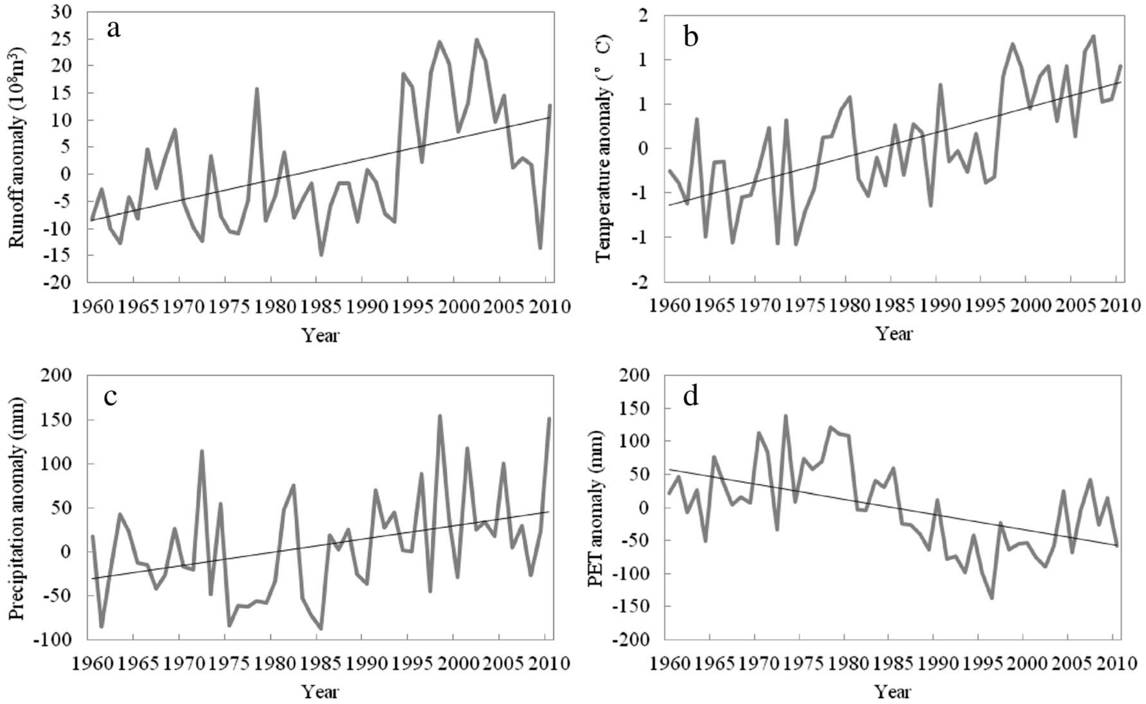

Fig. 2 Trend of runoff (**a**), temperature (**b**), precipitation (**c**), and PET (**d**) for Aksu River from 1960 to 2010

has the most importance effect on runoff change in recent 50 years, which may be related to runoff recharge larger proportions from glacier and snow melt water; on the other hand, the air temperature rises faster than other areas. Meanwhile, we can calculate the contributions of temperature, precipitation, and PET to runoff change in Aksu River with 45, 22, and 27 %, respectively, which indicates that the importance of runoff change for other factors (such as human activities, etc.) is about 6 %.

In addition, the research results in Table 1 are basically consistent with those Zheng et al. (2009) who came up with the other method obtained (Eq. 13), which implies that the suitability of this method (elasticity theory) to the area is credible and the conclusion of this article has the rationality and reliability. The conclusion in two methods is that the importance of runoff change in Aksu River for climate factors is more than 90 %. Similarly, the research results of Chen et al. (2013) revealed that due to climate change, the increasing percentage in runoff of Kaidu River accounted for 90.5 % for the Tarim Basin, which is basically consistent with our results. Kaidu River also belongs to the Tarim Basin, plus, its runoff recharge proportion is from glacier and snow smelt water is also large. Thus, we can see that our results are believable.

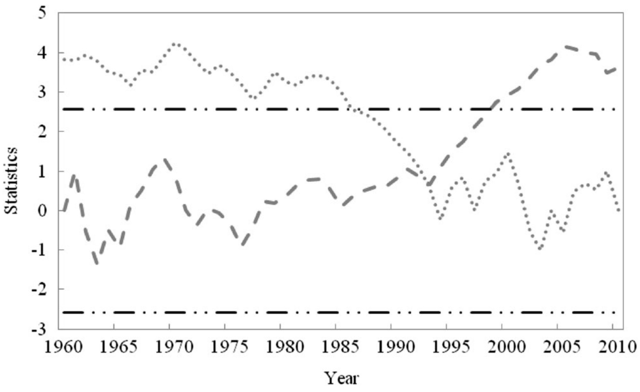

Fig. 3 The step change point of annual runoff for Aksu River in recent 50 years

4 Discussion and conclusion

It is important to determine the impact of climate factors on runoff variation based on observation data. As a result, many methods have been widely adopted to assess the impact. However, it is hard to quantify the effects of temperature rising on runoff change. In this study, we defined a conceptual framework and applied the improved elasticity method to calculate the elasticity of runoff change to climate factors (CF, especially the temperature) in the past 50 years and then evaluated the contributions of CF to runoff change roughly. The results show that this method can be effective to evaluate quantitatively the influence of climate factors on runoff change. Concurrently, we realize that there are the uncertainties associated with estimating the impact of climate change on runoff using the elasticity method. First, based on

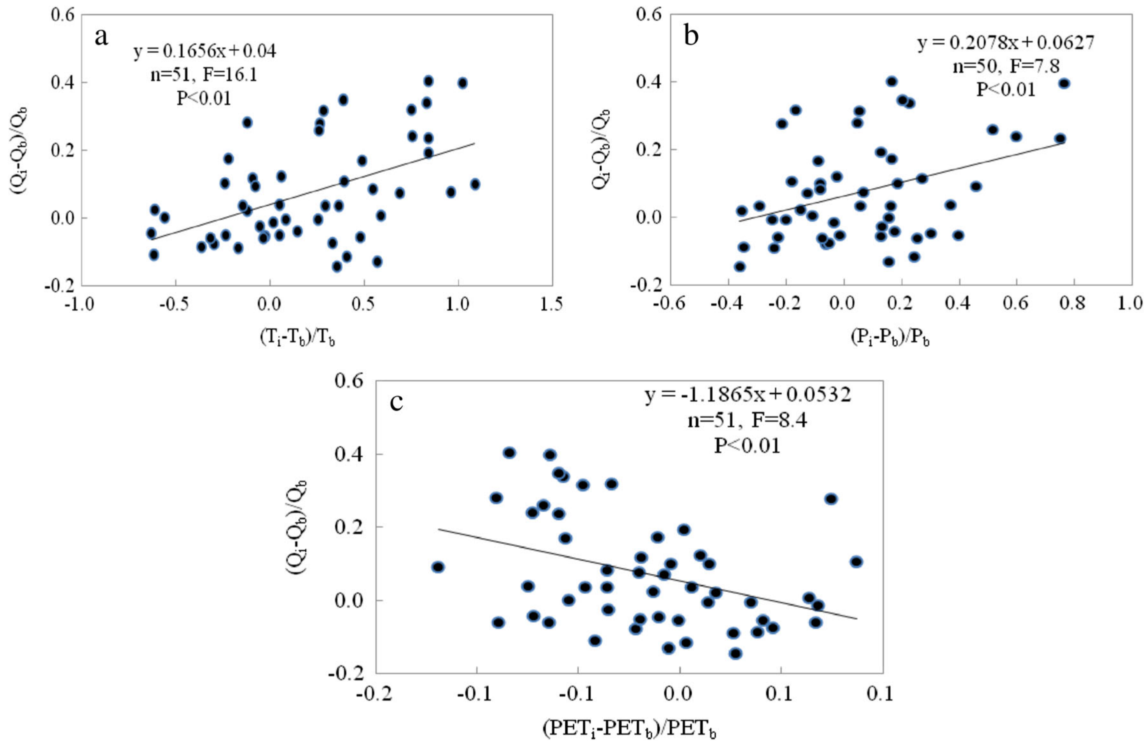

Fig. 4 **a**–**c** The regression relationships between the proportional change of runoff and proportional change of temperature, precipitation (remove an abnormal point, $n=50$), and PET for Aksu River from 1960 to 2010

the assumption that every factor is independent of the others, the framework is used to estimate the proportional contribution of climate and other factors changes to runoff. However, in reality, the climate factors and other factors interact with each other. Second, a nonparametric statistical estimator of elasticity (ε) was employed to identify the relationship between runoff and CF, which may involve inevitable uncertainty, for instance, the observation values may be influenced by undetermined factors. Third, we should attempt to use physics-based hydrological models to quantitatively evaluate the effects of climate factors on runoff change and verify it further in the future. All presented uncertainties would affect the results to some degree, and so estimation uncertainties need be further explored in further studies.

The contribution of climate factors (especially the temperature) to runoff change has not quantitatively been assessed clearly for the arid region during the period 1960–2010. From the current study, we can conclude that the temperature change in Aksu River is the most important (45 %) to runoff variation, while the non-climate factors (such as human activities, etc.) are responsible for about 6 % of the runoff change in recent 50 years. Similarly, Chen et al. (2013) research results showed that due to human activities, the increasing percentage in runoff of Kaidu River in Tarim Basin only accounted for 9.5 % in the arid region, which is basically consistent with our results. Meanwhile, Huo et al. (2008) studied the effects of climate changes and water-related human activities on annual stream flows of the Shiyang River Basin in arid northwest China and pointed out that climate change was responsible for a large proportion of the runoff decreases in the upstream section of the catchment during the 1980s and 1990s, while human activities gave rise to runoff decreases in the

Table 1 Quantitatively evaluating the effects of climate factors on runoff change on the basis of different climate elasticity estimators

Item	Change rate (%)	ε_i		CF result in runoff change (10^8 m^3)		Importance of runoff change for CF (%)	
		This study	Equation (13)	This study	Equation (13)	This study	Equation (13)
Temperature	60 %	0.1656	0.1815	7.2	7.9	45 %	50 %
Precipitation	23 %	0.2078	0.1602	3.5	2.7	22 %	17 %
PET	5 %	−1.1865	−1.0507	4.3	3.8	27 %	24 %
Total	–	–	–	15	14.4	94 %	91 %

downstream for the same period. Our study area is the upstream of Aksu River, so regional climate is the important reason for the annual runoff change. Ma et al. (2008a) found that precipitation variability was the most important factor that decreased runoff for Zamu catchment in the arid region, which was different from our study. Because the Zamu Basin runoff recharge from mountain precipitation is the largest, while less runoff recharge proportion (1.4 %) is from glaciers melt water (Ma et al. 2008b). There are three reasons: (1) large runoff recharges proportion (about 42 %) from glaciers and snow melt water in Aksu River (Jiang et al. 2005). (2) The air temperature in the study area had a significant rising trend (Chen et al. 2009), at a rate of 0.28 °C/decade, higher than the average of entire globe (0.13 °C/decade) for the same period (IPCC 2007). (3) The selected hydrological station located in the mountain pass has a good representativeness in runoff change, while human activity intensity is weak in the mountains area.

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