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Effect of Climate Variability and Human Activities on Runoff in the Jinghe River Basin, Northwest China

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Abstract: Much attention has recently been focused on the effects of climate variability and human activities on the runoff. In this study, we analyzed 56-yr (1957–2012) runoff change and patterns in the Jinghe River Basin (JRB) in the arid region of northwest China. The nonparametric Mann–Kendall test and the precipitation-runoff double cumulative curve (PRDCC) were used to identify change trend and abrupt change points in the annual runoff. It was found that the runoff in the JRB has periodically fluctuated in the past 56 yr. Abrupt change point in annual runoff was identified in the JRB, which occurred in the years around 1964 and 1996 dividing the long-term hydrologic series into a natural period (1957 – 1964) and a climate and man-induced period (1965 – 1996 and 1997 – 2012). In the 1965 – 1996 period, human activities were the main factor that decreased runoff with contribution of 88.9%, while climate variability only accounted for 11.1%. However, the impact of climate variability has been increased from 11.1% to 47.5% during 1997 – 2012, showing that runoff in JRB is more sensitive to climate variability during global warming. This study distinguishes the effect of climate variability from human activities on runoff, which can do duty for a reference for regional water resources assessment and management.

Keywords: Water resource; Runoff; Climate variability; Precipitation; Jinghe River Basin

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Introduction

With the intensification of water shortage problems and the increasing water-related disaster events globally (Chen et al. 2013; IPCC 2013), the effects of climate variability and human activities on hydrological cycle have been a focus of global hydrology research (Ren et al. 2002; Scanlon et al. 2007; IPCC 2007), and related research throughout the world (Bronstert et al. 2002; Legesse et al. 2003; Pfiste et al. 2004; Xu 2005; Piao et al. 2007) for over a decade. Climate variability is believed to have led to global warming and changing patterns of precipitation and evaporation by intensifying the global hydrological cycle (Brutsaert and Parlange 1998; IPCC 2007). Human activities have changed the temporal and spatial distribution of water resources through land use/land cover change, reservoir construction, river diversion, and other engineering and management practices (Ye et al. 2003; Milly et al. 2005). In continental arid regions, the effects of climate variability and human activities on runoff are significantly more sensitive, and these effects have resulted in serious eco-environmental degradation and water resources crises (Liu and Xia 2004; Ma et al. 2008; Jiang et al. 2011). Quantitative evaluation of these effects is important for regional water resources assessment and management.

Studies on the effect of human activities have mainly focused on the relationship between land use change and runoff (Scanlon et al. 2007). Ren et al. (2002) estimated the effect of human activities on the runoff by computing the impacts on each component of a water balance equation. This method, however, is limited because it is difficult to count the direct effect of human activities on each component for the water supply and water utilization, factors which are complex and subject to rapid change. New attempts, including regression analysis (Ye et al. 2003; Tian et al. 2009), runoff coefficients analysis (Wang et al. 2013), sensitivity analysis (Dooge et al. 1999; Milly and Dunne 2002; 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 address this problem. This hydrological sensitivity analysis method (HSAM) has in recent years been used to separate the effects of climate change and human activities on runoff in the Wuding River Basin, Shiyang River Basin, and Kaidu River Basin (Li et al. 2007; Ma et al. 2008; Chen et al. 2013). HSAM is a framework for evaluating the sensitivity of the annual runoff to precipitation and potential evapotranspiration (Dooge et al. 1999; Milly and Dunne 2002). These researches showed that the impacts of climate change and human activities on runoff were more significant in arid areas than that in more humid areas.

The Jinghe River Basin (JRB) was selected as our study area. It has an area of 12,215 km^2, and the river is a main tributary of the North Tianshan Mountains in northwestern China. The Jinghe River provides crucial water resource supplies to Ebinur Lake in northwestern China. Owing to rapid socio-economic development and climate change, quality and quantity of available water resources within the JRB have changed (Zhang 2011). Water crises, including drying up of lakes and eco-environmental degradation, have occurred frequently. To develop water resources sustainably for the JRB, quantitative assessments of the effects of climate change and human activities on runoff are important.

Many studies investigating climate change and human activities and hydrological responses in the JRB and surrounding area have been published (Mu et al. 2007; Sun et al. 2010; Bai et al. 2010; Zhang et al. 2011; Liu et al. 2011). However, these studies have not systematically and quantitatively estimated the effects of climate change and human activities. The objectives of this study, therefore, are to: (1) determine trends and abrupt change points in annual runoff of the basin and (2) quantitatively estimate the effects of climate change and human activities on runoff.

1 Study Area

The Jinghe River starts from the north slope of the Ponoramio Mountain and ends in the Ebinur Lake which is located in Jinghe county of Xinjiang (Figure 1). The Jinghe River flows from south to north approximately 114 km and covers a basin area of the 1419 km^2 which is above of the Jinghe Hydrological Station. Administrative boundaries are within 81°46' – 83°51'E and 44°02'– 45°10'N, and cover an area of approximately 12,215 km^2 (25% of the Ebinur Basin), in which the land is divided into mountains (6882 km^2), plains (6791 km^2) and water area (542 km^2). The topography of the basin is high in the southern part and low in the northern part. The annual mean temperature is 7.8°C, extreme minimum and maximum temperatures are -36.4°C and 41.5°C. The annual mean precipitation is about 252 mm during past 50 years, and varies from 100 mm in the north to 700 mm in the south. The annual average potential evaporation is about 1625 mm. The annual runoff is mainly concentrated in the rainy season from June to August, which accounts for 65% of the annual total. The long-term annual runoff of the Jinghe River is

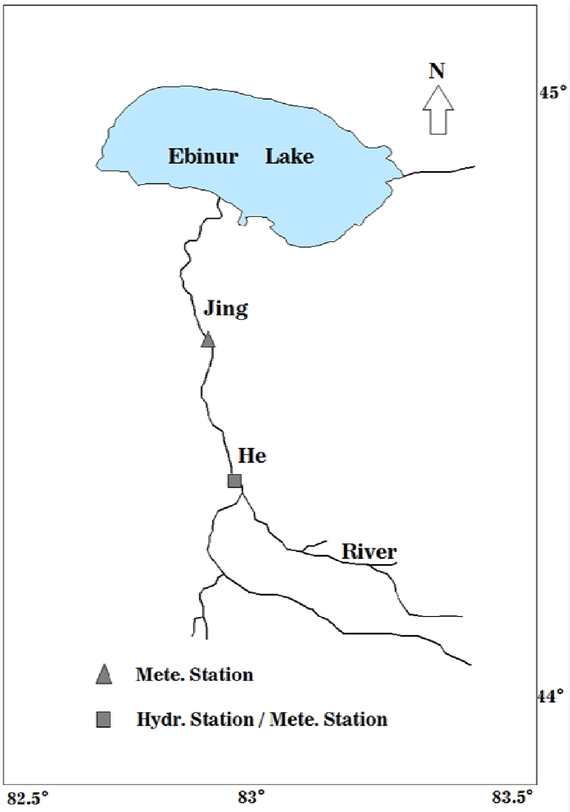

Figure 1 Location of the Jinghe River Basin and the distribution of meteorological and hydrological station.

4.74×10^8 m^3 (33 mm). Snowfall is a significant proportion of precipitation and there also exist glaciers with an area of 91 km^2 in this river basin.

The JRB has the highest concentration of wetlands in Northwestern China with the most diverse ecosystems in the arid region. These wetlands are more vulnerable than other ecosystems to climate change (Bai 2010). The water level of the Ebinur Lake has been reported to have significantly declined in recent years (Liu et al. 2011). Therefore, the analysis of the runoff variations of the Jinghe River is of great importance.

2 Datasets and Methods

2.1 Datasets

Monthly stream flow records from Jinghe hydrological station for the period of 1957–2012 were used in this study. Climatic data from 2 meteorological stations located within the basin were collected. These climatic data included daily mean air temperature, minimum and maximum air temperature, precipitation, relative humidity, sunshine hours, and wind speed. They were provided by the National Climatic Centre (NCC) of the China Meteorological Administration (CMA) and Xinjiang Hydrological Administration (XHA). The daily potential evapotranspiration (PET) was calculated using the daily air temperature, precipitation, sunshine hours, relative humidity and wind speed by the Penman–Monteith equation, as recommended by the Food and Agriculture Organization (FAO) (Allen et al. 1998). The annual precipitation and PET were obtained by summing the daily precipitation and PET at 2 stations from 1957 to 2012. Furthermore, the land use/land cover (LULC) changes data in the entire river basin were interpreted from the satellite remote sensing images (Landsat MSS, 21 September, 1972; Landsat TM, 25 August, 1990; ALOSAVNIR-2, 24 September, 2010) by Wang et al. (2013).

2.2 Methods

2.2.1 The nonparametric Mann-Kendall (MK) 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).

In this method, H_0 represents distribution of random variables, and H_1 represents possibility of bi-directional changes. The test statistic S is given by

$$S = \sum_{i=1}^{n-1} \sum_{k=i+1}^{n} \operatorname{sgn}(x_k - x_i) \tag{1}$$

in which x_k and x_j are the sequential data values, n is the length of the data set, and

$$\operatorname{sgn}(\theta) = \begin{cases} +1, & \theta > 0 \\ 0, & \theta = 0 \\ -1, & \theta < 0 \end{cases} \tag{2}$$

In particular, if the sample size is larger than ten, the statistic S is nearly normally distributed, i.e., the statistic

$$Z_c = \begin{cases} \dfrac{S-1}{\sqrt{\operatorname{var}(S)}}, & S > 0; \\ 0, & S = 0; \\ \dfrac{S+1}{\sqrt{\operatorname{var}(S)}}, & S < 0; \end{cases} \quad (3)$$

is a standard normal random variable, whose expectation value and variance are:

$$E(S) = 0 \quad (4)$$

$$\operatorname{var}(S) = \left[n(n-1)(2n+5) - \sum_t t(t-1)(2t+5) \right] \Big/ 18 \quad (5)$$

in which t is the extent of any given tie and Σ denotes the summation over 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 indicates an increasing trend, and a negative value corresponds to a decreasing trend. Furthermore, the nonparametric Mann-Kendall test was applied in this study to determine the occurrence of a step change point (Mann 1945; Kendall 1975; Sneyers 1975).

2.2.2 Precipitation-runoff double cumulative curve

The precipitation-runoff double cumulative curve (PRDCC) analysis provides a visual representation of the consistency of the precipitation and runoff data (Matouskova 2009). The PRDCC should be a straight line, and changes in the gradient of the curve may indicate that the characteristics of the precipitation or runoff have changed. In this study, we used the PRDCC method to auxiliary detect the change-point of the precipitation and runoff series.

Through trend and PRDCC analysis, the runoff series can be divided into a natural period series and a human-induced period series (Huo et al. 2008; Jiang et al. 2011). Based on the period division, the impacts of climate variability and human activities on runoff were assessed using a hydrologic sensitivity analysis method, as described below.

2.2.3 Hydrologic sensitivity analysis method

The water balance for a basin can be written as follows:

$$P = E + W + \Delta S \quad (6)$$

where P is precipitation, E is the actual evapotranspiration (AET), W 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 $\Delta S=0$.

The AET can be estimated from precipitation and PET. Budyko (1974) developed a framework for estimating the AET based on the aridity index,

$$S = PET \,/\, P \quad (7)$$

where S is aridity index, P is precipitation, PET is the potential evapotranspiration.

The PET was estimated through FAO56-PM model (Allen et al. 1998),

$$PET = \frac{0.408\Delta(R_n - G) + \gamma \dfrac{900}{T+273} U_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \quad (8)$$

where annual PET was accumulated from daily PET; R_n is the net radiation (MJ/(m^2/d)); G is the soil heat flux density (MJ/(m^2/d)); γ is the psychrometric constant (kPa/°C); Δ is the slope of the vapor pressure curve (kPa/°C); U_2 is the wind speed at 2 m height (m/s); e_s is the vapor pressure of the air at saturation (kPa); e_a is the actual vapor pressure (kPa); T is daily average temperature (°C). A complete set of equations is proposed by Allen et al (1998) to compute the parameters of Eq. (8) according to the available weather data and the time step computation, which constitute the so-called FAO-PM method.

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

$$\frac{AET}{P} = \frac{1 + wS}{1 + wS + \dfrac{1}{S}} \quad (9)$$

where S is the aridity index. w is a model parameter related to the vegetation type, soil hydraulic property, and topography (Fu 1996). Fu (1996) verified the formula for w parameter in mountainous area, its expression is deduced theoretically as follows:

$$w = 1 + 0.2928 r^{1.21} \left(\frac{1-a}{a}\right) \quad (10)$$

where w is parameter depending on the nature of underlying surface, r is the precipitation intensity (mm/d), a is the runoff coefficient, can be expressed as river runoff divided by precipitation.

$$a = R \,/\, P \quad (11)$$

Perturbations in both the precipitation and the PET can lead to changes in the water balance (Dooge et al. 1999). As a first-order approximation, the total change in the mean annual runoff can be estimated as follow:

$$\Delta Q_{\text{total}} = \Delta Q_{\text{climate}} + \Delta Q_{\text{human}} \qquad (12)$$

where ΔQ_{total} is the total change in the mean annual runoff (MAR); $\Delta Q_{\text{climate}}$ represents the change in MAR due to climate change and ΔQ_{human} indicates the change in MAR due to various human activities.

Precipitation and PET are the dominant factors that determine water balance (Budyko 1974; Zhang et al. 2001). Basing on the hydrologic sensitivity relationship, the change in MAR due to climate variability can be approximated as follows (Koster and Suarez1999; Milly and Dunne 2002):

$$\Delta Q_{climate} = \frac{\partial Q}{\partial P}\Delta P + \frac{\partial Q}{\partial PET}\Delta PET \qquad (13)$$

where ΔP, ΔPET are changes in the precipitation and PET, respectively.

The coefficients of sensitivity of runoff to precipitation and PET can be expressed as follows (Li et al. 2007):

$$\frac{\partial Q}{\partial P} = \frac{1+2S+3wS}{(1+S+wS^2)^2} \qquad (14)$$

$$\frac{\partial Q}{\partial PET} = \frac{-(1+2wS)}{(1+S+wS^2)^2} \qquad (15)$$

where $\frac{\partial Q}{\partial P}$ is the coefficients of sensitivity of runoff to precipitation, and $\frac{\partial Q}{\partial PET}$ is the coefficients of sensitivity of runoff to PET.

In this study, w is the main model parameter, calibrated by comparing long-term annual AET estimated by using Eq. (9) and the water balance Eq. (6). With a value of ω=1.161, the results of annual AET estimated by using Eq. (9) are realistic and acceptable (Figure 2), and which accords with the result Zhang et al (2001). Thus, we set ω=1.161 for the Jinghe River Basin.

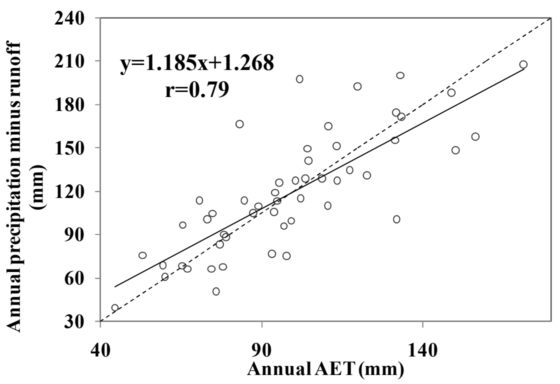

Figure 2 Scatter diagram and correlation coefficient of annual AET calculated directly from water balance equation and estimated by using Eq. (9).

3 Results and Discussion

3.1 Changes in the annual precipitation, PET and runoff series

Long-term change trends in hydrologic processes are potentially affected by climate change and human activities. Examining historical trends in these processes can help confirm the start of the human-induced period. For the past 56 years, the JRB showed an annual mean precipitation of 151 mm varying from 69 mm to 243 mm. Annual mean temperature, ranging 5.7°C to 11.6°C with an average of 8.1°C. The calculated PET in JRB averaged 884.5 mm per year, ranging from 723.4 mm to 1087.8 mm. Annual observed runoff in JRB averaged 4.72×10⁸ m³ (33 mm, which is smaller than average precipitation), fluctuating from 3.7×10⁸ m³ to 4.72×10⁸ m³ (from 26 mm to 43 mm). Figure 3

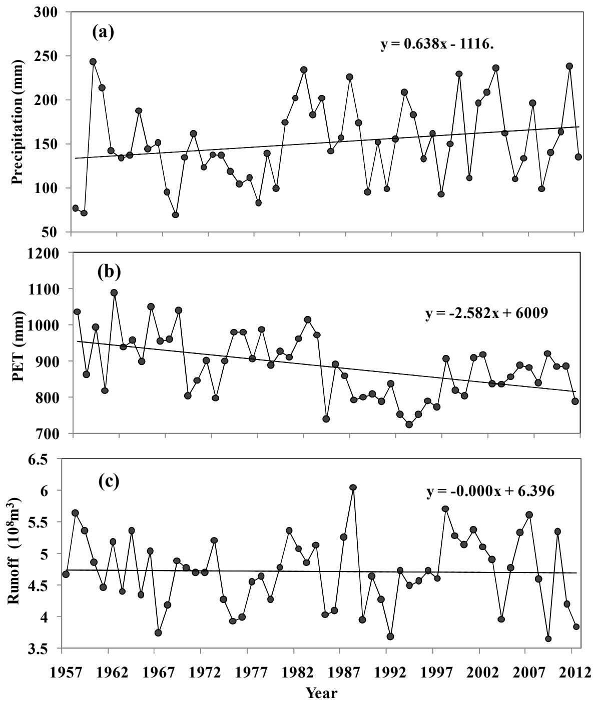

Figure 3 Changing trend of annual precipitation (a), PET (b) and runoff (c) during the period of 1957 –2012.

Table 1 Trend and abrupt change point analysis of annual precipitation, PET, and runoff

Factor	Mean value (mm/a)	Trend rate (mm/10a)	*Z* value—MK trend	Change-point analysis	Sig. level
Precipitation	151.2	6.38	2.08	1980	0.01
PET	884.5	-25.8	-3.91	1978	0.01
Runoff	33.2	0.09	0.79	1964, 1996	0.05

Note: PET means the daily potential evapotranspiration.

shows long-term trends and mean values in annual precipitation, PET, and runoff. Figure 3 and the M-K test (Table 1), combined, indicate that the observed runoff series shows an inconspicuous increasing trend, and the precipitation have a remarkable increasing trend (at a significance level of p = 0.01) at a rate of 6.38 mm every 10 years. The PET, however, showed a considerable decrease at a rate of 25.8 mm every 10 years (at a significance level of p = 0.01).

The M-K statistical test showed that there was a significant increasing trend in the mean annual temperature (MAT) in JRB during the 1957-2012 time frame (P < 0.01), at a rate of 0.32°C/10a. The rate is consistent with rising average global temperatures (0.13°C/ 10a) and rising temperatures in northwestern China (0.34°C/ 10a, 1961-2009a) (Li et al. 2012), but is much higher than the average in the East Asian Monsoon area (0.19°C/ 10a, 1901-2003a) (Wang et al. 2008). It shows that the sensitivity of the climate variability of the JRB to global warming.

The M-K test and PRDCC method were applied to detect the abrupt change point of the annual observed runoff series. Generally, the PRDCC is approximately linear if there has been no impact of human activities on hydrological processes. Table 1 shows the computed probability series of the abrupt change point years. The intersection of the M-K statistics curves indicates that there are two abrupt change points (in 1964 and 1996 at the 0.05 significance level, Table 1, figures not shown) for the observed runoff series. In addition, the PRDCC test shown in Figure 4 demonstrates that before 1964, precipitation and runoff were relatively uniform, and thereafter, the characteristics of precipitation or runoff changed, but after 1996, the changed is more apparent. Combining the M-K test and PRDCC analysis, 1964 could be the abrupt change point reflecting that climate variability and human activities started obviously to affect the river runoff. Therefore, 1957 – 1964 was taken as the natural period during which the effect of climate variability and human activities on runoff was less recognized. The period from 1964 to 2012 was considered as the climate and human-induced period during which climate warming and human activities intensifying resulted in obvious perturbations of the runoff. Therefore, the period was divided into three durations: 1957 – 1964, 1965 – 1996, and 1997 – 2012.

3.2 Correlation between precipitation and runoff

Linear and correlation relationships between annual precipitation and annual observed runoff were used to identify the relationship between precipitation and hydrologic variations. The correlation between the annual precipitation and annual observed runoff was not very strong in the JRB, where the correlation coefficient was only 0.40 (at a significance level of 0.05). In Xinjiang, the natural land cover has been significantly changed by the increase of population by migration, large-scale agricultural development and urban construction activities since the mid-1960s, especially after the 1990s.

To separate and quantify the effect of climate

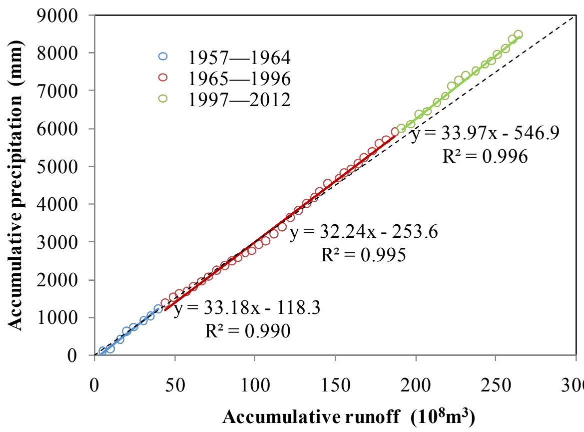

Figure 4 Double cumulative curve of annual precipitation and runoff.

variability and human activities on runoff variations, the baseline period was defined as prior to the mid-1960s. We selected the runoff coefficient as a parameter, defined as the ratio of the runoff to the precipitation over a given time period (Chow et al. 1988), to represent the hydro-climatic conditions of the JRB (Figure 5). The runoff coefficient of the whole study period in the JRB was 0.24, showed an inconspicuous decreasing trend at a rate of -0.01 per 10 year (at a significance level of 0.05).

Changes in the runoff due to climate variability and human activities have been shown to be sensitive to variations in the precipitation (Ma et al. 2008). In 1957 – 1964, results for precipitation correlated runoff for the JRB was 0.28, after the mid-1960s correlations decreased to 0.24 (1965 – 1996) and 0.23 (1997 – 2012), respectively. The runoff coefficients for the human-induced period (1965 – 1996, 1997 – 2012) were less than that for the baseline period (1957 – 1964). These results show that the runoff was dramatically impacted by the water-related human activities (e.g. intensive land use change, agricultural irrigation, river engineering) after the mid-1960s in the JRB.

3.3 Effects of climate change and human activities on runoff

Runoff is a result of basin hydrological processes and is affected by many factors, such as climate and human activities., and their role can vary spatially and temporally (Dong et al. 2012). The hydrologic sensitivity analysis method was used to estimate the quantitative effect of climate change on runoff. The effect of climate change on runoff was assessed by using annual precipitation and PET. The quantitative effects simulated in the JRB (Table 2) showed that the percentage changes in the runoff due to human activities were 88.9% for the 1965 – 1996, while climate variability only accounted for 11.1%, indicated that human activities were the main factor that decreased runoff from the mid-1960s to mid-1990s. However, the impact of climate variability appeared to become stronger from 11.1% to 47.5% during the 1997 – 2012, which may be due to strengthen of climate variability in the mid-1990s in Xinjiang (Zhang et al. 2010). The result showed that runoff in JRB is more sensitive to climate variability during the after 1998.

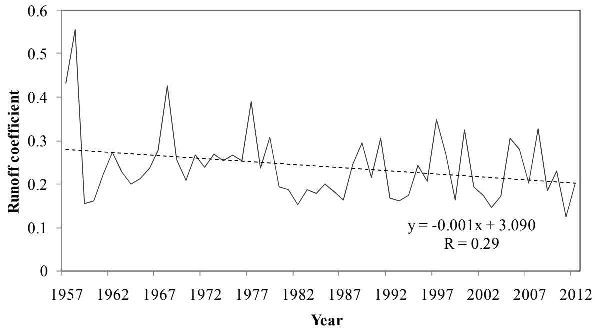

Figure 5 Time series of the runoff coefficients for 1957–2012 within the Jinghe River Basin.

Estimated changes in runoff due to climate variability and human activities were sensitive to the quantity of precipitation. When precipitation was less than average, the surface runoff was obviously reduced and would also spur agricultural production and local residents to utilize more groundwater (e.g. in 1965 – 1996, exceeding 2 times of the available groundwater in baseline). However, when precipitation was more than average, the impact of human activities on runoff was relatively less, and the PET on decreased runoff was strengthened (e.g. in 1990 – 1999). Thus, it can be seen that precipitation plays an important role in variability of the river runoff for Jinghe River Basin.

The land use and land cover in the JRB have changed substantially since 1970s (Table 3). The moderate and high vegetation coverage area showed a sharp decline during this period, while the cultivated and construction land had an increasing trend. There were 259.81 km² of vegetation coverage which changed into cultivated

Table 2 Effects of climate change and human activities on runoff in the Jinghe River Basin

Period	ΔP(mm)	ΔPET(mm)	ΔQ(mm)	$\Delta Q_{climate}$(%)	ΔQ_{human}(%)
1965—1996	-4.1	-71.4	-2.8	11.1	88.9
1997—2012	11.7	-83.9	-1.2	47.5	52.5

Notes: ΔP means the change in the precipitation; ΔPET means changes in the daily potential evapotranspiration; ΔQ means the change in the mean annual runoff $\Delta Q_{climate}$ means the change in the mean annual runoff due to climate change; ΔQ_{human} menas the change in the mean annual runoff due to various human activities.

Table 3 The Land use and cover change transition matrix for difference land use types in 1972 to 2010 (Unit: km^2)

Land use type		2010							
		C1-land	Water	C2-land	U-land	Low VC	Moderate VC	High VC	Total
1972	C1-land	91.48	2.92	1.79	75.04	71.71	106.78	48.73	398.45
	Water	0.89	419.48	0.03	9.21	13.08	19.56	1.02	463.26
	C2-land	7.62	0.01	7.25	5.37	4.48	6.09	1.26	32.43
	U-land	0.58	45.16	0.85	545.06	212.43	56.25	5.02	865.35
	Low VC	3.40	135.38	0.11	222.63	191.74	121.22	4.40	678.67
	Moderate VC	0.57	7.71	0.02	9.69	18.71	16.48	3.40	56.57
	High VC	0.54	12.20	0.02	7.83	20.71	21.59	14.15	77.41
	Total	105.07	622.66	10.06	874.83	533.22	347.96	78.32	2572.16

Notes: C1-land = Cultivated land; C2-land = Constructed land; U-land = Unused land; VC = Vegetation Coverage

land between 1972 and 2010, accounting for about 65.21% of the cultivated land in 2010. While the cultivated land and construction land of 2010 were converted from 1972 with 293.3 km^2 and 22.36 km^2. The Ebinur Lake area presented a decline from 622.66 km^2 to 463.26km^2 during the 1972 to 2010.

3.4 Discussion on the uncertainty of the method

There are various uncertainties in the hydrologic sensitivity analysis method in separating the effects of climate change and human activities on the runoff which may have arisen from the input data and model parameters. First, the function of the hydrologic sensitivity analysis method is based on the data for a long-term period of natural runoff without the effects of human activities. In reality, there was only short-term period observation data in JRB, and even during the baseline period, there may be some human disturbances, such as the building of reservoirs and human grazing. Second, the uncertainty due to the number and distribution of the hydro-meteorological stations affected the accuracy of the simulation, within the JRB is data only from one meteorological station. Third, the AET was calculated using the PET and w parameter, which increases the uncertainty of the simulations relative to the use of PET rates measured in the field. Finally, uncertainty of the model parameter can also affect the results (Jiang et al. 2010; Dong et al. 2012; Chen et al. 2013). Therefore, these uncertainties would influence computational results to a certain extent, and so estimation uncertainties should be further investigated in future studies.

4 Conclusion

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

(1) Annual runoff in the JRB has periodically fluctuated during the period of 1961-2012. through Mann–Kendall test and PRDCC, an abrupt change point in annual runoff was identified in the JRB, which occurred in the years between 1964 and 1996 dividing the long-term hydrologic series into a natural period (1957 – 1964) and a climate and man-induced period (1965 – 1996 and 1997– 2012).

(2) The hydrologic sensitivity analysis method estimated the effects of climate variability and human activities on runoff in 1965 – 2012, indicating that human activities were the main factor that decreased runoff with contribution of 88.9% during 1965 – 1996, while climate change only accounted for 11.1%. However, the impact of climate change has been increasing from 11.1% to 47.5% during 1997 – 2012, showing that runoff in JRB is more sensitive to climate variability during a regional warming period.

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