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ORIGINAL PAPER

Quantifying the effects of climate variability and human activities on runoff for Kaidu River Basin in arid region of northwest China

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Abstract Much attention has recently been focused on the effects that climate variability and human activities have had on runoff. In this study, data from the Kaidu River Basin in the arid region of northwest China were analyzed to investigate changes in annual runoff during the period of 1960–2009. The nonparametric Mann–Kendall test and the Mann–Kendall–Sneyers test were used to identify trend and step change point in the annual runoff. It was found that the basin had a significant increasing trend in annual runoff. Step change point in annual runoff was identified in the basin, which occurred in the year around 1993 dividing the long-term runoff series into a natural period (1960–1993) and a human-induced period (1994–2009). Then, the hydrologic sensitivity analysis method was employed to evaluate the effects of climate variability and human activities on mean annual runoff for the human-induced period based on precipitation and potential evapotranspiration. In 1994–2009, climate variability was the main factor that increased runoff with contribution of 90.5 %, while the increasing percentage due to human activities only accounted for 9.5 %, showing that runoff in the Kaidu River Basin is more sensitive to climate variability than human activities. This study quantitatively distinguishes the effects between climate variability and human activities on runoff, which can do duty for a reference for regional water resources assessment and management.

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1 Introduction

The hydrological cycle of a basin is a complex process influenced by climate, physical characteristics of the basin, and human activities. With the worsening of the water shortage problems and the increasing number of water-related disasters globally, the effects of climate variability and human activities on water resources have long been a focus of global hydrology research (Ren et al. 2002; Scanlon et al. 2007; IPCC 2007). Climate variability is believed to have led to global warming and changing patterns of precipitation, while human activities have changed the temporal and spatial distribution of water resources (Govinda 1995; Ye et al. 2003; Milly et al. 2005). In arid and semiarid regions, the effects of climate variability and human activities on runoff are significantly more sensitive, and these effects have resulted in reduction or increase in water yield (Brown et al. 2005; Ma et al. 2008; Jiang et al. 2011). Evaluating these effects quantitatively is important for regional water resources assessment and management.

The effects of human activities on runoff in northern China have traditionally been estimated by computing their impact on each component in the water balance equation (Ren et al. 2002). This method, however, is limited because it is difficult to compute the direct effect of human activities on each component for complex and rapidly changing characteristics of water supply and utilization. New attempts, including regression analysis (Ye et al. 2003; Huo et al. 2008; Tian et al. 2009), sensitivity analysis (Dooge et al. 1999; Milly and Dunne 2002; Ma et al. 2008; Jiang et al. 2011), and hydrologic model simulation method (Jones et al. 2006; Wang et al. 2008; Liu et al. 2010), have been made recently to undertake this problem. Thereinto, sensitivity analysis method is widely used, and it is a framework to estimate the sensitivity of annual runoff to precipitation and potential evaporation (Dooge et al. 1999; Milly and Dunne 2002). Li et al. (2007), Ma et al.

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(2008), and Jiang et al. (2011) used sensitivity analysis method to separate the effects of climate variability and human activities on runoff in the Wuding River Basin, Shiyang River Basin, and Laohahe River Basin, respectively, and showed that the impacts of climate variability and human activities on river discharge were more significant in arid and semiarid areas than that in more humid areas.

In the last 50 years, the inland river basins in arid region of northwest China have experienced changes both in climate and land use/cover. Studies showed that the regional climate is becoming warmer and wetter (Shi et al. 2007; Piao et al. 2010) and the trend is likely to continue into the future (Shi et al. 2007). It is important to understand the hydrological responses to these changes in order to develop sustainable basin management strategies. In this study, we will investigate the changes in one of the inland river basins in the region, the Kaidu River Basin. In the basin, climate variability and water-related human activities have influenced water resources (Xu et al. 2008; Tao et al. 2011), and basin water resources management is facing a huge challenge. The objective of the study was to (1) determine trends and step change points in annual runoff of the basin and (2) estimate the effects of climate variability and human activities on runoff.

2 Materials and methods

2.1 Study area

The Kaidu River, a main tributary that discharges into the downstream of the Tarim River, is situated at the north fringe of the Yanqi Basin on the south slope of the Tian Shan Mountains in Xinjiang (41°47′–43°21′ N, 82°58′–86°55′ E). The river starts from the Hargat Valley and the Jacsta Valley in the Sarming Mountain and ends in the Bosten Lake which is located in Bohu county of Xinjiang. The basin area of the Kaidu River above Dashankou is 18,827 km^2, with the elevation of 1,042–4,796 m (Fig. 1). The small population living in the mountainous environment of the Kaidu River Basin upstream of the Dashankou station has only slightly perturbed the environmental conditions mainly through the grazing. In the basin, the average annual temperature is only −4.26 °C, extreme minimum temperature is −48.1 °C, annual rainfall is less than 500 mm, and pan evaporation is more than 1,100 mm. This river basin has long snowfall period during winter from November to next March, and the annual snowcover days are as many as 139.3 days with the largest average annual snow depth of 12 cm (Xu et al. 2008). In spring, the snowmelt water appears to be a cause of flooding. During the period of 1960–2009, the average annual runoff is about 35× 10^8 m^3. The proportions of major land use of the Kaidu River Basin in 2008 are listed in Table 1. Unfortunately, no information is available on historical land use in the basin, apart from some contextual data indicating conversion from grassland to others. Snowfall is a significant proportion of precipitation and there also exist glaciers with an area of 984.34 km^2 in the basin.

2.2 Data

Monthly streamflow data from the Dashankou hydrological station which are available for the period of 1960–2009 were used in this study, and streamflow data were transformed to millimeter (runoff) to compare with the precipitation and potential evapotranspiration (PET); the same-period time series of daily precipitation data from five rainfall gauges were used. Daily maximum and minimum

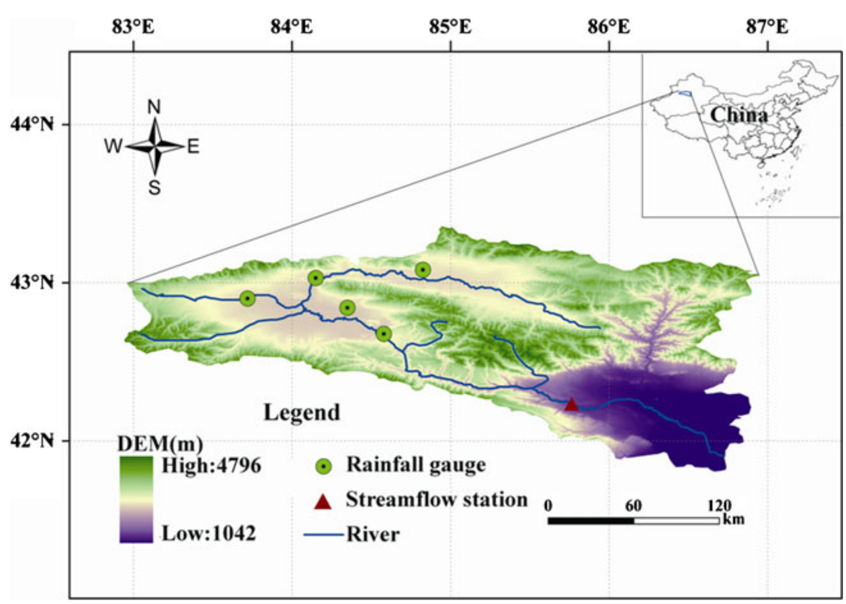

Fig. 1 Location of the Kaidu River Basin and the distribution of rainfall gauges and hydrological station

Table 1 Proportion of major land use of the Kaidu River Basin in 2008

Basin	Forest (%)	Grassland (%)	Waters (%)	Habitation (%)	Other area (%)
Kaidu River	0.50	75.43	6.40	0.04	17.63

air temperature, relative humidity, sunshine hours, and wind speed from Bayinbuluk meteorological station which is also one of the five rainfall gauges for the period of 1960–2009 were used to calculate PET via the Penman–Monteith equation recommended by FAO (Allen et al. 1998).

2.3 Trend test

The nonparametric Mann–Kendall (MK) trend test is commonly used to assess the significance of monotonic trends in meteorological and hydrologic series all over the world (Douglas et al. 2000; Chen and Xu 2005; Zhang et al. 2009; Poupkou et al. 2011; Zhang et al. 2011). For a time series $X = \{x_1, x_2, \ldots, x_n\}$, in which $n > 10$, the standard normal statistic Z is estimated as follows:

$$Z = \begin{cases} \frac{(S-1)}{\sqrt{\mathrm{var}(S)}}, & S > 0 \\ 0, & S = 0 \\ \frac{(S+1)}{\sqrt{\mathrm{var}(S)}}, & S < 0 \end{cases} \quad (1)$$

where

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \mathrm{sgn}(x_j - x_i) \quad (2)$$

$$\mathrm{sgn}(\theta) = \begin{cases} 1, & \theta > 0 \\ 0, & \theta = 0 \\ -1, & \theta < 0 \end{cases} \quad (3)$$

$$\mathrm{var}(S) = \frac{n(n-1)(2n+5) - \sum_t t(t-1)(2t+5)}{18} \quad (4)$$

where t is the extent of any given tie and $\sum_t$ denotes the summation of all ties.

The statistic Z follows the standard normal distribution. At a 5 % significance level, the null hypothesis of no trend is rejected if $|Z| > 1.96$. A positive value of Z denotes an increasing trend, and the opposite corresponds to a decreasing trend. The effects of the serial

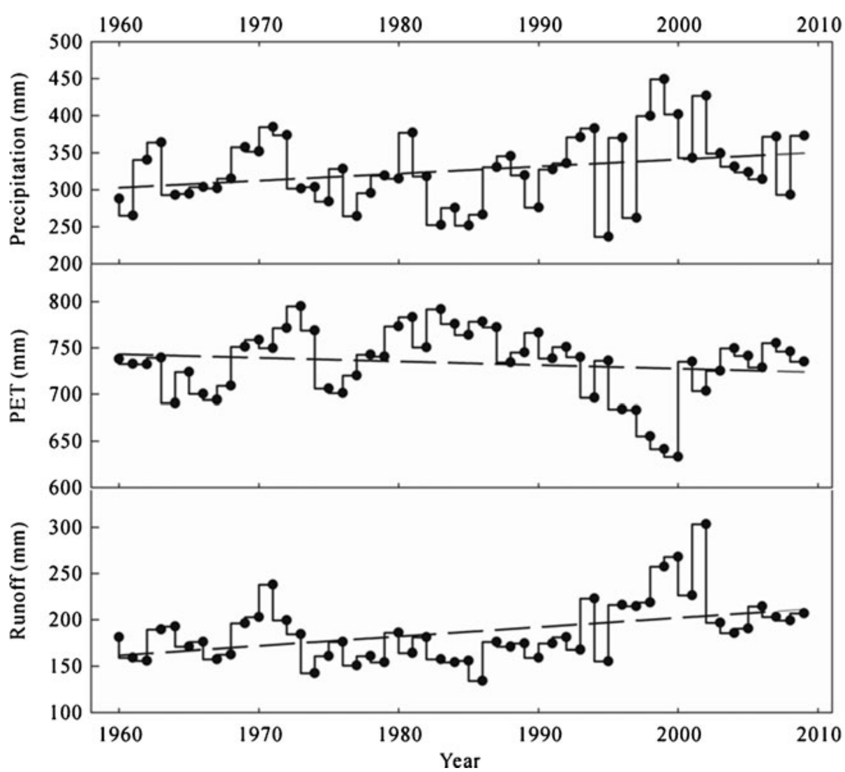

Fig. 2 Change trend of annual precipitation, PET, and runoff during the period of 1960–2009. The *long dashed line* means linear trend for this period

Table 2 Trend and step change point analysis of annual precipitation, PET, and runoff

Factor	Mean value (mm/a)	Trend rate (mm/10a)	MK trend test		Step change point analysis	
			Z	Significance level	Step change point	Significance level
Precipitation	333.9	10.5	2.07	0.05	1991	0.01
PET	733.5	−2.4	−0.67	–	1994	0.01
Runoff	186.4	8.4	2.84	0.01	1993, 1995	0.01

correlation on the MK test were eliminated via prewhitening technique (Yue and Wang 2002).

2.4 Step change point analysis

Identifying step change points is one of the most important statistical techniques for runoff data analysis to study the effects of climate variability and human activities. The nonparametric Mann–Kendall–Sneyers test (Mann 1945; Kendall 1975; Sneyers 1975) was applied in this study to determine the occurrence of a step change point. The test is a sequential version of the Mann–Kendall rank statistic proposed by Sneyers (1975). Let $x_1,\ldots,\ x_n$ be the data points. For each element x_i, the numbers m_i of elements x_j preceding it ($j < i$) such that $x_j < x_i$ are computed. Under the null hypothesis (no step change point), the normally distributed statistic t_k can be calculated via the following formula:

$$t_k = \sum_{i=1}^{k} m_i (2 \le k \le n) \tag{5}$$

Mean and variance of the normally distributed statistic t_k can be given by the following formulas:

$$\bar{t}_k = E(t_k) = \frac{k(k-1)}{4} \tag{6}$$

$$\mathrm{var}(t_k) = \frac{k(k-1)(2k+5)}{72} \tag{7}$$

The normalized variable statistic u_k is estimated as follows:

$$u_k = \frac{(t_k - \bar{t}_k)}{\sqrt{\mathrm{var}(t_k)}} \tag{8}$$

The normalized variable statistic u_k is the forward sequence, and the backward sequence u_{-k} is calculated using the same equation but with a reversed series of data. When the null hypothesis is rejected (i.e., if any of the points in the forward sequence are outside the confidence interval), the detection of an increasing (u_k >0) or a decreasing (u_k <0) trend is indicated. The sequential version of the test used here enables detection of the approximate time of occurrence of the trend by locating the intersection of the forward and backward curves of the test statistic. If the intersection occurs within the confidence interval, then it indicates a step change point (Demaree and Nicolis 1990; Moraes et al. 1998).

According to the analysis results of trend and step change point analysis, the runoff series will be divided into a natural period series and a human-induced period series (Huo et al. 2008; Jiang et al. 2011). Based on the divided periods, the effects of climate variability and

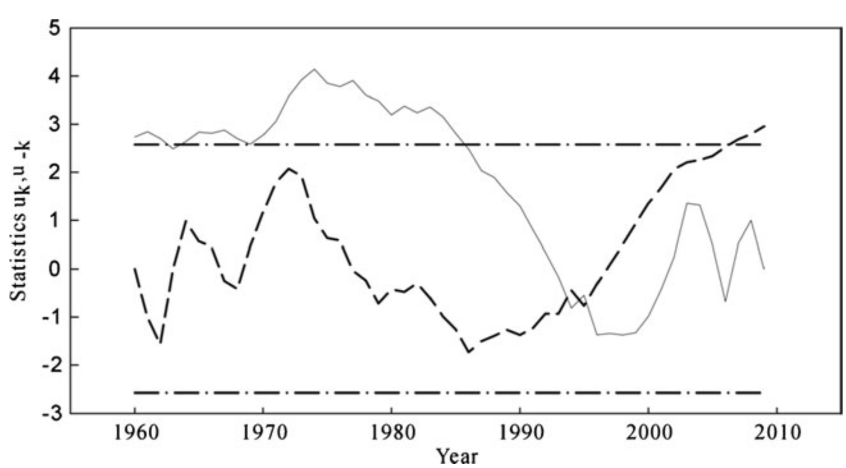

Fig. 3 Mann–Kendall–Sneyers test of annual runoff with forward (u_k, *short dashed line*) and backward (u_{-k}, *solid line*). The *dash dotted lines* represent the critical value corresponding to the 1 % significance level

Table 3 Changes in mean annual precipitation, PET, and runoff during the two periods

Period	Precipitation			PET			Observed runoff		
	mm/a	Change (mm)	Relative change	mm/a	Change (mm)	Relative change	mm/a	Change (mm)	Relative change
1960-1993	314.3	–	–	745.0	–	–	171.9	–	–
1994-2009	351.5	37.2	11.8 %	709.3	−35.7	−4.8 %	217.3	45.4	26.4 %

human activities on runoff can be separated by using the following method.

2.5 Hydrologic sensitivity analysis method

Hydrologic sensitivity analysis method can be described as the percentage change in mean annual runoff in response to changes in mean annual precipitation and PET (Jones et al. 2006; Li et al. 2007). The water balance for a basin can be written as follows:

$$P = E + Q + \Delta S \quad (9)$$

where P is precipitation, E is the actual evapotranspiration (AET), Q is runoff, and ΔS is the change in basin water storage. Over a long period of time (i.e., 10 years or more), it is reasonable to assume that ΔS=0.

Mean annual AET can be estimated from precipitation and PET. Following Zhang et al. (2001), long-term mean annual AET can be estimated as follows:

$$\frac{E}{P} = \frac{1 + \omega(PET/P)}{1 + \omega(PET/P) + (P/PET)} \quad (10)$$

where ω is the plant-available water coefficient related to vegetation type (Zhang et al. 2001). The details of the relationship can be found in Zhang et al. (2004). In this study, we calibrated parameter ω by comparing the long-term annual AET calculated from Eqs. (9) and (10).

A change in mean annual runoff can be calculated as follows:

$$\Delta Q_{tot} = Q_{obs2} - Q_{obs2} \quad (11)$$

where ΔQ_{tot} indicates the total change in mean annual runoff before and after the step change point, Q_{obs1} is the average annual runoff during the natural period and Q_{obs2} is the average annual runoff during the human-induced period. As a first-order approximation, the total change in mean annual runoff can be estimated as follows:

$$\Delta Q_{tot} = \Delta Q_{c\,lim} + \Delta Q_{human} \quad (12)$$

where ΔQ_{clim} is the change in mean annual runoff due to climate variability and ΔQ_{human} represents the change in mean annual runoff due to various human activities.

Perturbations in both precipitation and PET can lead to changes in the water balance (Dooge et al. 1999). Basing on the hydrologic sensitivity relationship, the change in mean annual runoff due to climate variability can be approximated as follows (Koster and Suarez 1999; Milly and Dunne 2002):

$$\Delta Q_{c\,lim} = \frac{\partial Q}{\partial P}\Delta P + \frac{\partial Q}{\partial PET}\Delta PET \quad (13)$$

where ΔP and ΔPET denote changes in precipitation and PET, respectively, $\frac{\partial Q}{\partial P}$ and $\frac{\partial Q}{\partial PET}$ are the coefficients of sensitivity of runoff to precipitation and PET,

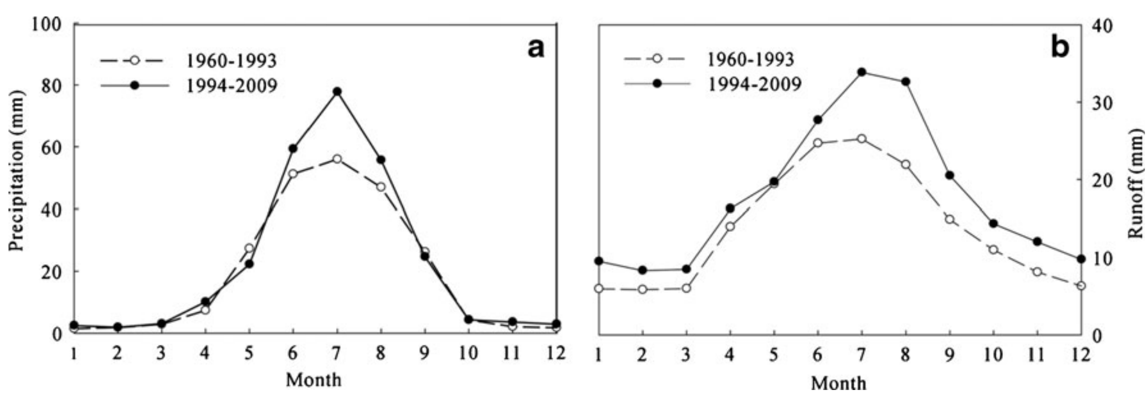

Fig. 4 Average monthly precipitation and runoff for the baseline (1960–1993) and changed periods (1994–2009)

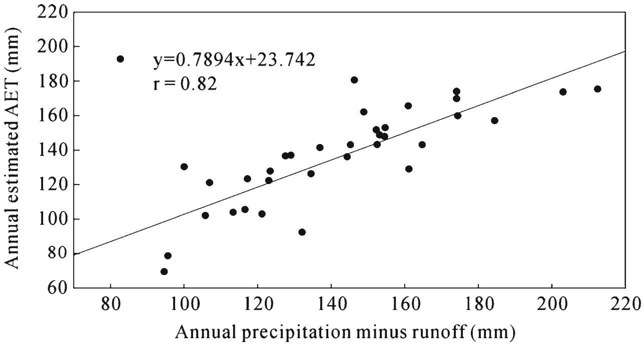

Fig. 5 Scatter diagram and correlation coefficient of annual AET calculated directly from water balance equation and estimated by using Eq. (10) for the baseline (1960–1993)

respectively. They can be expressed as follows (Li et al. 2007):

$$\frac{\partial Q}{\partial P} = (1 + 2x + 3\omega x) \Big/ \left(1 + x + \omega x^2\right)^2 \quad (14)$$

$$\frac{\partial Q}{\partial PET} = -(1 + 2\omega x) \Big/ \left(1 + x + \omega x^2\right)^2 \quad (15)$$

where x is the index of dryness and is equal to PET/P.

3 Results and discussion

3.1 Trend and step change point analysis of precipitation, PET, and runoff series

Long-term trends in hydrologic processes are potentially affected by climate variability and human activities. Checking up historical trends in these processes can help confirm the start of the human-induced period. Annual precipitation, PET, and runoff in 1960–2009 were analyzed utilizing the MK test to identify long-term trends. Figure 2 shows long-term trends and mean values in annual precipitation, PET, and runoff. Figure 2 and the MK trend test (Table 2) jointly indicate that PET shows an inconspicuous decreasing trend, and average PET from 1960 to 2009 is 733.5 mm. Precipitation and runoff, however, both have a remarkable increasing trend (at a significance level of 0.05 and 0.01, respectively) at a rate of 10.5 and 8.4 mm every 10 years, respectively. The average observed runoff from 1960 to 2009 is 186.4 mm, which is smaller than average precipitation.

The Mann–Kendall–Sneyers test was applied to detect the step change point of the annual runoff series over the period from 1960 to 2009. Figure 3 shows the computed probability series of the step change point years. The intersection of the curves indicates that there are two step change points (in 1993 and 1995 at the 0.01 significance level) for the runoff series. To investigate the effect of climate change on runoff, we also carried out the test for annual precipitation and PET. The results show that abrupt changes in annual precipitation and PET occurred in 1991 and 1994 (at the 0.01 significance level), respectively (Table 2, figures not shown). The step change points for annual precipitation, PET, and runoff were basically uniform, which indicates that the characteristics of annual precipitation, PET, and runoff all changed in the early 1990s.

Based on the Mann–Kendall–Sneyers test, 1993 could be the step change point reflecting that human activities started obviously to affect the runoff. Therefore, 1960–1993 was taken as the natural period during which the effect of human activities on runoff was less recognized. The period from 1994 to 2009 was considered as the human-induced period during which human activities intensifying resulted in obvious perturbations of the runoff. For the two periods, changes in mean annual precipitation, PET, and runoff were calculated, as shown in Table 3. Compared with the natural period, precipitation and observed runoff increased respectively by 11.8 and 26.4 % in the human-induced period; PET, however, decreased by 4.8 % which is lower than in precipitation and runoff.

The intra-annual variability of runoff is bound up with the monthly cycle of precipitation and basin water-related human activities. To further realize the intra-annual variability of precipitation and runoff, we compared the mean monthly precipitation and runoff between the natural period and the human-

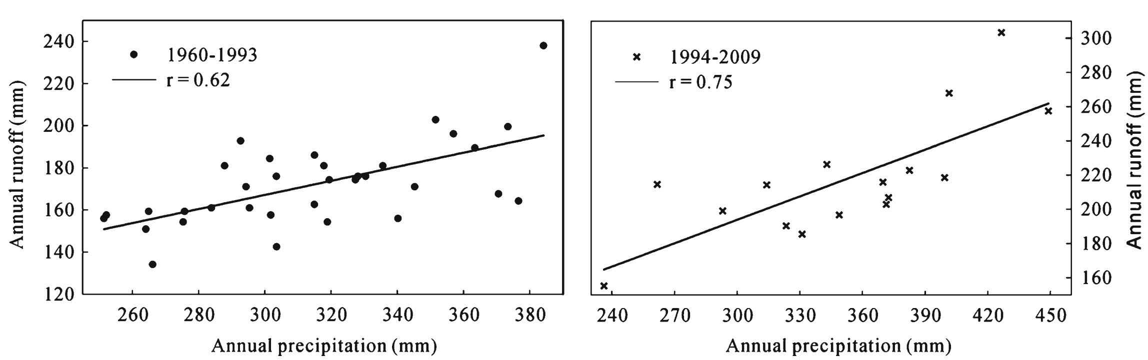

Fig. 6 Scatter diagram between annual precipitation and annual runoff for 1960–1993 and 1994–2009

Table 4 Quantifying the effects of climate variability and human activities on runoff

ΔQ_{tot} (mm)	Runoff change (mm)		Proportional change in annual runoff due to	
	ΔQ_{clim}	ΔQ_{human}	Climate variability (%)	Human activities (%)
45.4	41.1	4.3	90.5	9.5

induced period (Fig. 4). Lower changes in monthly precipitation were seen except July for the two periods (Fig. 4a). Runoff, however, showed significant changes in intra-annual variability, and the mean monthly runoff in 1994–2009 had a conspicuous increase in contrast with that for the natural period, especially in July and August (Fig. 4b). Thus, the increase in runoff for the human-induced period, to some extent, may be attributed to basin water-related human activities.

3.2 Calibration and validation of the hydrologic sensitivity analysis method

During the natural period, human activities did not cause significant perturbations of the runoff in the Kaidu River Basin, and so we could assume that human activities never affected runoff during the period. Thus, the natural period was considered as a baseline to estimate the effects of climate variability and human activities on runoff for the human-induced period using the hydrologic sensitivity analysis method. In this method, ω is the main model parameter. We calibrated ω by comparing long-term annual AET estimated by using Eq. (10) and the water balance Eq. (9) for the natural period of 1960–1993. With a value of ω=−0.28, the results of annual AET estimated by using Eq. (10) are realistic and acceptable (Fig. 5); thus, we set ω=−0.28 for the Kaidu River Basin. The terms $\partial Q/\partial P$ and $\partial Q/\partial PET$ in Eqs. (14) and (15) can be considered as the sensitivity coefficients of runoff to changes in precipitation and PET, respectively. When ω= −0.28, the values of sensitivity coefficients $\partial Q/\partial P$ and $\partial Q/\partial$PET were 1.2 and 0.1, respectively, revealing that the change in runoff was more sensitive due to precipitation than to PET.

The sensitivity coefficient to precipitation ($\partial Q/\partial P$) is higher for lower ω values and decreases with the dryness index increasing, and a change in precipitation will lead to a greater change in runoff in grassed basins than in forested basins as forested basins generally have larger ω values (Zhang et al. 2004; Ma et al. 2008). The magnitudes of $\partial Q/\partial P$ and $\partial Q/\partial$PET approach zero under very arid conditions (e.g., large E_0/P ratios), suggesting that basins in humid regions will respond more strongly to changes in precipitation and PET than basins in arid regions (Ma et al. 2008). However, the magnitude of the change in runoff depends on both the sensitivity coefficients and changes in precipitation and PET. The average dryness index for the Kaidu River Basin with 75.43 % grassland is 2.3, and the study area is expected to show higher sensitivity to precipitation. Figure 6 shows the scatter diagram between annual precipitation and runoff for 1960–1993 (r=0.62) and 1994–2009 (r=0.75), indicating that annual runoff and annual precipitation are closely related during the period of 1960–2009. The relationship between annual precipitation and runoff for 1994–2009 is much better than that for 1960–1993, implying that precipitation may have affected runoff more in 1994–2009 than during the baseline period.

3.3 Effects of climate variability and human activities on runoff

Runoff is a result of basin processes and is affected by many factors. Changes in any of the factors such as climate and human activities may result in changes in runoff. Nevertheless, quantifying the individual effect is difficult because changes in runoff are associated with changes in both climate variability and human activities. The effect of climate variability on runoff was estimated using the hydrologic sensitivity analysis method. In the Kaidu River Basin, average annual precipitation was approximately 314.3 mm in the baseline period and increased to approximately 351.5 mm during the change period; average PET showed a decreasing trend over the two periods (Table 3). It is clear that these changes in precipitation and PET would lead to an increase in runoff. The effect of climate variability on runoff was assessed by using average precipitation and PET. Results indicated that proportional change in annual runoff due to

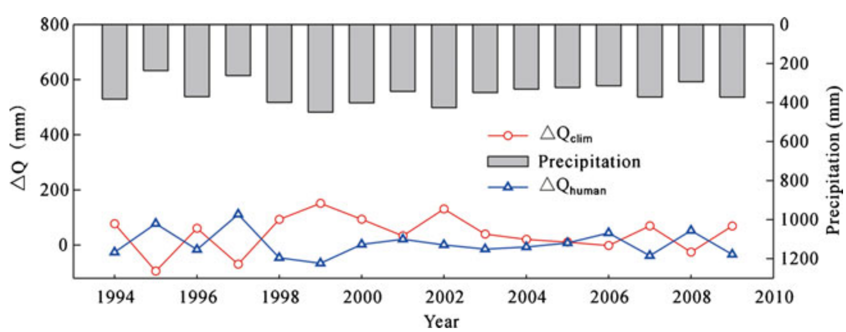

Fig. 7 Time series of ΔQ_{clim} and ΔQ_{human} computed by hydrologic sensitivity analysis for 1994–2009

the climate variability accounted for 90.5 % of the observed change in annual runoff and the human activities are responsible for 9.5 % of the change (Table 4). During the changed period, the effects of climate variability and human activities on runoff showed a significant difference. It could be inferred that the increase in runoff during the changed period was mainly attributed to climate variability. Fortunately, adopting the exclusion measures for preventing grassland degradation has made the vegetation recover to a certain extent, which also has a positive effect on runoff.

To identify the yearly effect, the series of ΔQ_{clim} and $\Delta Q_{\mathrm{human}}$ were estimated yearly using the hydrologic sensitivity analysis method for 1994–2009 (Fig. 7). Estimated changes in runoff due to climate variability and human activities were sensitive to the magnitude of precipitation. When precipitation was less than average, the river runoff was obviously reduced in that the more water was drawn from rivers and aquifers for agricultural production and the lives of local residents and meanwhile precipitation decreasing would also produce the less surface runoff. Nevertheless, when precipitation was more than average, the river runoff was obviously increased because increasing precipitation would produce more surface runoff and would also spur local residents to utilize less surface water and groundwater. Thus, it can be seen that precipitation plays an important role in variability of the river runoff for Kaidu River Basin.

3.4 Discussion on the uncertainty of the method

Some uncertainties lay in the hydrologic sensitivity analysis method separating the effects of climate variability and human activities on runoff, which might arise from the observation data and model parameter. The function of the hydrologic sensitivity analysis method depends on a long-term baseline period runoff data, without the effect of human activities, for model calibration. In reality, there was lack of detailed long-term period observation data in Kaidu River Basin, and even during the baseline period, there were some human disturbances produced by building reservoirs, grazing, and so on. Meteorological data used for the method were from five rainfall gauges and one meteorological station in the study area, which might not be of sufficient coverage for a mountainous basin with an area of 18,827 km^2 and limit the accuracy of the calculated PET and estimated runoff. In this study, although most model parameters had been estimated based on the baseline runoff series and meteorological data, uncertainties of the model parameters could still affect the estimation results. All presented uncertainties would influence computational results at a certain extent, and so estimation uncertainties should be further investigated in future studies.

4 Conclusions

Climate variability and human activities have significantly affected the runoff from the arid Kaidu River Basin in northwest China. This study defined a conceptual framework and applied the hydrologic sensitivity analysis method to quantify the effects of climate variability and human activities on runoff. In this study, the conclusions can be drawn as follows:

1. Annual runoff from the Kaidu River Basin had a significant increasing trend during the period of 1960–2009; through Mann–Kendall–Sneyers test, an abrupt change reflecting the effect of human activities on runoff was explored to have occurred in 1993. This accorded with the actual situation of the basin's economy and social development. Mean annual runoff in 1994–2009 increased by 26.4 % compared with the baseline period of 1960–1993.
2. The hydrologic sensitivity analysis method estimated the effects of climate variability and human activities on runoff in 1994–2009, indicating that climate variability was the dominant factor accounting for the 90.5 % increase in runoff; the increase percentage due to human activities was only 9.5 %. It is suggested that the increase in runoff in 1994–2009 was mainly attributed to the climate variability. Due to the government taking effective measures, human activities had played a positive effect on runoff increase as well.
3. Quantifying the effects of climate variability and human activities on runoff will contribute to regional water resources assessment and management. The Kaidu River Basin is a producing flow area providing water resources for the economy and social development of the oases around the Bosten Lake. Climate variability has distinctly increased runoff, which will play a positive effect on the economy and social development of the oases around the Bosten Lake and meanwhile suggests that the local government should take reasonable measures to deal with the flood disaster induced by climate variability.

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