ORIGINAL PAPER

Impacts of climate variability and human activities on decrease in streamflow in the Qinhe River, China

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Abstract Under the impacts of climate variability and human activities, there are statistically significant decreasing trends for streamflow in the Yellow River basin, China. Therefore, it is crucial to separate the impacts of climate variability and human activities on streamflow decrease for better water resources planning and management. In this study, the Qinhe River basin (QRB), a typical sub-basin in the middle reach of the Yellow River, was chosen as the study area to assess the impacts of climate variability and human activities on streamflow decrease. The trend and breakpoint of observed annual streamflow from 1956 to 2010 were identified by the nonparametric Mann–Kendall test. The results showed that the observed annual streamflow decreased significantly ($P < 0.05$) and a breakpoint around 1973 was detected. Therefore, the time series was divided into two periods: "natural period" (before the breakpoint) and "impacted period" (after the breakpoint). The observed annual streamflow decreased by 68.1 mm from 102.3 to 34.2 mm in the two periods. The climate elasticity method and hydrological model were employed to separate the impacts of climate variability and human activities on streamflow decrease. The results indicated that climate variability was responsible for 54.1 % of the streamflow decrease estimated by the climate elasticity method and 59.3 % estimated by the hydrological modeling method. Therefore, the climate variability was the main driving factor for streamflow decrease in the QRB. Among these driving factors of natural and anthropogenic, decrease in precipitation and increase in water diversion were the two major contributions of streamflow reduction. The finding in this study can serve as a reference for regional water resources management and planning.

1 Introduction

Climate variability and human activities are regarded as the two major factors for hydrological cycle change (Bao et al. 2012). Climate variability has direct impacts on temperature, precipitation, and evaporation (Liu et al. 2011a; Zhang et al. 2009), while human activities (such as land use practices, soil and water conservation, dam construction and water diversion) change the temporal and spatial distribution of water resources (Ma et al. 2010; Milly et al. 2005; Nawarathna et al. 2001). Over the recent decades, there was statistically significant decreasing trend in streamflow for the most rivers in northern China (Liu et al. 2012; Ren et al. 2002; Xu et al. 2010), especially in the Yellow River Basin—the second largest river in China (Li et al. 2007; Yang et al. 1998, 2004). The observed average annual streamflow began to reduce in the 1970s, and there was a sharp decline since the 1980s in middle reach of the Yellow River (MRYR). Compared with the period of 1950–1985, the average annual streamflow reduced about 88.7×10^8 m^3 during 1986–2008 and the rate of decrease is 45.1 % (Gao et al. 2011). The decrease in streamflow brought about great negative impacts on environment, economy, and society. Which is the main driving factor causing streamflow decrease in Yellow River basin, climate variability or human activities? The answer to this question is very important for future water resources planning and management decisions to ensure sustainable water resources utilization (Fu et al. 2004). Thus, some studies have found to identify the contributors to runoff change in the Yellow River basin. For example, Tang et al. (2008) and Cong

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et al. (2009) found that climate variability played a more important role than human activities in the upper reach of the Yellow River; Liu et al. (2013a) investigated that human activities contributed 58.4–64.1 % of the decrease in streamflow in Yiluo River basin. Zhang et al. (2012) concluded that human activities are the main driving factor to lead to significant decrease in annual streamflow in Fenhe basin. Results from all of these researches suggested high regional differences in assessment of the main cause.

Different methods have been used to explore the impacts induced by climate variability or human activities. The climate elasticity method and hydrological modeling are the two major methods widely used to separate the impacts of climate variation and human activities on runoff variation (Dooge et al. 1999; Li et al. 2007, 2012; Liu et al. 2012; Zhang et al. 2001). Li et al. (2007) applied the climate elasticity method to study the response of streamflow to changes in climate and human activities in Wuding River basin. Bao et al. (2012) used the VIC model in Haihe River and found that the human activities were the main factors to the streamflow reduction. Li et al. (2012) compared the two methods in three medium-sized basins of Australia and got similar results.

Qinhe River is the second largest river in China's Shanxi Province and a major tributary of the Yellow River. Climate variability along with human activities have greatly changed the regional hydrological cycle during the past decades (Liu et al. 2013b). It resulted in noticeably change in the relationship between rainfall and runoff. The annual runoff in Qinhe River basin (QRB) was also founded remarkable reduction since the 1970s (Alfieri et al. 2012; Hu et al. 2012). It provides an excellent example to analyze the causes of runoff decrease in the MRYR. This paper aims to estimate quantitatively the impacts of climate variability and human activities on runoff reduction in QRB by hydrological model and climate elasticity approach. The findings can enhance our understanding of the relative roles of climate variability and human activities on runoff decrease in the Yellow River basin.

2 Study area and data

2.1 Study area

The QRB (110.91°–113.50°E, 35.61°–37.13°N) is located in the Loess Plateau of China, and it is a major tributary of Yellow River (Fig. 1), covering an area of 13,532 km². The basin is with of temperate continental monsoon climate, with warm, humid summer, and cold winter. The annual mean temperature is about 9–12 °C. The average annual precipitation varies from 550–700 mm and more than 70 % of the total precipitation is concentrated during June to September. Observed discharge data from 1956 to 2010 produced a mean annual discharge of 7.2×10^8 m³, and the annual discharge

ranged from a minimum of 0.5×10^8 m³ in 1991 to a maximum of 30.8×10^8 m³ in 1963. The north of the basin is mountain area with high percentage of forest cover, accounting for about 48 % of the total catchment area. The middle and lower regions are hilly and plain, covering about 37 and 15 % of the total catchment area, respectively.

2.2 Data used

The daily meteorological records of six national meteorological stations are acquired from China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn). The dataset includes precipitation, temperature, wind speed, vapor pressure, and hour of sunshine. The dataset is used to calculate the potential evapotranspiration (E_0) using FAO Penman–Monteith method (Allen et al. 1998). The daily precipitation records at 13 rainfall gauges, monthly observed streamflow, and annual water diversion data are obtained from the Yellow River Hydrological Bureau. The basin-wide average of precipitation and E_0 are estimated by the Thiessen polygon method based on the distributed of gauges.

3 Methodology

3.1 Trend test and breakpoint detection

The trend of annual streamflow was analyzed based on the rank-based nonparametric Mann–Kendall (MK) test (Kendall 1975; Mann 1945). The method is widely used to detect trends in hydroclimatic series due to its robustness for non-normally distributed and censored data (Hamed 2008; Hirsch and Slack 1984; Liu et al. 2011b; Ma et al. 2010; Yue et al. 2002). More details of MK test are explained in Hamed (2008) and (Zhang et al. 2009). For the sequential time series $x_1, x_2, \ldots x_n$, m_i is the number of later terms in the series whose values exceed x_i. The MK rank statistic d_k is calculated as:
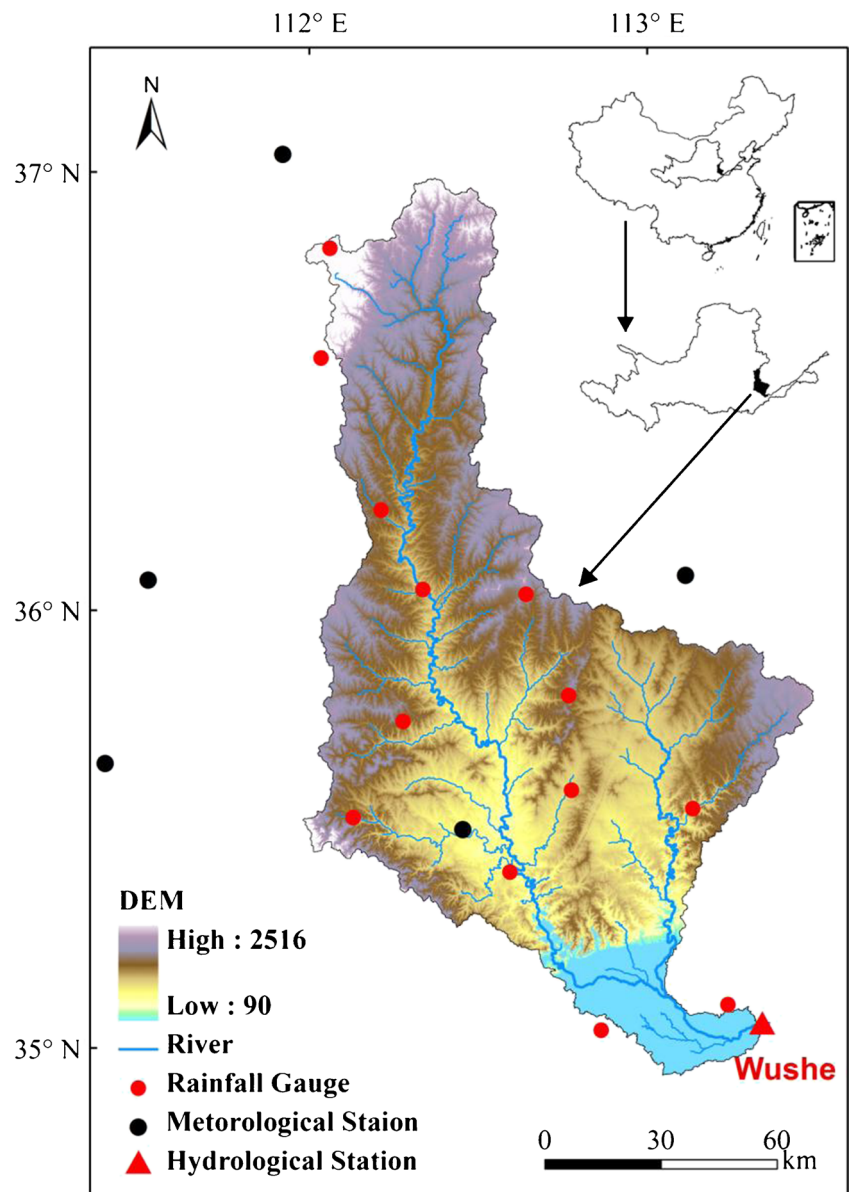
$$d_k = \sum_{i=1}^{k} m_i \qquad (2 \leq k \leq n) \tag{1}$$

The expected value $E(d_k)$ and variance $Var(d_k)$ could be estimated as follows:

$$\begin{cases} E(d_k) = \dfrac{k(k-1)}{4} \\ Var(d_k) = \dfrac{k(k-1)(2k+5)}{72} \end{cases} \qquad (2 \leq k \leq n) \tag{2}$$

The test statistic (UF_k) is calculated by the following formula:

Fig. 1 Map of the study area

$$UF_k = \frac{d_k - E(d_k)}{\sqrt{Var(S_k)}} \qquad (1 \le k \le n) \qquad (3)$$

The positive value of UF indicates an increasing trend, and negative value denotes a decreasing trend. Then according to the inverse time series: $x_n, x_{n-1}, \ldots x_1$, the same method is applied to get a series UB. The intersection point of UF and UB curves would be regarded as the breakpoint of the series.

3.2 Quantitative assessment of the attribution for streamflow decrease

3.2.1 The climate elasticity method

The Budyko hypothesis (Budyko 1948) describes the annual water balance as a function of available water and energy; the long-term change in basin water storage is negligible; precipitation and E_0 are the dominant factors that determine the mean annual water balance (Arora 2002; Yang et al. 2007). The water balance for a basin can be described as follows:

$$P = E + Q \qquad (4)$$

where P, E, and Q are annual precipitation, actual evapotranspiration (AET), and streamflow, respectively. In the drainage area of interest, the change in observed mean annual streamflow (ΔQ) between "natural period" and "impacted period" could result from climate variability (ΔQ_C) and human activities (ΔQ_H) (Li et al. 2007):

$$\Delta Q = \Delta Q_H + \Delta Q_C \qquad (5)$$

Perturbations in both precipitation and E_0 can lead to changes in the water balance (Dooge et al. 1999). Basing on the hydrological sensitivity relationship, the change in mean annual runoff due to climate variability can be approximately estimated as follows (Dooge et al. 1999; Milly and Dunne 2002):

$$\Delta Q_C = \Delta Q_P + \Delta Q_{E_0} = \left(\varepsilon_P \frac{\Delta P}{P} + \varepsilon_{E_0} \frac{\Delta E_0}{E_0} \right) Q \qquad (6)$$

where ΔQ_P and ΔQ_{E_0} are the contributions of change in precipitation and E_0 to change in streamflow, respectively. Q is the naturalized streamflow. ΔP and ΔE_0 are the change in precipitation and E_0 between the two periods, respectively. ε_P and ε_{E_0} are the elasticity of streamflow with respect to precipitation and E_0. They can be calculated as follows (Arora 2002):

$$\varepsilon_P = 1 + \frac{\varphi F'(\varphi)}{1 - F(\varphi)} \quad and \quad \varepsilon_P + \varepsilon_{E_0} = 1 \qquad (7)$$

where φ is the aridity index, which is the ratio of E_0 and precipitation. $F(\varphi)$ is the function of calculating the mean annual AET, and $F'(\varphi)$ is the derivative of with respect to φ. Based on the Budyko hypothesis, many forms of $F(\varphi)$ were proposed and more details can be found in Pike (1964), Fu (1981), and Zhang et al. (2001). In this study, the Zhang et al. (2001) method was used as expressions of $F(\varphi)$ and $F'(\varphi)$:

$$\begin{cases} F(\varphi) = (1 + \omega\varphi)/\left(1 + \omega\varphi + 1/\varphi\right) \\ F'(\varphi) = \left(\varphi^{-2} + 2\omega\varphi^{-1} + \omega - 1\right)/\left(1 + \omega\varphi + 1/\varphi\right)^2 \end{cases} \qquad (8)$$

where ω is plant-available coefficient relating to vegetation type. The value of ω can be calibrated by comparing the long-term annual AET calculated from Eqs. 4 and 8 (Zhang et al. 2001).

3.2.2 Hydrologic modeling

In this study, the dynamic water balance model (DWBM) was used to separate the effects of climate variability and human activities. The model is a lumped conceptual monthly water balance model and developed by Zhang et al. (2008) on the basis of the framework of Budyko (Wang et al. 2011). It is a parsimonious hydrological model with only four parameters. The model has been tested in Australia and China, and demonstrated a good performance both in humid and semi-arid areas (Li et al. 2011; Zhang et al. 2008). The model inputs are monthly precipitation, PET, and streamflow. The DWBM model was calibrated and validated using streamflow data from the "natural period". If the performance requirement can be satisfied, the model then can be used to simulate the

natural runoff in "impacted period". The difference between the simulated and observed runoff in "impacted period" are attributes to the impacts of human activities on the streamflow change (Jiang et al. 2011; Li et al. 2012).

For the parameter optimization, the Particle Swarm Optimization toolbox in MATLAB was used (Eberhart and Kennedy 1995; Thompson et al. 2013). The model was calibrated by Nash–Sutcliffe Efficiency (NSE) (Nash and Sutcliffe 1970) and Water Balance Error (WBE):

$$NSE = 1 - \frac{\sum_{i=1}^{n} \left(Q_{obs,i} - Q_{sim,i}\right)^2}{\sum_{i=1}^{n} \left(Q_{obs,i} - \overline{Q_{obs}}\right)^2} \qquad (9)$$

$$WBE = 100 \left(\frac{\sum_{i=1}^{n} Q_{sim,i} - \sum_{i=1}^{n} Q_{Obs,i}}{\sum_{i=1}^{n} Q_{obs,i}} \right) \qquad (10)$$

where Q_{sim} and Q_{obs} are the simulated and observed runoff, respectively. $\overline{Q_{obs}}$ is the arithmetic mean of the observed runoff.

4 Results

4.1 The change in annual streamflow, precipitation, and E_0

Figure 2a shows the variation of observed annual streamflow from 1956 to 2010 in the QRB. The observed annual streamflow indicates a higher variability, ranging from 4.0 to 239.3 mm with a mean of 57.4 mm. The observed annual streamflow shows significant decreasing trend ($P < 0.05$) based on the MK test. It can be seen from Fig. 2b that the breakpoint was detected around the year 1973 ($P < 0.05$). Therefore, the streamflow series was divided into two periods: "natural period" (period I:1956–1973) and "impacted period"(period II:1974–2010). The observed average annual streamflow was 102.3 mm in period I, while it was 34.2 mm in period II. Compared to that of period I, the relative change was −66.9 %. In "natural period", the hydrological cycle and water resources system is regarded as keep natural status and not impacted by human activities (Bao et al. 2012). Spontaneous, natural and anthropogenic influences combined result in the runoff variability in "impacted period".

Figure 3 shows the change of annual precipitation, E_0, and temperature from 1956 to 2010. Compared to the period I, the annual precipitation and E_0 decreased by 105.8 and 26.1 mm, respectively, while the temperature increased by 0.7 °C. The relative changes of precipitation, E_0, and temperature were −16.0, −2.7, and 6.5 %, respectively (Table 1).

As shown in Fig. 3d, these points in period I are obviously lower than them in period II. It indicates that the same precipitation in period II generated less runoff than that in period I.

Fig. 2 **a** Variation of annual observed streamflow in QRB. **b** The detection of breakpoint by MK test. The *black horizontal dotted lines* represent the critical values at the 5 % significance level
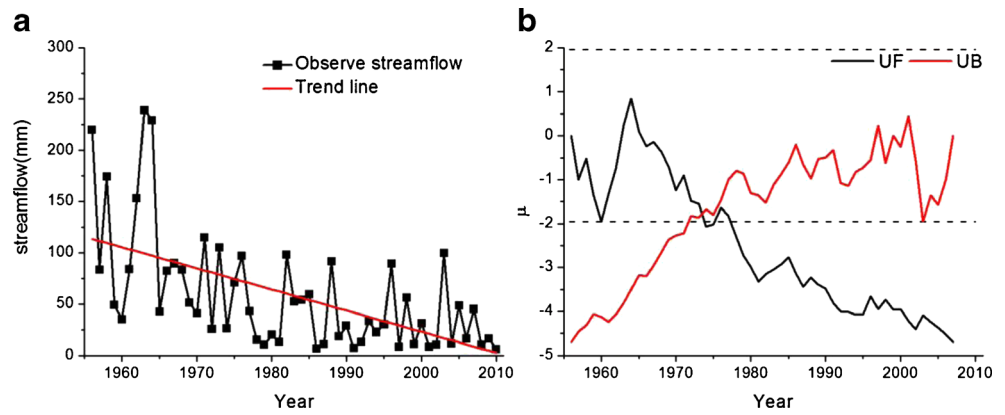

The relationship between the annual precipitation and streamflow presented a nonstationary state.

4.2 Separating the impacts of climate variability and human activities on streamflow decrease

4.2.1 Assessment using climate elasticity method

In the climate elasticity method, the ω is the most sensitive model parameter, which has the greatest influence on model results (Chen et al. 2012; Zhang et al. 2001). The ω can be calibrated based on the results estimated by water balance in natural period. In this study, the period I (1956–1973) was selected as the calibration period. With a value of $\omega = 0.90$, we found the best agreement between the results of Eqs. 4 and 8 (Fig. 4). When $\omega = 0.90$, the value of ε_P and ε_{E_0} were 2.17 and −1.17, respectively. It implied that 10 % increase in precipitation would result in 21.7 % increase in streamflow, while 10 % increase in E_0 would result in decrease 11.7 % in streamflow. Therefore, the response of the annual runoff is
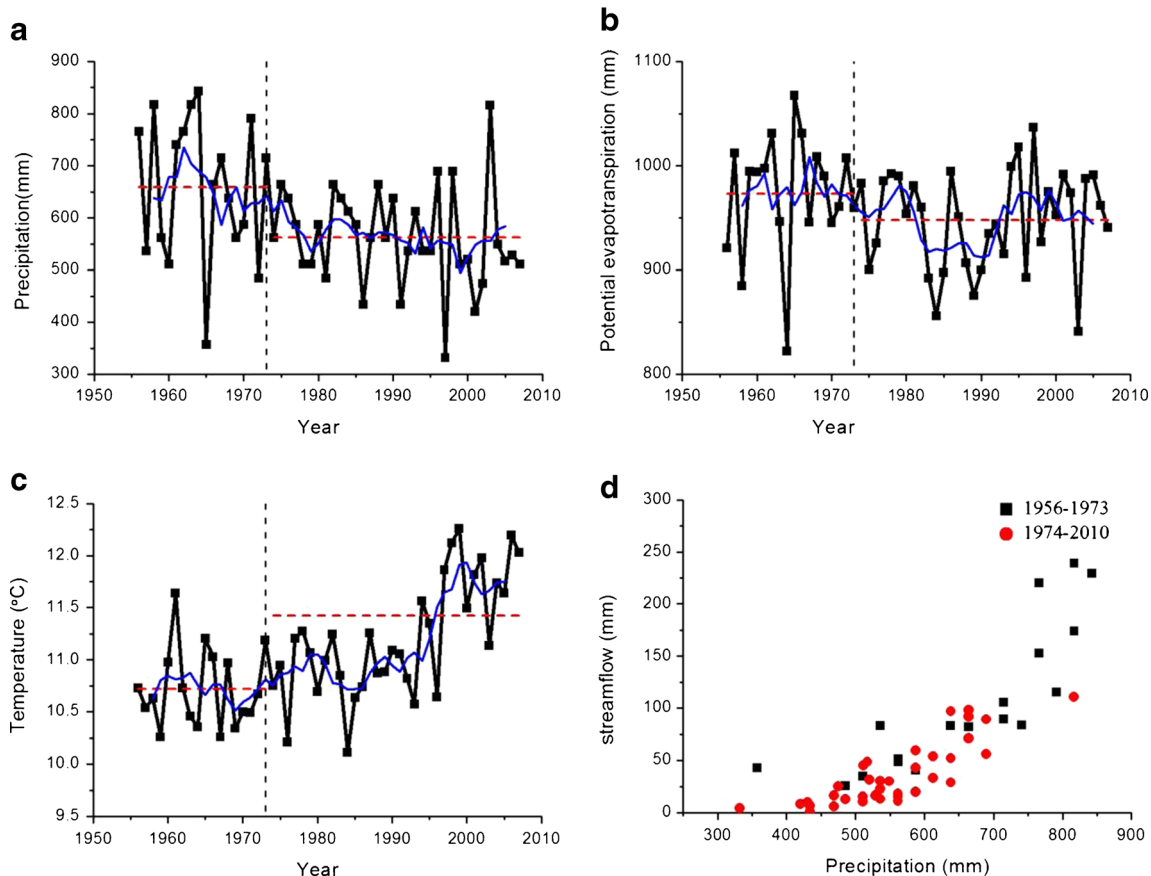
Fig. 3 Variation of annual precipitation (**a**), potential evapotranspiration (**b**), and temperature (**c**). The *blue line* shows the 5-year moving average and the *red horizontal dotted lines* represent the averages of the corresponding period. The relationship between precipitation and runoff in the two periods was shown in (**d**)

Table 1 Hydrological variable statistics during the two periods

| Hydrological variables	Period I	Period II	Relative change	
			(mm)	(%)
Observed streamflow (mm)	102.3	34.2	−68.1	−66.6
Precipitation (mm)	659.6	553.8	−105.8	−16.0
Temperature (°C)	10.72	11.42	0.7	6.5
E_0 (mm)	973.4	947.3	−26.1	−2.7

more sensitive to precipitation changes rather than to E_0 changes. Based on the Eq. 8, the percentage changes in the runoff due to the changes in precipitation and E_0 were −65.1 and 5.9 %, respectively. The change in precipitation and E_0 together led to 59.3 % of decease in streamflow, while the human activities led to 40.7 % of decease in streamflow.

4.2.2 Assessment using hydrological modeling method

In this study, the time series in natural period (1956–1973) was divided into two parts: 1956–1967 and 1968–1973, which were used as the calibration period and validation period for DWBM model, respectively. Figure 5 shows good agreement between monthly observed and simulated runoff by DWBM model. The NSE in calibration period and validation period was 0.86 and 0.82, respectively, and the WBE was 3.3 and 4.6 % in the two periods. Then, the same model parameters were used to simulate the natural streamflow in period II. The difference between the simulated and observed streamflow in period II was the streamflow change caused by human activities. From Fig. 6b, it can be seen that the difference between the simulated and observed annual streamflow in period I is very small; it implies that the human activities are limited. However, the gap between
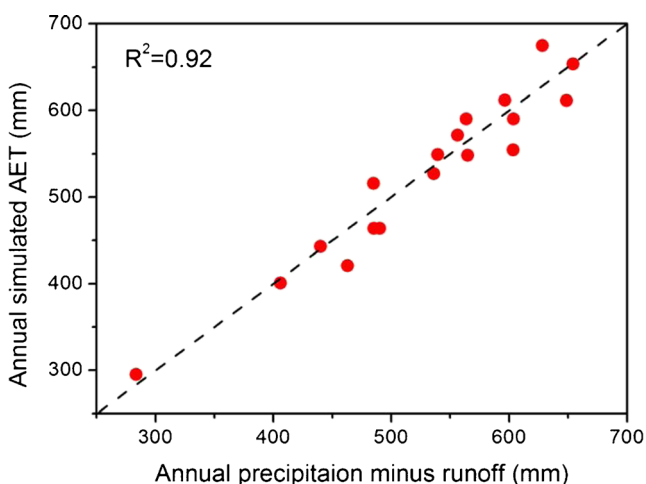
Fig. 4 Correlation relations between annual actual evapotranspiration (AET) calculated directly from water balance equation and simulated by Zhang's curve for "natural period"
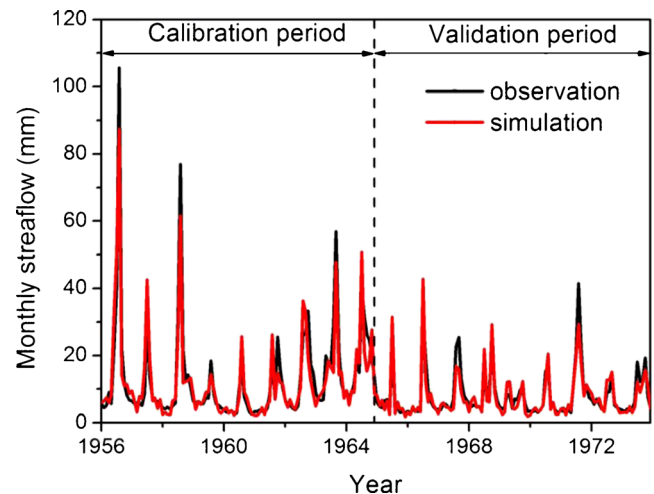
Fig. 5 Comparison of the observed and simulated monthly streamflow

the simulated and observed streamflow increased gradually since the 1970s. It indicates that the human activities played an increasing important role after 1970s. The observed annual streamflow decreased by 68.1 mm during the two periods, while the natural streamflow simulated by DWBM model decreased by 40.4 mm. It suggests that climate variability was responsible for 59.3 % streamflow decrease.

### 4.2.3 Comparison of the results between climate elasticity and hydrological modeling

The effect of climate variability on runoff decrease, calculated by the climate elasticity and hydrological model, varies from 54.1 to 59.3 %. Therefore, the effect of human activities on runoff decrease ranges from 40.7 to 45.9 %. The results from those two methods are closely similar to each other. The results from both method indicated that the climate variability was the major driving factor for streamflow decrease in QRB. Compared to hydrological model method, the climate elasticity method has lower input requirements. It has been proved as a reliable method to assess the impacts of climate variability on large no-regulated catchments. However, this method can only be applied to the annual streamflow responding to climate variability (Zhao et al. 2010). Compared to the elasticity method, the hydrological model needs more input data but it can used at a daily, monthly, or annual time-step and provides more information about the detailed description of hydrological process.

5 Discussion

5.1 Human activities

Although anthropogenic factors played a secondary role based on the above analysis, the impacts on runoff variation are
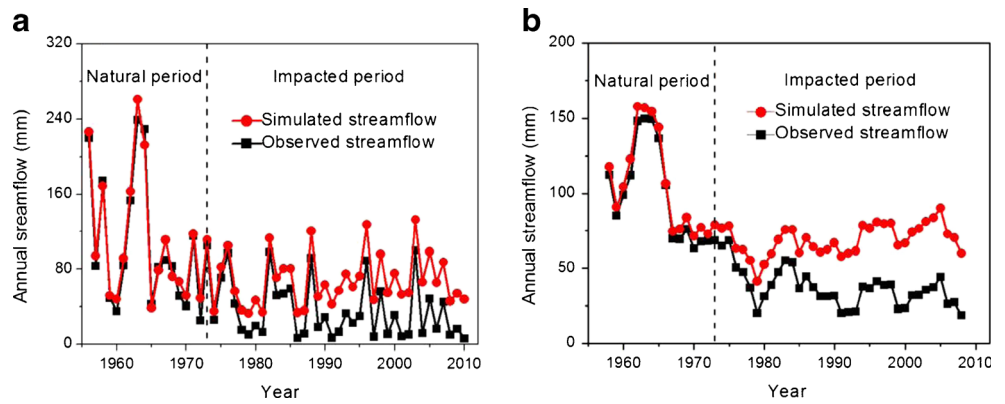
controllable by new policies or technologies to some degree. Thus, it is necessary to assess the major contributors in various human activities for better water resources planning and management.
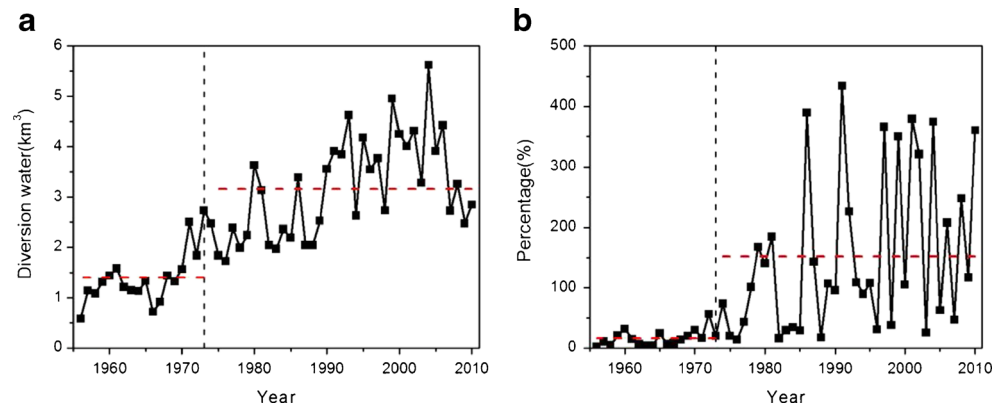
In the study area, the rocky mountain and hilly region account for about 85 % of total area, where it is not fit for development of agriculture extensively, and the soil erosion area accounts for only about 2.0 % of total area. Thus, there has been no significant change in land use/land cover since the 1950s. However, there was a remarkable increase in the number of dams since 1950s. By the end of 2000, there were five medium-sized (the capacity of reservoir storage between 0.01 to 0.1 km^3) and 103 small-sized (the capacity of reservoir storage less than 0.01 km^3) reservoirs, most of them were built from the mid-1950s to the early 1970s. On the one hand, reservoirs increased the losses of evaporation and leakage; on the other hand, large amount of water storage in reservoirs was used for irrigation and industrial water consumption by water diversion projects. As shown in Fig. 7, the average amount of water diversion was 1.4 km^3 per year in period I, while it increased to 3.2 km^3 per year in period II. The proportion of average diversion water to average annual streamflow in the two periods was 16.4 and 151.5 %, respectively. The maximum percentage was 434.8 % in 1991. Therefore, among various anthropogenic factors, increasing

water diversion was the main cause to lead to streamflow decrease in Qinhe River basin.

5.2 The uncertainty of the hydrological simulations

This study presents a quantitative assessment of the effects of climate variability and human activities on streamflow decease in Qinhe River based on the methods of climate elasticity and hydrological model. However, there are various uncertainties in model input, model structure, and model parameters. First, the spatial variability of annual precipitation in the QRB is very large. The precipitation data from limited number hydro-meteorological stations could not represent the real regional precipitation. Second, for climate elasticity method, the impacts of precipitation and potential evapotranspiration were separated with the assumption that they are independent. However, in fact, they are impacted each other (Zheng et al. 2009). Finally, for the climate elasticity method and hydrological model, the parameters are usually calibrated based on the data for a long-term period of natural runoff without the effects of human activities. However, 18 years of time series was insufficient for reliable parameter calibration. Moreover, the impacts of human activities existed certainly in "natural period" more or less. Thus, the errors for the calibration of model parameters were unavoidable.

6 Conclusion

The observed annual streamflow in QRB decreased significantly from 1956 to 2010. The trend and breakpoint of streamflow was identified by Mann–Kendall test. On this basis, the methods of climate elasticity and hydrological model were applied to find out main driving factor resulted in runoff decrease. The results indicated that climate variability was responsible for 54.1 % of the streamflow decrease estimated by the climate elasticity method and 59.3 % estimated by the hydrological modeling method. Therefore, the climate variability was the main driving factor for streamflow decrease in QRB. Among various driving factors of natural and anthropogenic, decreasing precipitation and increasing water diversion were the two major contributions of decrease in streamflow. At last, the responses of streamflow to climate variability and human activities are extremely complicated processes; there are various uncertainties in this study, and they will affect the assessment results to a certain extent.

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