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ORIGINAL PAPER

Quantitative assessment of the impact of climate variability and human activities on runoff changes for the upper reaches of Weihe River

Yuan Guo · Zhijia Li · Mark Amo-Boateng · Peng Deng · Pengnian Huang

Abstract In the wake of global and regional climate change and heightened human activities, runoff from some rivers in the world, especially in the arid and semi-arid regions, has significantly decreased. To reveal the varying characteristics leading to the change in runoff, detecting the influencing factors has been important in recent scientific discussions for water resources management in drainage basins. In this paper, an investigation into attributing the runoff response to climate change and human activities were conducted in two catchments (Wushan and Shetang), situated in the upper reaches of Weihe River in China. Prior to the identification of the factors that influenced runoff changes, the Mann–Kendall test was adopted to identify the trends in hydro-climate series. Also, change-points in the annual runoff were detected through Pettitt's test and the precipitation–runoff double cumulative curve method. It is found that both catchments presented significant negative trend in annual runoff and the detected change-point in runoff occurs in 1993. Hence, the pre-change period and post-change period are defined before and after 1993, respectively. Then, runoff response to climate change and human activities was quantitatively evaluated on the basis of hydrologic sensitivity analysis and hydrologic model simulation. They provided similar estimates of the percentage change in mean annual runoff for the post-change period over the considered catchments. It is found that the decline in annual runoff over both catchments can be mainly attributed to the human activities, the reduction percentages due to human activities range from 59 to 77 %. The results of this study can provide a reference for the development, utilization and management of the regional water resources and ecological environment protection.

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1 Introduction

Changes in runoff can be attributed to the combined effects of climate, land cover and human activities in the basin. With the global warming on the rise, as well as, the current overexploitation of water resources, decreases in streamflow has appeared in a large number of rivers (e.g. Zhang et al. 2012a; Wang et al. 2012; Chen et al. 2013). The reduction in runoff could impact the river functions, and further induce severe ecological and environmental problems. Hence, the investigations into the factors that affect changes in runoff have recently drawn considerable concerns.

During the past decades, due to the climate warming and the significant regional precipitation variation coupled with strong human activities (such as the drastic agricultural and industrial development, soil and water conservation projects and water conservancy projects) in China (Piao et al. 2010), more attention has been given to assess the impacts of climate change and human activities on runoff change. Chen et al. (2012) found changing points of monthly streamflow series are roughly in good agreement with those of annual, winter and summer precipitation across the Pearl

River basin, and implied precipitation changes have tremendous influences on streamflow variations. For sake of understanding the abrupt behavior of hydrological processes, Tu et al. (2012) analyzed monthly streamflow and precipitation series using the likelihood ratio statistic and schwarz information criterion (SIC). Meanwhile, the influence of human activity on streamflow has also been assessed in the basins where water conservancy projects have been constructed. For example, Zhang et al. (2012b) investigated the influence of Three Gorges Dam (TGD) on streamflow of the Yangtze River.

In order to further identify the main factor that affects changes in runoff, a number of researchers focus on assessing the percentages of human activities and climate variability impact on runoff. Owing to its impacts varying from place to place, it is usually investigated at a local scale (the basin or sub-basin scale). Wang et al. (2010) reported that in the Baimasi Basin (sub-basin of the Yellow River) percentage change in runoff due to climate change is 89, 66, and 56 % for the years 1970s, 1980s and 1990s, respectively. Li et al. (2009) pointed out that climate variability influenced the surface hydrological process more significantly than land use change during the 1981–2000 in an agricultural catchment of the Loess Plateau, a tributary of Jinghe River. Du et al. (2011) assessed streamflow in response to precipitation variation and anthropogenic factors, in the Zhengshui River basin, China. It is found that an abrupt change point occurs in 1990, and human activities and precipitation contributed 53 and 47 %, respectively, to increase in stream flow during 1991–2003. Hao et al. (2008) suggested the impact of human activities on the decrease of surface runoff in the main stream is 41.59 % (in 1970s), 63.77 % (in 1980s) and 75.15 % (in 1990s) in Tarim River. Jiang et al. (2011) quantitatively analyzed the effects of climate variability and human activities on runoff from the Laohahe basin in northern China. Wang et al. (2012) concluded that human activities are primarily responsible for runoff reduction in the three sub-basins (Luanhe River catchment, Chaohe River catchment and Zhanghe River catchment) of the Huaihe River Basin.

For a certain river basin, the following steps can be adopted to quantify the effects of climate variability and human activities. Firstly, the change points are determined by the standard statistical methods, e.g. Mann–Kendall (MK) trend test (Kendall 1975), the Pettitt's test (Pettitt 1979; Kiely et al. 1998) or DDC method (Huo et al. 2008), and the period before the change is regarded as a baseline period. Therefore the period that shows the impact of climate variability and human activities are separated from the baseline period. This is followed by application of methods that summarize the effect of climate variability. The remainder of the effect is then attributed to other factors such as human activities (Zhao et al. 2010).

There have been a great number of methods used to separate the impacts of climate change and human activities on runoff. However, the hydrological model simulation method is traditionally the most widely used. For instance, Zhang et al. (2012b) and Fan et al. (2010) employed soil and water assessment tool to measure the effect of natural and human factors on the water cycle in Huifa River Basin, the Variable Infiltration Capacity model was applied by Jiang et al. (2011) in Laoha River basin. Similar studies have also been conducted on the basis of monthly water balance model (e.g. Wang et al. 2009, 2012). In addition, some new methods have been developed and have been widely used in many regions to estimate the effect of climate variability and human activities on streamflows. These methods include the regression analysis and hydrological sensitivity analysis methods. For example, Tian et al. (2009) and Zhang et al. (2009) employed regression analysis to estimate the impact of human activities on streamflow in the Hutuo River and lower Xijiang basins. The hydrological sensitivity method, developed by Dooge et al. (1999) and applied by Milly and Dunne (2002), describes first-order effect of changes in precipitation and potential evaporation on streamflow, has been successfully used to evaluate the effects of climate variability and human activities on the hydrologic cycle (e.g. Jones et al. 2006; Zhao et al. 2010).

The Weihe River, the largest tributary of the Yellow River, plays an important role in the Yellow River's ecological and environmental improvement. In recent years, the annual runoff in the upper reaches has decreased significantly (Wang et al. 2006; Song et al. 2007; Zhang et al. 2009). For example, comparing the periods 1981–1990 and 1991–2000, the annual runoff obtained from Linjiacun gauging station decreased by 53.9 %. The rapid decrease in runoff leads to reductions in Wei River's discharge into the Yellow River; thereby impacting Yellow River's ecology and environment. To date, there have been some studies reporting that the streamflow for the upper reaches in the Weihe River basin has dramatically decreased in recent years. Liang et al. (2012) concluded that the inter-annual variation of runoff in upper reaches was large, and thus the decrease in runoff was significant during that period (1960–2000). Wang et al. (2006) argued that human activities are the main reasons behind runoff reduction since the 1980s, and the extent of the influence was intensifying. However, systematically quantifying the effects of climatic variability and human activities on runoff change in the upper reaches in the Weihe River basin has not yet been reported. Therefore, the objectives of this study are to (1) identify change trends and change points in annual runoff and (2) separate the effects of climatic variability and human activities on runoff with two methods. This paper is organized as follows: First, a brief description of the study area and data sources is given. Next, details of the methods used are provided. This is followed by a presentation of the results, which include change points determination and the inter-comparison of models in the estimation of the influence of climate variability and human activities on runoff. Finally, discussions and conclusions of the study are given.

2 Study area and data

2.1 Study area

The Weihe River, the largest tributary of the Yellow River, originates from the north of the Niaoshu Mountains at an altitude of 3,485 m, runs across 818 km through the provinces of Gansu and Shanxi and feeds into the Yellow River (Fig. 1). The upper reaches of the Weihe River refer to the catchment above the Linjiacun gauging station, extend from longitude 104.00°E to 107.00°E, and latitude 34.25°N to 36.25°N. It covers an approximate area of 30,661 km^2. The elevation within the basin ranges from 647 to 3,635 m above the sea level. It is characterized by semi-arid continental climate. The average annual temperature is between 9 and 13 °C, the annual rainfall ranges from 315 to 664 mm, the main flooding season usually occurs in July, August and September, accounting for nearly 60–70 % of annual total runoff over the upper reaches of Weihe River. In addition, the average annual evaporation in the study area is about 1,400 mm.

As a result of serious soil and water loss, many soil and water conservation projects have been implemented in the last 30 years. The detailed soil and water conservation measures include terraced fields, warping dams and afforestation (Wang et al. 1994; Ma et al. 2002). Unfortunately, no information is available on historical land use in the basin, apart from some contextual data indicating the increasing intensity in soil and water conservation projections since middle 1980s. For instance, the controlling soil and water loss was up to 23.9 % in 1989, and was increased to 31.4 % in 1996 (Ma et al. 2002).

2.2 Data

The Wushan (in the period 1975–2007) and Shetang (in the period 1972–2007) gauging station were selected to examine the annual runoff variations of the Wushan and Shetang River basins, respectively. Daily precipitation data in the consistent period were obtained from the hydrologic Year-book (1975–2007, Wushan station; 1972–2007, Shengtang station). The same-period time series of daily streamflow in Wushan and Shetang hydrologic station were prepared. The meteorological data used for simulation of potential evapotranspiration, include daily mean air temperature, wind speed, relative humidity and sunshine. They are collected from the National Climate Center, China Meteorological Administration. However, the observed are not available for the two considered catchments. The closest available observations are for the meteorological station of Huajialing, approximately 50 km to the east of the Wushan river basin. Similarly, meteorological data from Tianshui station are applied to the simulation in the Shetang river basin. The Penman–Monteith equation recommended by Food and Agriculture Organization of the United Nations was used to calculate Potential Evapotranspiration (Allen et al. 1998).

3 Methodology

3.1 Trend test and change point analysis method

3.1.1 Trend test

Mann–Kendall test The rank-based Mann–Kendall test (Kendall 1975) was used to detect trends in the hydro-climatic series in this study. The method, recommended by the World Meteorological Organization and widely used by many researchers (e.g. Zhang et al. 2008; Wang et al. 2011a, b), is usually adopted to estimate the significance of monotonic trends in hydrological and meteorological time series.

For a time series $X = \{x_1, x_2, x_3 \ldots, x_n\}$, where $n > 10$, the standard normal statistic Z is estimated as follows:

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

where

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

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

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

In which t is the extent of any given time.

The statistic Z follows the standard normal distribution. At a 10 % significance level, the null hypothesis of no trend is rejected if $|Z| > 1.64$. Similarly, the

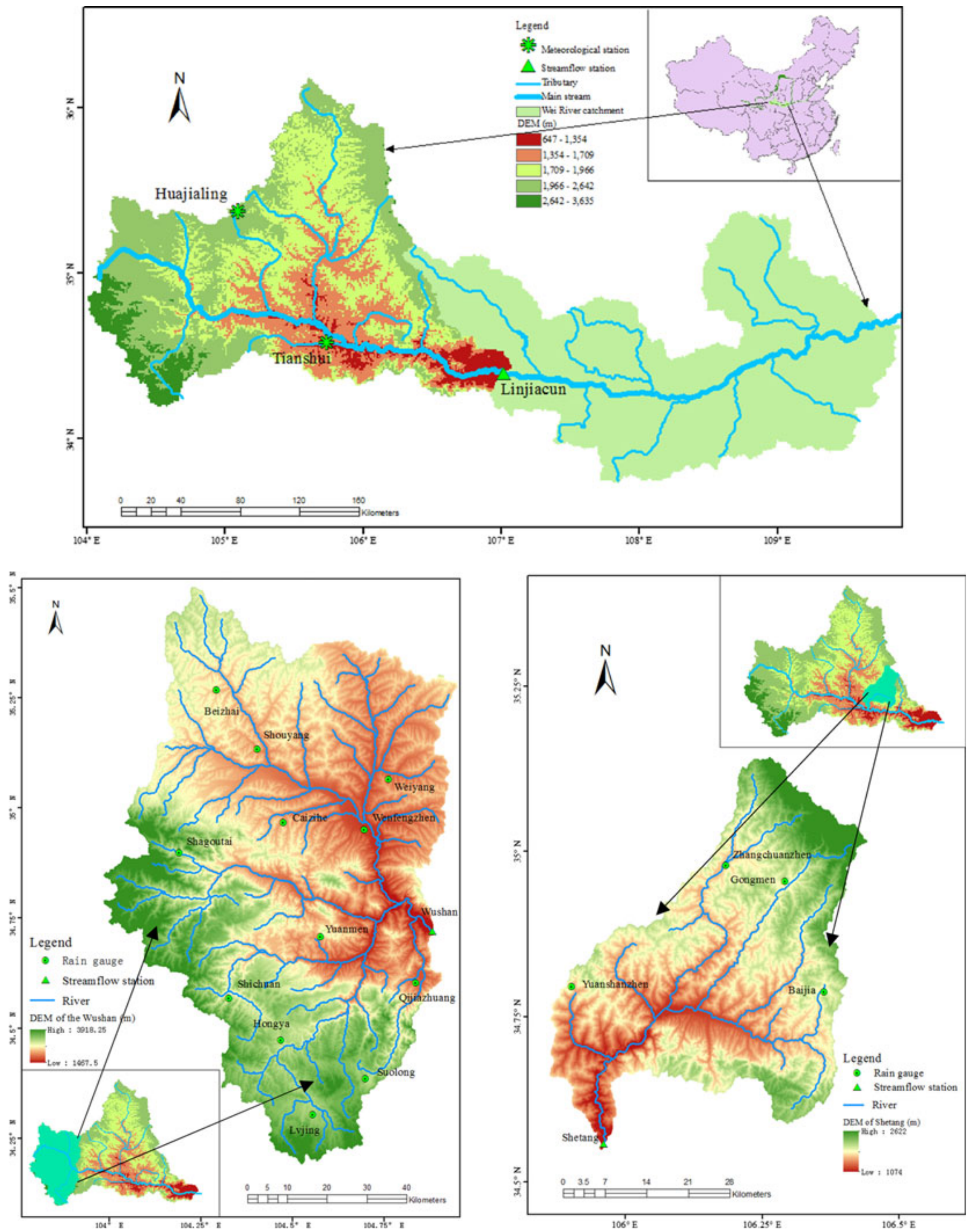

Fig. 1 Location and hydro-meteorological stations of the study area **a** upper reaches of the Weihe River, **b** Wushan catchment and **c** Shetang catchment

threshold values of $|Z|$ can reach up to 1.96 (at a 5 % significance level) and 2.58 (at a 1 % significance level). A positive value of Z indicates an increasing trend, and the opposite corresponds to a decreasing trend. The pre-whitening technique (Yue and Wang 2002) was adopted to eliminate the effects of the serial correlation on the MK test.

3.1.2 Change point analysis method

Pettitt's test The Pettitt's test (Pettitt 1979) is a non-parametric approach to determine the occurrence of a change point. It has been commonly used to detect changes in the hydrological series as well as climatic ones (e.g. Verstraeten et al. 2006). This approach considers a time series as two samples represented by $x_1, x_2, \ldots, x_t$ and $x_{t+1}, \ldots, x_n$. The Pettitt indices $U_{t,n}$ can be calculated from the following formula (Kiely et al. 1998):

$$U_{t,n} = \sum_{j=1}^{t} \sum_{i=1}^{n} \mathrm{sgn}(x_j - x_i) \quad (t = 1, \ldots, n) \tag{5}$$

where the maximum $U_{t,n}$ corresponds to the change point year

Double cumulative curve method The double cumulative curve (DCC) is the plot of the accumulated values of one variable against the accumulated values of another related variable for a concurrent period (Searcy and Hardison 1960). DCC between precipitation and runoff has recently become an effective tool for detecting the changes of hydrological regime due to anthropogenic disturbances (e.g. Huo et al. 2008). Normally the DCC between precipitation and runoff is a straight line, a change in the gradient of the curve may present that the original relationship between variables has been broken. In this study, the DCC will be utilized to identify the change point of the runoff series as a confirmation of the change points detected by Pettitt's test.

Using trend and change-point analysis, the runoff series can be divided into the pre-change and the post-change periods. Thus, the impacts of climate variability and human activities on runoff can be separated by using the following methods.

3.2 Hydrologic sensitivity analysis method

Hydrological sensitivity can be described as the percentage change in mean annual runoff in response to the change in mean annual precipitation and potential evapotranspiration. In general, the water balance for a basin can be described as:

$$P = E + Q + \Delta S \tag{6}$$

where P is precipitation, E is the actual evapotranspiration (AET), Q is streamflow, and ΔS is the change in soil water storage. For a long period (i.e. 10 years or more), ΔS can be assumed as zero.

Following a simple model (called Zhang's curve) developed by Zhang et al. (2001).

Long-term mean annual AET can be estimated as follows:

$$\frac{E}{P} = \frac{1 + w(PET/P)}{1 + w(PET/P) + (PET/P)^{-1}} \tag{7}$$

where PET is the potential evapotranspiration and w 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. (2001). In this study, the parameter w is calibrated by comparing the long-term annual AET from Eqs. (6) and (7).

Perturbations in both precipitation and PET can lead to changes of water balance. It can therefore be assumed that a change in mean annual runoff may be caused by climate variability and this can be determined in the following expression (Milly and Dunne 2002):

$$\Delta Q_{climate} = \beta \Delta P + \gamma \Delta PET \tag{8}$$

where $\Delta Q_{climate}$ represents the change in mean annual runoff due to the effect of climate change. ΔP and ΔPET denote changes in mean annual precipitation and potential evaporation, respectively, and β and γ are the sensitivity coefficients of runoff to precipitation and potential evaporation, which are expressed (Li et al. 2007) as:

$$\beta = \frac{1 + 2x + 3wx}{(1 + x + wx^2)^2} \tag{9}$$

$$\gamma = -\frac{1 + 2wx}{(1 + x + wx^2)^2} \tag{10}$$

In which x is the mean annual index of dryness (equal to PET/P).

3.3 Hydrologic model simulation method

For the sake of evaluating the impacts of climate change and human activities on runoff variation, the method of reconstructing natural runoff based on hydrological models is used. The hydrological model is first calibrated based on observed runoff in the pre-change period, and natural runoff during the post-change period is reconstructed by changing only meteorological input without any change in the calibrated parameters and consideration of local human activities.

Then the impact of human activities on runoff can be calculated as follows:

$$\Delta Q_{human} = Q_h - Q_{hr} \tag{11}$$

where ΔQ_{human} represents the change in mean annual runoff due to the effect of human activities, Q_h denotes the observed annual average runoff of the post-change period; Q_{hr} expresses the reconstructed annual average runoff for of the post-change period.

In this study, the limited information and the available data sets fail to meet the minimal requirements for physical-based hydrological model. Instead, a simple lumped hydrological model is used to estimate the effects of climate variability and human activities on annual streamflow.

The HBV model (Seibert 1998; Abebe et al. 2010) simulates daily discharge using daily rainfall, temperature and potential evaporation as inputs. Meanwhile, the automatic calibration of the model is conducted by Monte Carlo approach (Seibert and Vis 2012).

Precipitation is simulated as either snow or rain depending on whether the temperature is above or below a threshold temperature, TT (°C). Snow melt is calculated with the degree-day method [Eq. (12)]. Meltwater and rainfall are retained within the snow pack until it exceeds a certain fraction. Liquid water within the snow pack refreezes according to a refreezing coefficient, *CFR* [Eq. (13)].

$$melt = CFMAX \times (T(t) - TT) \tag{12}$$

where *melt* represents the amount of snowmelt, *CFMAX* represents degree-day factor, $T(t)$ represents the daily mean temperature at the time t, TT is a threshold temperature.

$$refreezing = CFR \times CFMAX \times (TT - T(t)) \tag{13}$$

where *refreezing* denotes the amount of frozen water within the snow pack. *CFR* is a refreezing coefficient.

Rainfall and snow melt (P) are divided into water filling the soil box and runoff recharge depending on the relation between water content of the soil box [SM (mm)] and its largest value [FC (mm)] [Eq. (14)]. Actual evaporation E_{act} from the soil box equals the potential evaporation E_{pot} if $\frac{SM}{FC}$ is above LP, while a linear reduction is used when $\frac{SM}{FC}$ is below LP [Eq. (15)].

$$\frac{recharge}{P(t)} = \left(\frac{SM(t)}{FC}\right)^{BETA} \tag{14}$$

where *recharge* represents the amount of runoff recharge, P is Rainfall and snow melt, SM represents soil water content, FC is maximum soil moisture storage, $BETA$ is a parameter that determines the contribution to runoff from rainfall and snow melt and it depends on the relationship between SM and FC.

$$E_{act} = E_{pot} \times \min\left(\frac{SM(t)}{FC \times LP}, 1\right) \tag{15}$$

E_{act} denotes actual evaporation, E_{pot} is the potential evaporation. LP denotes soil water content threshold for reduction of evaporation, ranging from 0 to 1.

Runoff recharge is added to the upper water box [SUZ (mm)]. PERC (mm d^{-1}) defines the maximum percolation rate from the upper to lower water box [SLZ (mm)]. Runoff from the water boxes is computed as the sum of the two or three linear outflow equations [K_0, K_1 and K_2 (d^{-1})] depending on whether SUZ is above a threshold value, UZL (mm), or not. This runoff is finally transformed by a triangular weighting function defined by the parameter $MAXBAS$ [Eq. (16)] to give the simulated runoff (mm d^{-1}).

$$Q_{sim}(t) = \sum_{i=1}^{MAXBAS} c(i) \times Q_{GW}(t - i + 1) \tag{16}$$

with

$$Q_{GW}(t) = K_2 \times SLZ + K_1 \times SUZ + K_0 \times \max(SUZ - UZL, 0) \tag{17}$$

$$c(i) = \int_{i-1}^{i} \left(\frac{2}{MAXBAS} - \left|u - \frac{MAXBAS}{2}\right| \times \frac{4}{MAXBAS^2}\right) du \tag{18}$$

where Q_{sim} represents simulated runoff, $MAXBAS$ is a transformation function parameter. SUZ and SLZ are storage in upper and lower zone, respectively. UZL is a threshold parameter. K_0, K_1, K_2 represents recession coefficient of upper, lower and deep zone, respectively.

The Nash–Sutcliffe coefficient (*NSCE*, Nash and Sutcliffe 1970) and Relative Bias (*BIAS*), defined by Eqs. (19), (20), are used to evaluate the model performance:

$$NSCE = 1 - \frac{\sum_{i=1}^{n}(Q_{sim}(i) - Q_{obs}(i))^2}{\sum_{i=1}^{n}(Q_{obs}(i) - \overline{Q_{obs}})^2} \tag{19}$$

$$BIAS = \frac{\sum_{i=1}^{n}(Q_{sim}(i) - Q_{obs}(i))}{\sum_{i=1}^{n}Q_{obs}(i)} \tag{20}$$

where $Q_{obs}(i)$ is the observed runoff (mm/month) at time step i, $Q_{sim}(i)$ is the simulated runoff (mm/month) at the corresponding time, $\overline{Q_{obs}}$ is the mean value of the observed values (mm/month), and n is the number of data points.

3.4 Estimating the contribution of climate change and human activities to runoff

Observed runoff during the natural period is taken as benchmark value, the difference between it and observed runoff in the post-change period was assumed to the result of both climate variability and human activities (Wang et al. 2008; Ma et al. 2009; Liu et al. 2010). In this study, the impact of climate change and human activities on runoff variation can be separated thus:

$$\Delta Q_{tot} = Q_h - Q_b. \tag{21}$$

$$\Delta Q_{tot} = \Delta Q_{human} + \Delta Q_{climate} \tag{22}$$

$$I_{human} = \frac{\Delta Q_{human}}{|\Delta Q_{tot}|} \times 100\,\% \tag{23}$$

$$I_{climate} = \frac{\Delta Q_{climate}}{|\Delta Q_{tot}|} \times 100\,\% \tag{24}$$

where ΔQ_{tot} is the total annual average change of runoff, Q_h, ΔQ_{human} and $\Delta Q_{climate}$ are defined as previously. Q_b denotes the measured annual average runoff of the pre-change period (baseline period), I_{human} and $I_{climate}$ show the percentage of runoff change due to human activities and climate variability, respectively.

ΔQ_{tot} can be easily acquired by Eq. (21), on the basis of the available observed discharge. According to Hydrologic sensitivity analysis method described in Sect. 3.2, $\Delta Q_{climate}$ can be obtained, so that ΔQ_{human} is determined by Eq. (22). Similarly, once ΔQ_{human} is determined by Hydrologic model simulation method (described in Sect. 3.3); $\Delta Q_{climate}$ can also be obtained by Eq. (22). Then the percentages of human activities and climate variability impact on runoff are simulated by Eqs. (23) and (24).

4 Results and discussion

4.1 Trend and change-point analysis of PET, precipitation and runoff series

Historical trends of hydro-meteorology factors can help to understand the effects of climate change on water resources systems. Mann–Kendall trend test method was applied to identify the change in trends of annual precipitation, PET and runoff depth in Wushan and Shetang catchments of Weihe River. The statistical results on the basis of the MK test are shown in Table 1. Combined with Fig. 2, it was found that in despite of the annual precipitation deceased in both the catchments, the statistically significant trend of rainfall cannot be identified in either watershed. However, annual runoff in two watersheds showed remarkable negative trends at the rates of 2.64 mm (Wushan catchment, confidence levels of 99 %) and 0.97 mm (Shetang catchment, confidence levels of 90 %) each year. Moreover, significant increasing trend is shown for PET at the rates of 1.72 mm (Wushan catchment) and 1.16 mm (Shetang catchment) every year at the confidence levels of 99 and 90 %, respectively.

The Pettitt's test and DCC method were applied to identify the change-point of the annual runoff series. The results of Pettitt's test are shown in Fig. 3, it was concluded that 1993 could be the detected significant change points reflecting the period after which the effect of human activities on runoff for the two catchments were significant.

Furthermore, we use the DCC method to detect the change points in runoff series. Figure 4 shows the cumulative annual precipitation and runoff over the two catchments. It shows that the relationships between cumulative annual precipitation and cumulative annual runoff can be expressed nearly with two straight lines in different slopes before and after 1993, suggesting the characteristics of precipitation or runoff changed after 1993.

Overall, the change points detected in annual runoff occurred in early 1990s (listed in Table 2). Therefore, the study period for both catchments could then be divided into the pre-change periods and post-change periods based on the change points.

Table 1 Trend analysis for annual precipitation, potential evapotranspiration and streamflow by Mann–Kendall test

	Wushan catchment		Shetang catchment	
	z test	Significant	*z* test	Significant
Annual precipitation	−0.89	N	−0.24	N
Annual PET	3.14	***	1.72	*
Annual streamflow	−3.99	***	−1.66	*

***, ** and * indicate confidence levels of 99, 95 and 90 %, respectively; N indicates confidence level under 90 %

In order to better understand the characteristics of the changes in runoff, the differences between the means of the annual runoff during the pre-change and post-change periods were analyzed using *T* test. The test-statistics at 90 % confidence level imply that the existed differences in the factors impacting on runoff for the pre-change and post-change periods. In addition, the average monthly precipitation and runoff for the two periods (Fig. 5) were compared to further understand the impacts of climate and other factors on runoff during the two periods. For both catchments, the changes in mean monthly precipitation were not obvious for the two periods. However, the dramatic reductions were present in average monthly runoff during the post-change period (1993–2007). And the greatest decline is shown in flood seasons (July, August, and September). As an example, the slightly increasing precipitation and consistent largely decreased runoff happens in July at both catchments.

Hence, to some degree, the reduction in runoff during 1993–2007 might be due to basin-related human activities.

4.2 Calibration and validation of different methods

In the hydrological sensitivity analysis method, three calibrated parameters including w, β (the runoff sensitivity coefficients to precipitation) and γ (the runoff sensitivity coefficients to PET) are shown in Table 3. The obtained w values are 1.94 (Wushan River) and 1.45 (Shetang River). For both catchments, the absolute value of β (the sensitivity coefficients of runoff to precipitation) is larger than γ (the sensitivity coefficients of runoff to PET), revealing that the change in runoff was more sensitive to precipitation than to PET.

For the hydrologic model simulation method, the HBV model was calibrated by Monte Carlo method during the period of 1975–1984 at Wushan station and 1972–1984 at Shetang station; their corresponding validation periods for both stations were 1985–1992. Table 4 shows the optimal parameter values of HBV model in Wushan and Shetang

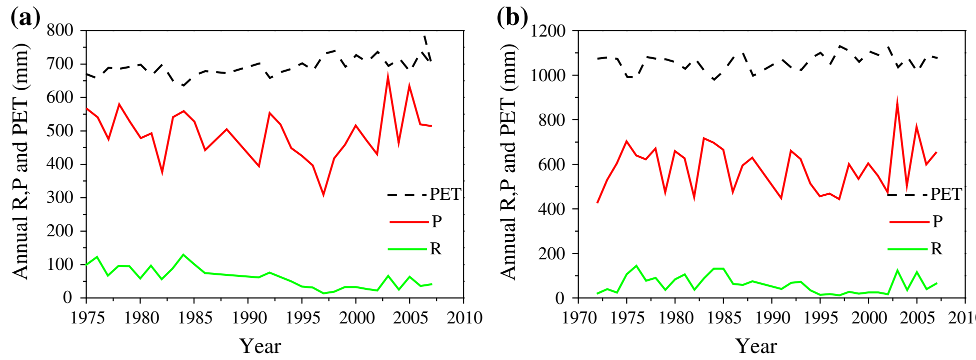

Fig. 2 Time series of precipitation (P), potential evapotranspiration (PET) and runoff series (R) in **a** Wushan catchment (during 1975–2007) and **b** Shetang catchment (during 1972–2007) of the Weihe River basin

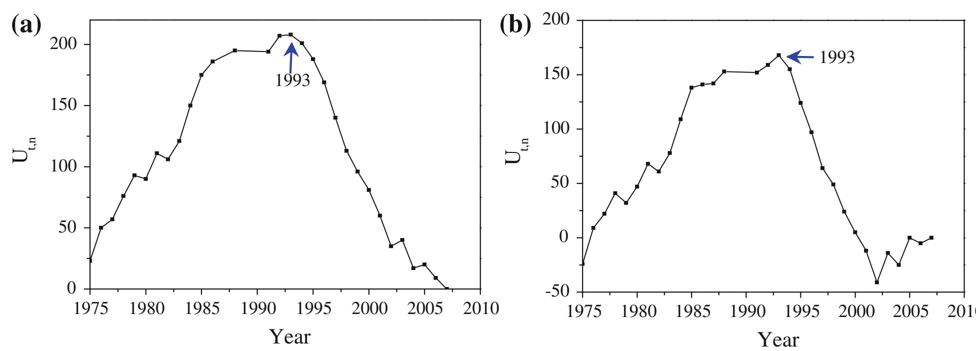

Fig. 3 Change points of runoff series detected by Pettitt's test in **a** Wushan catchment (during 1975–2007) and **b** Shetang catchment (during 1972–2007) of the Weihe River

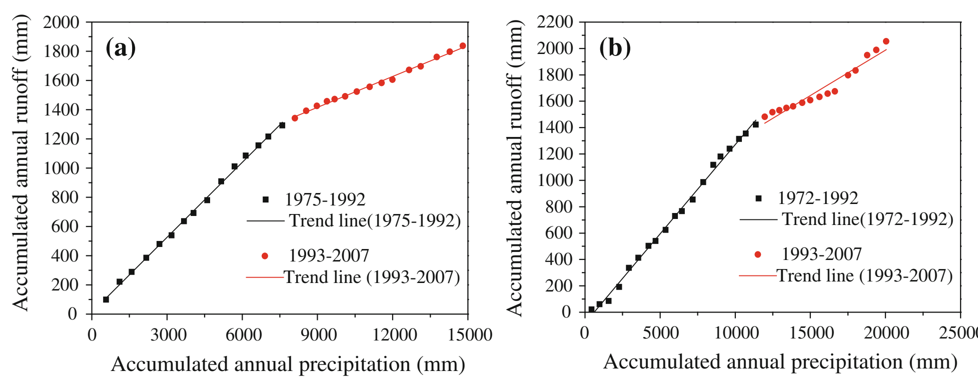

Fig. 4 Double cumulative curves of annual precipitation and runoff for **a** Wushan catchment (during 1975–2007) and **b** Shetang catchment (during 1972–2007) of the Weihe River

catchments, and performances of the HBV model during the calibration and validation periods are summarized in Table 5. During the calibration period, the *NSCE* coefficient reaches up to 0.79 (Wushan station) and 0.84 (Shetang station), and the absolute values of *BIAS* in two stations are both lower than 10 %. In comparison with the calibration period, the validation of the HBV model had lower performance, however, the overall model performances are acceptable. Meanwhile, the pre-change period shows good agreement between monthly observed and simulated runoff at both stations (Fig. 6). Afterwards, the natural runoff during the post-change period was reconstructed using the calibrated hydrologic model and the actual meteorological and hydrologic data. The reconstructed runoff series during the post-change period and the corresponding observed runoff series provide the opportunity to quantitatively estimate the effects of climate variability and human activities on runoff.

4.3 Effects of climate variability and human activities on runoff

With the simulated results of the two different estimation methods, the evaluated effects of climate variability and human activities on runoff are shown in Table 6. For both catchments, the hydrologic model simulation method and hydrologic sensitivity analysis method provided approximate estimates of the change in mean annual runoff for post-change period induced by climate variability and human activities. In a sense, the approximate results offer confidence to the methods which are applied. The runoff reduction during the post-change period (from 1993 to 2007) should be

Table 2 Summary for the annual runoff change points

Change point	Wushan catchment 1993	Shetang catchment 1993
Pre-change period		
ME (mm)	86.13	74.88
SD (mm)	22.45	37.18
Post-change period		
ME (mm)	37.16	42.99
SD (mm)	16.41	35.64
Change in mean (%)	−56.86	−42.59

ME indicates mean; SD indicates the standard deviation

mainly attributed to human activities for Wushan and Shetang catchments. Human activity should be responsible for 59 and 71 % runoff change computed by hydrological model and hydrological sensitivity analysis in Wushan catchment. For the Shetang catchment, the 66 % (detected by hydrological model) and 77 % (detected by hydrological sensitivity analysis) of reduction in runoff for post-change period are induced by human activities. Figure 7 presents the time series of Q_{human} for the post-change period, based on the two methods. Overall, the Q_{human} series computed by different methods were comparable, inferring that they are capable of simulating the effects of climate variability and human activities. Moreover, a positive effect of climate variability on runoff can be easily found when the annual precipitation is high. This phenomenon was also found in some earlier studies in another area of China [e.g. Laohahe River catchment (Jiang et al. 2011); Huaihe River basin (Wang et al. 2012)]. In order to understand the larger effect of human activities in the human-induced period, four pairs of measured runoff under approximately equal amount of evaporation are shown in Table 7. From the table one can get the conclusion that when under the same evaporation but different underlying surface conditions, a higher annual precipitation during post-change period results in the lower observed annual runoff in both catchments. Moreover, 1991 and 2001 are selected as two sample years to identify the difference in the runoff response to precipitation at Wuhan sub-basin (with the similar annual evaporation) before and after 1993 (Fig. 8a, b). It is concluded that the relationship between precipitation and runoff become weaker in post-change period (in the year 2001). In flood seasons (from June to August), the heavy precipitation just resulted in lower flow within the Wushan sub-basin. Also the similar result can be observed in Shetang River basin (Fig. 8c, d). Therefore, with Fig. 8 and Table 7, it is suggested that the runoff was dramatically affected by human activities during the post-change period.

5 Discussion

5.1 Human activities impact on runoff change

In spite of no clear trends in annual precipitation, significant decreasing trends in runoff can be found in two

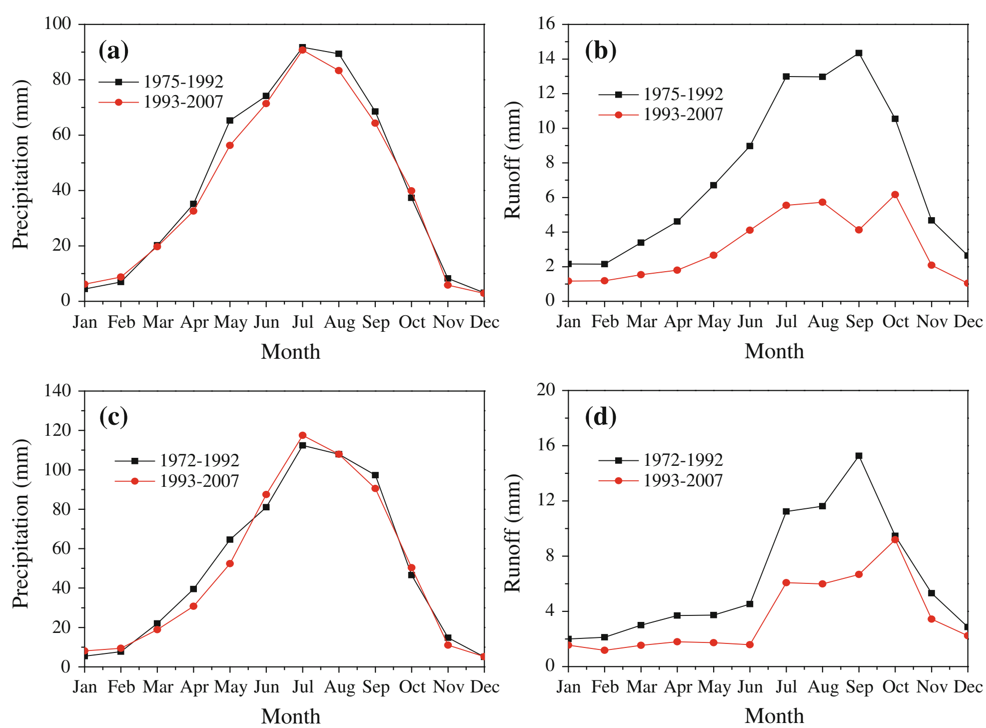

Fig. 5 Average monthly precipitation and runoff for the pre-change periods and post-change periods **a** average monthly precipitation in Wushan catchment; **b** average monthly runoff in Wushan catchment; **c** average monthly precipitation in Shetang catchment and **d** average monthly runoff in Shetang catchment

Table 3 Parameters for hydrological sensitivity analysis method

Catchment	w	β	γ
Wushan catchment	1.94	0.34	−0.18
Shetang catchment	1.45	0.22	−0.11

Table 4 The optimal parameter values of HBV model in Wushan and Shetang catchments

Parameter	Optimal value for Wushan	Optimal value for Shetang
TT (°C)	0.02	0.01
CFMAX (mm/°C)	2.08	2.50
FC (mm)	228.12	248.71
LP	0.72	0.61
BETA	1.98	1.82
PERC (mm/day)	0.53	0.75
UZL (mm)	23.31	37.80
K_0	0.80	0.72
K_1	0.05	0.18
K_2	0.0002	0.0003
MAXBAS	2.41	2.06

Table 5 Performance assessment of HBV model in calibration and validation periods

Catchment	Period	NSCE	Bias (%)
Wushan catchment	Calibration period	0.79	−3.12
	Validation period	0.77	+9.98
Shetang catchment	Calibration period	0.84	−9.67
	Validation period	0.83	+8.89

catchments of the upper reaches of the Weihe River basin. This infers, to some degree, that runoff in the considered catchments may be affected by other factors (mainly human activities) apart from the climate change. Usually, related human activities are considered as the reasons leading to the sharp decline in runoff and they include agricultural irrigation, industrial development, dam construction as well as soil and water conservation measures. The change points of runoff in the two catchments happened in the early 1990s, which corresponds to the fact that the constructions of soil and water conservation projects have been gradually increasing since 1985 (Wang et al. 2006). For example, the increase in area of terraced fields extends up to 74.70 hm^2 during 1994–2000 in Gansu province including the two catchments. Yuan and Lei (2004) addressed the effect of different soil and water conservation measures on runoff change. It is found soil and water conservation projection measures have a more direct and quick effect on the runoff decrease, in comparison with afforestation construction. In detail, project measures, including terraced fields and warping dams, could increase soil surface roughness and infiltration, hence changing the pathway of runoff and making surface runoff reduce. This point is confirmed by Qi et al. (2008). Therefore, the change in land covers due to the constructions of the water conservation projects (e.g. terraced fields, warping dams and so on) may be the main driving factors of runoff decline.

The upper reaches of the Weihe River basin is a heavily sediment and runoff–laden area. Owing to serious soil and water loss, a great number of soil and water conservation projects have been constructed. At the same time, it changes the land cover, which distinctly decreases runoff and sediment in the watershed outlet at upper reaches. The significantly decreased annual runoff in upper reaches can not only influence living, production and ecological use of water resource in lower reaches, but can also decrease the water discharge to the midstream and downstream of the Yellow River, thereby intensify the water shortage in the Yellow River Basin. Thus, proposing sustainable human activities is important for this regional water resources' sustainable development. The measures can be summarized as the reasonable layout for the soil and water conservations, as well as moderately returning farmland to forest or grassland, in term of increasing the produced runoff. For instance, on the premise of ensuring production and living

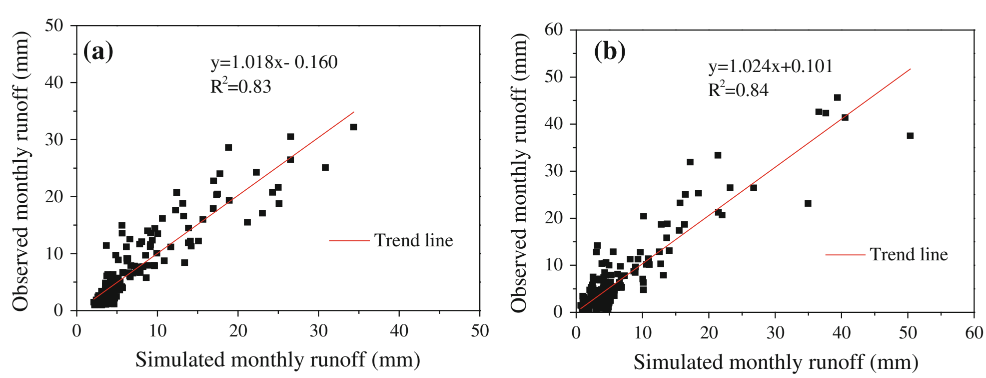

Fig. 6 Scatter diagram between observed and simulated monthly runoff (using HBV model) in **a** Wushan catchment and **b** Shengtang catchment for the pre-change period

Table 6 Impacts of climate variability and human activity on mean annual runoff for post-change period with different estimation methods

Catchment	Hydrological model simulation method		Hydrological sensitivity analysis method	
	C (%)	H (%)	C (%)	H (%)
Wushan catchment	41	59	29	71
Shetang catchment	34	66	23	77

C represents climate change; H expresses human activities

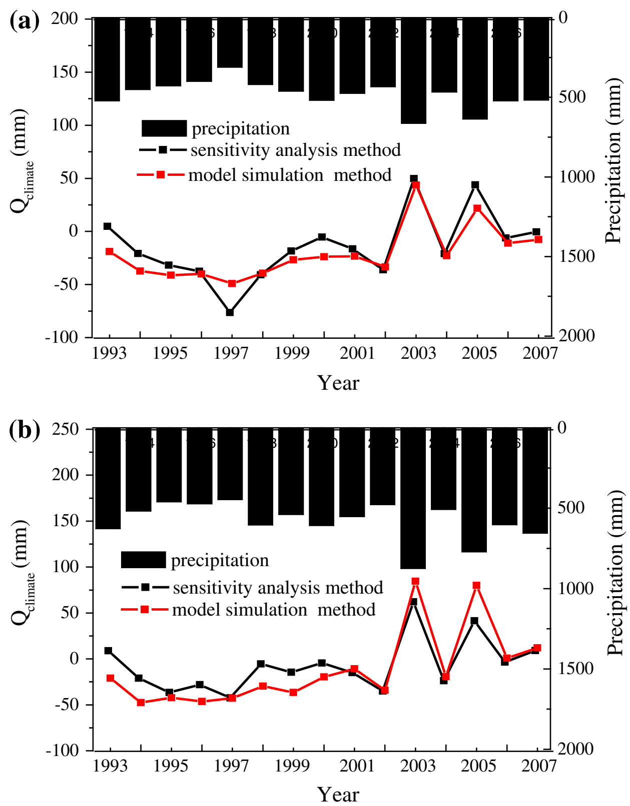

Fig. 7 Time series of $Q_{climate}$ computed by sensitivity analysis method and model simulation methods in **a** Wushan catchment and **b** Shengtang catchment during 1993–2007

Table 7 Observed runoff under the years with equal amount of evaporation

Wushan catchment				Shetang catchment			
Years	R (mm)	P (mm)	PET (mm)	Years	R (mm)	P (mm)	PET (mm)
1991	61.50	396.9	699.57	1986	63.44	479.7	1076.82
1995	34.29	428.0	700.18	1994	34.44	517.5	1072.69
2001	27.11	474.6	703.01	2004	35.97	507.8	1077.41
2007	40.74	517.7	695.52	2007	64.84	655.8	1074.94

water usage, a certain amount of warping dams situated in the former rivers and areas interflow concentrated could be pulled down or slashed. So the unnecessary evaporation and soil water infiltration can be reduced, basin's hydrological cycle accelerated, further making the produced runoff in graffs increased.

5.2 Uncertainty of methods

Usually, distributed physically based hydrological model may be preferred for hydrological effect study (Legesse et al. 2003). However, the limitations, such as its complexity in model setup as well as data set requirements involving topography, vegetation and soil hydraulic properties (Wei and Zhang 2010), lie when its application at basin scale. In this study, a simple lumped hydrological model was selected for making hydrological simulation. The simple lumped hydrological model is not expected to provide spatial information about hydrological processes, whereas our results show that it did not affect the performance of the simple water balance model in terms of quantifying the climate and anthropogenic effects on runoff.

It should be noted that some uncertainties lie in assessing effects of climate variability and human activities on runoff. First, uncertainty may arise from the limited hydro-meteorological observation data. Because no meteorological station exists in Wushan and Shetang catchment, meteorological data such as daily mean temperature, wind speed and relative humidity from a nearby meteorological station are used, which may limit the accuracy of the calculated PET and simulated runoff. Second, the hydrological sensitivity analysis denotes the response of runoff to the annual precipitation and PET, however, runoff can be influenced by changes in other influencing factors, as an example, when under the same underlying surface condition and annual precipitation, the higher the percentage of the precipitation during flood season the larger the simulated runoff (Zhang et al. 2012b). The absence of these aspects may affect the accuracy of the hydrological sensitivity analysis method (Zhao et al. 2010). Moreover, uncertainty in model parameters can also inevitably affect the simulation results (Jiang et al. 2011). More work should be conducted in future studies to quantify and reduce these uncertainties.

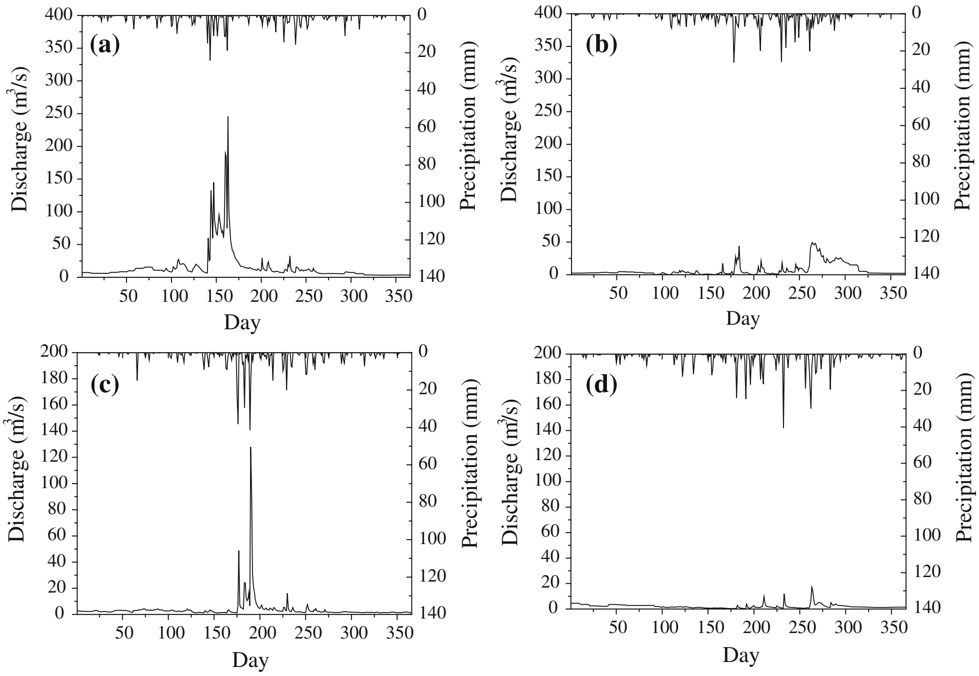

Fig. 8 Daily precipitation and observed runoff series in sample years **a** daily time series of 1991 in Wushan catchment; **b** daily time series of 2001 in Wushan catchment; **c** daily time series of 1986 in Shetang catchment and **d** daily time series of 2004 in Shetang catchment

6 Conclusion

With global or regional climate change and enhanced human activities, decrease in a large number of river streamflow especially in the arid and semi-arid areas has appeared. It is hence useful to investigate the factors that influence changes in runoff. In this study, hydrological model method and hydrological sensitivity method were applied to quantitatively estimate the impacts of climate variability and human activities on runoff in two catchments (i.e. the Wushan catchment and Shetang catchment) located in the upper reaches of the Weihe River basin. The main conclusions are shown as follows:

(1) Significant decreasing trends in runoff can be found in both catchments, especially in Wushan basin, which are dominated by significant decreasing trends at 99 % confidence level, whereas no significant trend in precipitation is found in either catchment. For both catchments, the detected change points in annual runoff series occurred in 1993, based on the Pettitt's test and DCC method. Accordingly, the annual runoff series were divided into two periods (pre-change and post-change periods). Compared with the pre-change period, reductions in mean annual runoff range from 42.6 to 56.9 % during 1993–2007.

(2) Similar estimates of the impacts of climate variability and human activities on runoff in 1993–2007 are obtained, by means of the hydrological model simulation method and hydrological sensitivity analysis method. Human activities should be mainly responsible for the runoff reduction in the Wushan catchment (accounting for 59 and 71 % by hydrological model method and hydrological sensitivity method, respectively), and Shetang catchment (accounting for 66 and 77 %, respectively).

(3) The results of the present study can supply a reference to regional water resources management and planning. Water and soil conservation is not the sole purpose and means of development, at the same time, a practically possible proposition in term of increasing the produced runoff can be put forward for local managers to reasonably arrange the local actions, synthetically considering the sustainable development in the regional water resource and ecological environment.

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