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Quantitative Estimation on Contributions of Climate Changes and Human Activities to Decreasing Runoff in Weihe River Basin, China

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Abstract: Human activities and climate changes are deemed to be two primary driving factors influencing the changes of hydrological processes, and quantitatively separating their influences on runoff changes will be of great significance to regional water resources planning and management. In this study, the impact of climate changes and human activities was initially qualitatively distinguished through a coupled water and energy budgets analysis, and then this effect was further separated by means of a quantitative estimation based on hydrological sensitivity analysis. The results show that: 1) precipitation, wind speed, potential evapotranspiration and runoff have a significantly decreasing trend, while temperature has a remarkably increasing tendency in the Weihe River Basin, China; 2) the major driving factor on runoff decrease in the 1970s and 1990s in the basin is climate changes compared with that in the baseline 1960s, while that in the 1980s and 2000s is human activities. Compared with the results based on Variable Infiltration Capacity (VIC) model, the contributions calculated in this study have certain reliability. The results are of great significance to local water resources planning and management.

Keywords: climate changes; human activities; runoff decrease; quantitative analysis; Weihe River Basin

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1 Introduction

Water resources system and hydrological cycle are greatly affected by climate changes and human activities (Vorosmarty *et al.*, 2000; Kezer and Matsuyama, 2006; IPCC, 2007). The IPCC (2007) reported that the mean temperature of global surface had increased by approximately 0.74℃ during the last 100 years. According to Huntington (2006), the changing climate was likely to impact the global hydrological cycle. Meanwhile, many researchers found that climate changes primarily characterized by global warming tended to result in high-frequency extreme weather, resulting in enormous losses (Milliman *et al.*, 2008; Jung *et al.*, 2012; Thompson, 2012). Furthermore, the intensifying human activities (e.g., irrigation, urban construction, afforestation, the construction of water conservancy project, *etc*.) also influence runoff mechanism (Li *et al.*, 2004; Yang *et al.*, 2004; Zhang *et al.*, 2011; Jiang *et al.*, 2012; Zhang *et al.*, 2012).

Under the background of the changing global climate and the increasing local anthropogenic pressures, many regions in the world have witnessed extremely frequent floods and droughts within the past decades. Estimating

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the relative contributions of human activities and climate changes to the decreasing runoff is essential for further understanding the hydrological mechanism under the context of the changing environment, and will be useful in guiding the relevant departments in relieving droughts and floods. Therefore, many researchers have attempted to investigate the effects of human activities and climate changes on runoff processes. However, the majority of them used hydrological models to study the responses of streamflow processes to climate changes and human activities under different catchment scenarios. Wang and Zhang (2006) have employed the SIMHYD model to investigate the influences of human activities and climate changes on streamflow in the Fenhe River which is in the middle of the Huanghe (Yellow) River catchment. Wang *et al*. (2010) used the Variable Infiltration Capacity (VIC) model to quantitatively estimate the effects of human activities and climate changes on runoff in a sub-catchment of the Huanghe River. Although the hydrological models mentioned above are effective tools to deal with these problems, the results of the researches have some uncertainties caused by the uncertain parameter calibration, the lack of the structure as well as the scale problem in these hydrology models.

Long-term historical records of hydrological data present temporal variations influenced by the changing climate and human activities. Analyzing the changes in the time series can not only obtain the rule of runoff change, but also helps to understand the intrinsic mechanism of hydrological processes. Hence, there are many statistical methods to analyze the trend of runoff on a regional scale (Mu *et al*., 2007; Hamed, 2008; Zhang and Lu, 2009). Nevertheless, they fail to quantitatively estimate influences of climate changes and human activities on runoff change. Based on what outlined above, a new method based on a coupled water-energy budget method was introduced in this study to quantitatively assess influences of climate changes and human activities on the decreasing runoff, which was based on the results of long-term small-catchment experiment (Rodriguez-Iturbe, 2000; Tomer and Schilling, 2009).

The Weihe River, the largest tributary of the Huanghe River in China, is located in the middle reaches of the Huanghe River. The Weihe River Basin with a total area of 135 000 km^2 is an important region for China, especially in the establishment of the Guanzhong-Tianshui Economic Zone, which will vastly promote the economic development in the whole western region in China. However, within the recent decades, the runoff in this basin has a significantly decreasing trend induced by climate changes and human activities, which has heavily restricted the economic and social development of the basin, even has impacted the strategy of the national economic development to a great extent. Therefore, it is of significant importance to distinguish effects of climate changes and human activities on the decreasing runoff in order to further ensure sustainable water resources utilization. Furthermore, since the Weihe River Basin is a typical arid and semi-arid region in China, the investigation of hydrological response to climate changes and human activities will be an effective reference for the similar areas of the world.

Influences of human activities and climate changes on the variation of runoff are highly complex, especially for the arid and semi-arid lands, which result in severe water crises, economic stagnation as well as environmental degradation. According to previous studies (Yao *et al*., 2003; Fan *et al*., 2007; Yang and Tian, 2009), the effects of human activities and climate changes vary from region to region. As far as we know, the influences of human activities and climate changes on runoff in the Weihe River Basin has not been fully investigated, and further studies are essential to provide a conclusive and scientific interpretation of the runoff change. The interpretation will play a major role in further understanding the hydrological mechanism under the background of the changing environment. Therefore, the main objectives of this study are: 1) to investigate the trends of long-term meteorological and hydrologic time series in the Weihe River Basin; 2) to quantitatively estimate the contributions of human activities and climatic changes to runoff decrease.

2 Study Area and Data

2.1 Study area

The Weihe River Basin (33°30′–37°30′N, 103°30′–110°30′E) is selected as the study area in this study (Fig. 1). Located in a continental monsoon climate zone, the basin is characterized by relatively abundant precipitation and high temperature in summer, and sparse precipitation and low temperature in winter. The annual precipitation is approximately 559 mm (Zhang *et al*.,

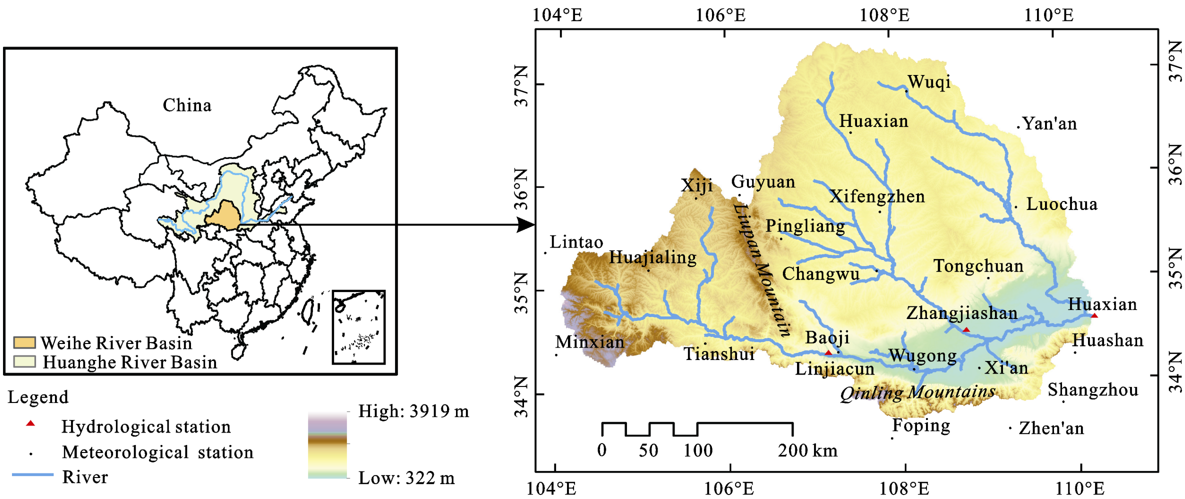

Fig. 1 Location of Weihe River Basin and hydro-meteorological stations

2008). Additionally, the precipitation varies monthly and annually, which in flood season (from June to September) generally accounts for approximately 60% of the total annual precipitation. The annual precipitation also varies greatly due to the unstable characteristics of the intensity, duration and influencing area of the subtropical high pressure belt over the northern Pacific. For instance, the annual precipitation is more than 800 mm in wet years, while it is less than 370 mm in drought years, which tends to result in highly frequent droughts and floods in the basin.

Topographically, the altitude decreases from the highest northwest mountainous areas to the lowest Guanzhong Plain which is in the southeastern and southern parts of the basin. The Guanzhong Plain has a strong effect on the economic development of the surrounding areas. Therefore, its economic development will directly affect the sustainable development of economy and society in the Weihe River Basin. However, in recent decades, the runoff of the basin has a remarkably decreasing trend due to climate changes and human activities, failing to meet the water demand for socioeconomic development and eco-environment in the basin. Furthermore, the serious water pollution makes the water resources availability dramatically reduced.

Within the past several decades, the impact of human activities has become more and more extensive in the basin. The supply of surface water and groundwater has been greatly increasing because of the increasing population and high-speed development of economy. With regards to the part of the Weihe River Basin in Shaanxi Province, the population was 2.204×10^7 in 2000, while that in 2010 was 2.462×10^7, the greatly increasing population results in consuming a large amount of water due to increasing area of farmland. Moreover, the economy of the basin has achieved a rapid development during the past 10 years, with an average economic growth speed of approximately 10.5%. Additionally, its urbanization rate was only 38.6% in 2000, whilst that was increased to approximately 50% in 2010. Furthermore, there have been approximately 300 reservoirs constructed after 1949 and the total storage capacity has been more than 2.73×10^8 m^3. As a result of the construction of reservoirs, the annual distribution of runoff in this basin may change.

2.2 Data sources

Daily precipitation, wind speed, air temperature, sunshine duration, vapour pressure and relative humidity data collected from 21 meteorological stations in the Weihe River Basin and its adjacent area were employed in this study (Fig. 1). Meteorological data from January 1st, 1960 to December 31st, 2005 for each station were acquired from the National Climate Center (NCC) of the China Meteorological Administration (CMA). Potential evapotranspiration (PET) of the meteorological stations were calculated by using the Penman-Monteith equation (Allen *et al.*, 1998).

The quality of data was strictly controlled during their releases. Amongst the 21 stations, two of them have some missing values, however, the total lost data are less than 0.01%, and the missing data were reconstructed by calculating the average value of their neighboring stations. The reconstructed approach had little effect on their long-term temporal trend. Additionally, the double-mass curve method was used to check the data consistency, and the results indicated that all the daily meteorological data used in this study were consistent.

Daily runoff data from the hydrological stations of Linjiacun, Zhangjiashan and Huaxian in the middle and lower reaches of the Weihe River Basin were employed in this study. Runoff data from January 1st, 1960 to December 31st, 2005 for each station were obtained from the hydrologic manual. The Linjiacun station is located in the middle reaches of the basin, its catchment area is approximately 3.3×10^4 km^2. The Zhangjiashan station is in the lower reaches of the Jinghe River, the largest tributary of the Weihe River, whose catchment area is approximately 4.2×10^4 km^2. The Huaxian station is in the lower reaches of the basin, its catchment area accounts for approximately 97.16% of the whole basin. Therefore, the runoff at Huaxian station can stand for the runoff of the whole basin.

The monthly and annual data were calculated by the daily data from the meteorological and hydrological stations. In view of the uneven distribution and the dramatic change in the topography of the meteorological stations in the basin, the mean potential evapotranspiration and precipitation of the whole basin as well as the sub-catchments were computed by an area-based weighting approach. The weight coefficient of each meteorological station was calculated by the Thiessen Polygon approach.

3 Methodology

3.1 Modified Mann-Kendall (MMK) trend test method

The modified Mann-Kendall (MMK) trend test method (Mann, 1945; Kendall, 1955; Hamed and Rao, 1998) was employed to capture the trend of the meteorological variables and runoff in the Weihe River Basin. The initial Mann-Kendall (MK) trend test method recommended by the World Meteorological Organization is a nonparametric approach, however, the results of the MK test are affected by the persistence of the hydro-meteorological series. Therefore, Hamed and Rao (1998) made an improvement on the MK test by taking into account the lag-*i* autocorrelation to overcome the persistence of the hydro-meteorological series, and Hamed and Rao (1998) and Daufresne *et al*. (2009) concluded that the MMK test was robust. Considering the completeness of this study, the MMK test (Daufresne *et al*., 2009) therefore was used.

The Mann-Kendall (MK) test method used in this study refers to Gerstengarbe and Werner (1999). The test statistics is as follows:

$$d_k = \sum_{i=1}^{k} r_i \ (2 \le k \le n) \tag{1}$$

$$r_i = \begin{cases} +1, & if \ x_i > x_j \\ 0, & otherwise \end{cases} \ (i, \ j = 1, 2, ...) \tag{2}$$

where x_i and x_j denote tow variables of time *i* and *j* from a time series, respectively; r_i and d_k stand for a statistic of time *i* and *k*, respectively.

On the null hypothesis of no trend, the statistics d_k is distributed as a normal distribution with the expected value of $E(d_k)$ and the variance $Var(d_k)$ as follows:

$$E(d_k) = \frac{k(k-1)}{4} \tag{3}$$

$$Var(d_k) = \frac{k(k-1)(2k+5)}{72} \ (2 \le k \le n) \tag{4}$$

On the above assumption, the statistic index Z_k is calculated as follows:

$$Z_k = \frac{d_k - E[d_k]}{\sqrt{Var[d_k]}} \ (k = 1, 2, 3, ..., n) \tag{5}$$

where Z_k denotes the standard normal distribution (UF). In a two-side test for trend, the null hypothesis is rejected under the significance level of α if $|Z| > Z_{(1-\alpha/2)}$, where $Z_{(1-\alpha/2)}$ denotes the critical value of the standard normal distribution with a probability exceeding $\alpha/2$. A positive Z value represents a positive trend and vice versa. In this study, $\alpha = 5\%$. Then, Z_k will be calculated based on the adverse course, meaning that the original time series will be x_n, x_{n-1}, …, x_1. Following the same procedure shown in equations (1)–(5), another Z_k(UB) is obtained. The two line, UF and UB (k = 1, 2, 3, …, n) may make an intersection point during a certain time interval. If the point is significant at the 95% significance level, the critical point occurs in the analyzed time series at the same time.

For a time series of n observations ($X = x_1, x_2, \ldots, x_n$), the MK trend statistic (S) is computed as follows:

$$S = \sum_{i<j} \mathrm{sgn}(x_j - x_i) \tag{6}$$

where

$$\mathrm{sgn}(x_j - x_i) = \begin{cases} 1 & x_j > x_i \\ 0 & x_j = x_i \\ -1 & x_j < x_i \end{cases} \tag{7}$$

The variance of S ($Var(S)$) is proposed by Kendall (1955):

$$Var(S) = \frac{n(n-1)(2n+5)}{18} \tag{8}$$

Then, the standardized test statistic $Z = \frac{S}{\sqrt{Var(S)}}$ with the standard normal variable under the desired significance level is calculated to test the significance of the time series trend. The results from Hamed and Rao (1998) indicated that the significant temporal autocorrelations of a time series disturbs the evaluation of the variance of S. In order to removing the influence of persistence, Hamed and Rao (1998) suggested extracting a nonparametric trend estimator from the original time series to estimate the autocorrelation coefficients of the new time series ranked by size. Autocorrelation coefficients ($\rho_s(i)$ at lag(i)) which are significantly different from zero at the 5% significance level are then employed to estimate the modified variance of S ($V^*(S)$) as follows:

$$V^*(S) = Var(S)Cor \tag{9}$$

where Cor denotes a correction due to the autocorrelation of the time series, which is calculated as follows:

$$Cor = 1 + \frac{2}{n(n-1)(n-2)} \sum_{i=1}^{n-1} (n-1)(n-i-1)(n-i-2)\rho_S(i) \tag{10}$$

3.2 Contribution of climate changes and human activities to runoff based on a coupled energy and water budget

For a natural watershed, the annual water balance is expressed as follows (Shen and Huang, 2008):

$$P - Q - ET = \Delta W \tag{11}$$

where P is precipitation, Q is runoff, ET is actual evapotranspiration, and ΔW is the variation of the water storage. For a long time (≥ 10 years), ΔW can be regarded as zero, thus ET can be calculated as the difference between P and Q. According to the water balance equation, ET is mainly influenced by available energy (evaporative demand-potential evapotranspiration (PET)), available water (P) of a watershed and human activities (e.g., farmland irrigation, land cover change, *etc*.). Based on ET, P and PET values of a watershed, the analysis of a coupled energy and water budget is used to estimate the efficiency of energy and water use in an ecosystem (Milne *et al*., 2002; Tomer and Schilling, 2009). Where, the unused energy ($PET - ET$) and unused water ($P - ET$) in the system denote the proportions of the available energy and water, E_{ex} and P_{ex}, which are unused (in excess) energy and water and can be expressed as follows:

$$\begin{aligned} E_{ex} &= (PET - ET)/PET \\ P_{ex} &= (P - ET)/P \end{aligned} \tag{12}$$

where both the values of E_{ex} and P_{ex} vary between 0 and 1. Tomer and Schilling (2009) built a conceptual model to estimate the effects of climate changes and human activities on catchment hydrology based on the E_{ex} and P_{ex} (Fig. 2).

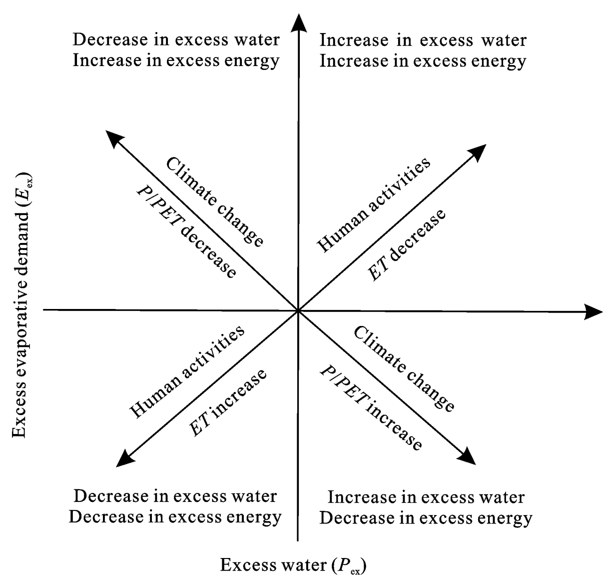

Fig. 2 Conceptual model of hydrological changes corresponding to climate changes and human activities (Tomer and Schilling, 2009). P, PET and ET denote precipitation, potential evaporation and actual evapotranspiration, respectively

According to Fig. 2, climate changes affect *PET* and *P*, leading to the decease of excess energy (E_{ex}) and the increase of excess water (P_{ex}), or vice versa, while the variations of human activities will directly influence *ET* rather than *PET* and *P*, which results in the change in excess energy and water, thereby determining the change in *ET*.

Figure 2 provides an effective method for empirically identifying the effects of climate changes and human activities on runoff for any two different periods. It is worth noting that the proposed conceptual model is under the assumptions that human activities and climate changes are independent of each other, and the variation of human activities only influences *ET*. In fact, human activities are closely related to climate changes, and the correlation between them is complicated and extensive. According to Tomer and Schilling (2009) and Zhang and Lu (2009), the influence of climate changes on runoff coincides with land use change in a large region. The construction of big reservoirs or other water conservancy projects will influence local precipitation and temperature, thereby leading to the variation of hydrological mechanism (Li *et al*., 2002; Wu *et al*., 2006). Although climate system is associated with human activities, it is not considered in the quantitative estimation studies (Fan *et al*., 2010; Wang *et al*., 2012).

In the Weihe River Basin, human activities include the construction of water conservancy projects, land cover change, the change in water utilization structure, the increasing population, rapid economy development, *etc*. Since the human activities such as river regulation, land cover change and farmland irrigation may exist at the same time in a given basin, the assumption is extended that all the anthropogenic stresses in the basin only influence *ET*. Thus, climate changes and human activities are likely to lead to a change in excess energy and water. As shown in Fig. 2, the directions of the hydrological changes can generally indicate the effects of human activities and climate changes on runoff in a region. This empirical method was used to provide an auxiliary analysis of the influences of human activities and climate changes, and then the preliminary result was checked by a quantitative estimation. According to Zhang *et al*. (2001), the relationship of the long-term average annual *ET*, *PET* and *P* can be expressed as follows:

$$\frac{ET}{P} = \frac{1 + w(PET/P)}{1 + w(PET/P) + (PET/P)^{-1}} \tag{13}$$

where *w* is a model parameter of water available coefficient associated with the vegetation type (Zhang *et al*., 2001), which can be calibrated by annual hydro-meteorological data.

Hydrologic sensitivity can be depicted as the proportion of the change in average annual runoff affected by the changes in average annual *P* and *PET*. The changes of *P* and *PET* will result in the variations of water balance. According to Koster and Suarez (1999) and Milly and Dunne (2002), the change of average annual runoff induced by climate changes can be calculated as follows:

$$\Delta Q_{\mathrm{clim}} = \alpha \times \Delta P + \beta \times \Delta PET \tag{14}$$

where ΔQ_{clim}, ΔP and ΔPET are the variations of runoff, *P* and *PET*, respectively; α and β are the sensitivity parameters, which can be calculated as follows:

$$\alpha = \frac{1 + 2x + 3wx}{(1 + x + wx^2)^2} \qquad \beta = \frac{1 + 2wx}{(1 + x + wx^2)^2} \tag{15}$$

where *x* is the drought index described as *PET*/*P*, and *w* is the same parameter in Equation (8).

The change of average annual runoff can be expressed as:

$$\Delta Q_{\mathrm{obs}} = \hat{Q}_{\mathrm{obs2}} - \hat{Q}_{\mathrm{obs1}} \tag{16}$$

where $\hat{Q}_{\mathrm{obs1}}$ is the average annual runoff of the reference period, and $\hat{Q}_{\mathrm{obs2}}$ is the average annual runoff of the comparative period.

As runoff is primarily impacted by human activities and climate changes, the variation of average annual runoff can be calculated as follows:

$$\Delta Q_{\mathrm{hum}} = \Delta Q_{\mathrm{obs}} - \Delta Q_{\mathrm{clim}} \tag{17}$$

where ΔQ_{clim} and ΔQ_{hum} are the variations of the average annual runoff caused by climate changes and human activities, respectively. The contributions of human activities and climate changes to runoff change can be calculated as:

$$\eta_{\mathrm{clim}} = \frac{\Delta Q_{\mathrm{clim}}}{|\Delta Q_{\mathrm{obs}}|} \times 100\% \qquad \eta_{\mathrm{hum}} = \frac{\Delta Q_{\mathrm{hum}}}{|\Delta Q_{\mathrm{obs}}|} \times 100\% \tag{18}$$

where η_{hum} and η_{clim} are the percentages of the impacts of human activities and climate changes on runoff change, respectively.

4 Results and Discussion

4.1 Variation of regional climate

In order to analyze the changes of the regional climate in the Weihe River Basin, the trends of seven annual meteorological series including temperature, vapor pressure, sunshine duration, precipitation, wind speed, relative humidity and PET during 1960–2005 were investigated by the MMK trend test method. The results are shown in Table 1.

It can be found from Table 1 that the PET, temperature and vapor pressure have an increasing trend, while precipitation, wind speed, relative humidity and sunshine duration have a decreasing trend on the annual scale. Moreover, the trend of vapor pressure is significant at the 0.05 significance level, and those of wind speed and temperature are significant at the 0.01 significance level. Amongst the seven variables, precipitation has the highest variation coefficient of 19.0%, indicating that precipitation has the highest variability, directly affecting the annual distribution of runoff. The temperature in this basin has the highest MMK value of 5.00, indicating that temperature has the most remarkably increasing tendency.

On the seasonal scale, precipitation has a positive trend in summer and winter and a negative trend in spring and autumn, which has a significantly negative trend in autumn. Although PET has an increasing trend in spring and autumn and a decreasing trend in summer and winter, no significant trends are found in four seasons. Temperature has a statistically significantly increasing trend in spring, summer and winter at 0.99 significance level, while it has a non-significantly increasing trend in autumn. Regarding vapor pressure, it increases significantly in spring and summer, while it has a non-significantly decreasing trend in autumn. Both relative humidity and sunshine duration have a non-significantly positive trend in spring and a negative trend in winter. For relative humidity, it has a statistically significantly decreasing trend in autumn at 0.95 significance level, however, regarding sunshine duration, it has a statistically significantly decreasing trend in summer at 0.95 significance level.

4.2 Changes in annual and monthly runoff

The results of the MMK test method of the annual runoff at hydrological stations of Linjiacun, Zhangjiashan and Huaxian are shown in Fig. 3. It can be found in Fig. 3a that the UF curves of Linjiacun, Zhangjiashan and Huaxian stations after 1970 are below zero and have remarkably downward trends for almost the whole period. There are no obvious break points at the two stations. Generally, the annual runoff in the Weihe River Basin has a long-term decreasing trend in almost the whole period.

Differently, it can be seen from Fig. 3b that the monthly runoff at Linjiacun and Huaxian stations has a decreasing trend, and most of the trends are significant at the 0.95 significance level. There is a difference between the two stations in June, July and August, the monthly runoff at the Linjiacun station has a significantly decreasing trend which is significant at the 0.01 significance level, while that at the Huaxian station has a negative trend which is not significant at the 0.01 sig nificance level. Amongst the three stations, only the Zhangjiashan station has an increasing tread in January,

Table 1 Results of seven variables by modified Mann-Kendall (MMK) test method during 1960–2005

Variable	Annual average	C_V (%)	MMK value				
			Spring	Summer	Autumn	Winter	Annual
P (mm)	548.17	19.0	–0.89	0.34	–2.50*	1.42	–1.53
PET (mm/yr)	842.90	5.7	0.81	–1.16	1.48	–0.55	0.13
W (m/s)	2.10	7.0	–3.88**	–2.94*	–3.23**	–5.10	–4.09**
T (℃)	9.38	6.0	5.40**	4.38**	1.00	3.75**	5.00**
VP (hPa)	9.17	2.8	2.57*	3.61**	–1.59	1.04	2.73*
RH (%)	65.50	3.3	0.99	0.76	–2.42*	–0.34	–1.89
SD (h)	2243.54	6.2	0.17	–2.52*	0.42	–1.65	–1.08

Notes: C_V, coefficient of variation; P, precipitation; PET, potential evapotranspiration; W, wind speed; T, temperature; VP, vapour pressure; RH, relative humidity; SD, sunshine duration. * denotes significant at 0.05 significance level; ** denotes significant at 0.01 significance level

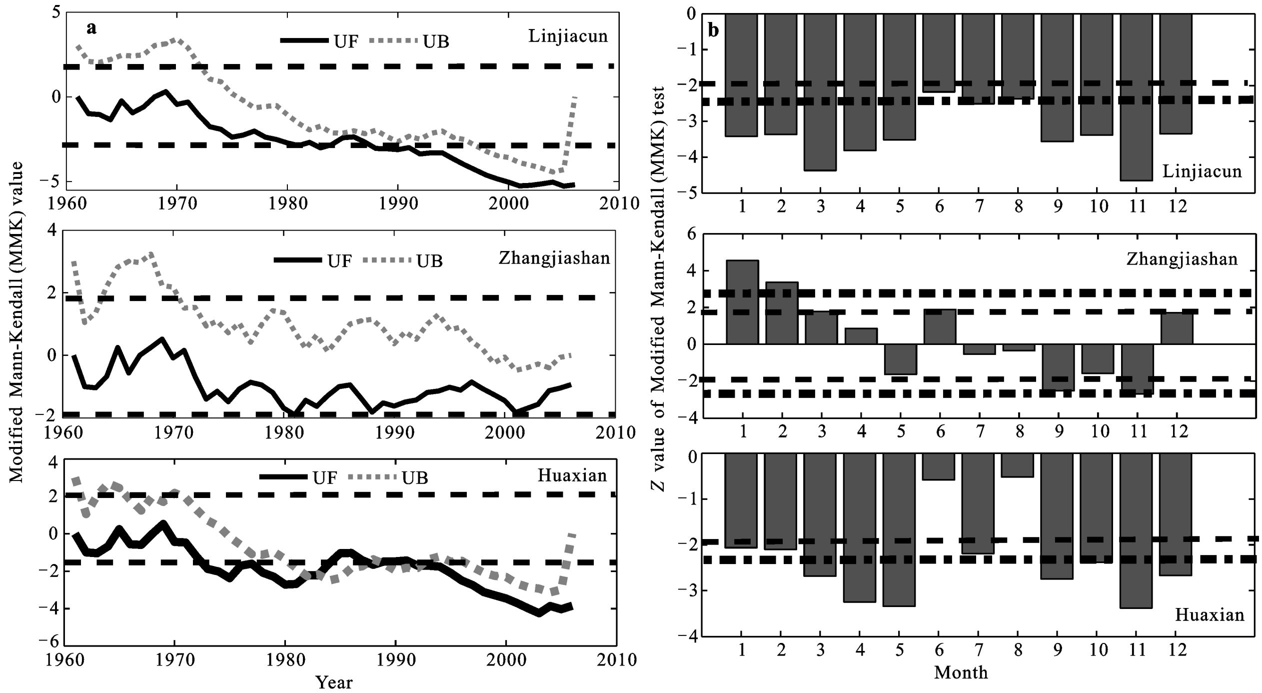

Fig. 3 Trend analysis for annual (a) and monthly (b) runoff from 1960 to 2005

February, March, April, June and December, while that in the other months has a decreasing trend. Additionally, the runoff in January and February at this station has a remarkably increasing tendency which is significant at the 0.01 significance level, whereas that in September and November has a significance decreasing trend which is significant at the 0.01 significance level.

4.3 Hydrological response to climate change and human activity

The changes of runoff reflect the combined impacts of human activities and climate changes, which provides a large amount of useful information for local water resources management and watershed planning. In this study, the impacts of human activities and climate changes on runoff in two sub-basins and the whole basin were investigated.

The variations of runoff, precipitation, PET and ET in the two sub-basins and the whole basin compared with the baseline period (1960s) were analyzed (Fig. 4). Compared with the runoff and precipitation in the 1960s, those drastically decreased in the other decades, especially in the 1990s, and the decrease in the two sub-basins and the whole basin ranged between 62.6–99.9 mm and 10.0–70.7 mm, respectively. The results indicate that the variation of the runoff is consistent with that of precipitation in the three basins. Compared with the PET in the 1960s, it increased in the basin above Linjiacun which ranged between 13.7–45.7 mm except in the 1980s when it was declined, while that in the whole basin ranged between –50.0 and 24.6 mm. Moreover, the calculated ET of the basin above Zhangjiashan obviously decreased, while that of the whole basin significantly increased except in the 1990s when it was decreased.

The excess energy (E_{ex}) and excess water (P_{ex}) of the two sub-basins and the whole basin were calculated under different decades according to the water-energy budget analysis. The human activities and local climate conditions in the 1960s are taken as the baseline, the changes in E_{ex} and P_{ex} compared with the 1960s are illustrated in Fig. 5. In the two sub-basins and the whole basin, a decreasing trend of P_{ex} and increasing trend of E_{ex} are found in the other decades except in the 1980s, indicating that the variations of the runoff in the 1970s, 1990s and 2000s are primarily influenced by climate changes compared with the baseline period 1960s, while human activities play a subordinate role. However, the P_{ex} and E_{ex} in the 1980s in the two sub-basins have a decreasing tendency, indicating that the main driving factor for the changes of runoff in the two sub-basins is human activities rather than climate changes in this period.

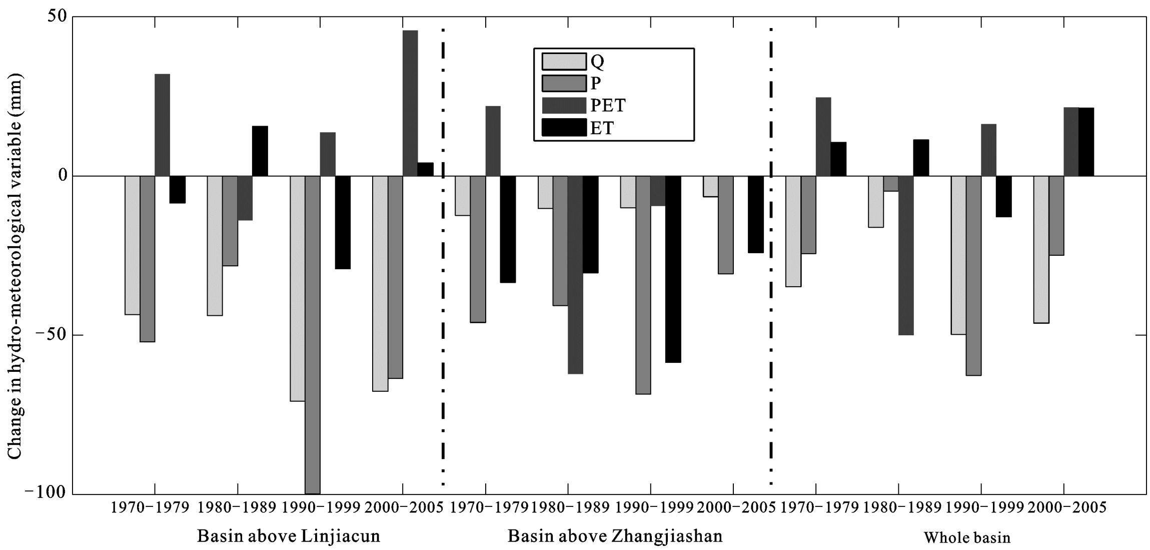

Fig. 4 Changes of runoff (Q), precipitation (P), potential evapotranspiration (PET) and evapotranspiration (ET) compared with baseline period

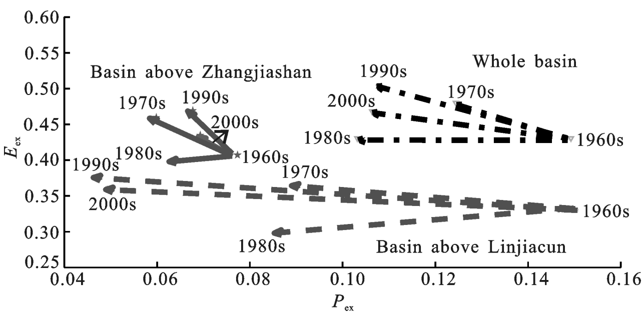

Fig. 5 Changes of excess energy (E_{ex}) and excess water (P_{ex}) compared with those in 1960s

4.4 Contribution of human activity and climate change to runoff

The hydrologic sensitivity analysis approach was employed to estimate the impacts of climate changes on runoff. In this approach, w is an important model parameter denoting available water coefficient that is closely associated with the local vegetation type (Zhang *et al.*, 2001). According to Equation (13), the optimized w values of the basin above Linjiacun, the basin above Zhangjiashan and the whole basin are 0.57, 0.45 and 0.48, respectively.

Based on the optimized w, the sensitivity coefficient α and β can be calculated. After completing the hydrological sensitivity analysis, all of the calculated parameters are then applied to estimate the influences of human activities and climate changes on the runoff change (Table 2). Compared with the baseline period 1960s, the ΔQ of the other decades in the three basins are negative, implying that the mutual influence of climate changes and human activities leads to the runoff decrease. Take the whole basin for example, climate changes including the variation of precipitation and PET are the major driving factors on the runoff decrease in the 1970s, 1990s and 2000s, whose contributions are 54.25%, 60.35% and 57.39%, respectively, while human activities play a subordinate role in these periods, whose contributions to the runoff decrease are 45.75%, 39.65% and 42.61%, respectively. The result is generally consistent with that from Bi *et al.*, (2013), who found that the primary driving factor for the runoff decrease in the Weihe River Basin is precipitation change. In addition, Wei *et al.* (2008) analyzed the runoff trend and influence factors in the Weihe River Basin, regarding 1956–1969 as the baseline, and found that the contributions of climate changes and human activities to runoff decrease during 1970–2000 were 51.7% and 48.3%, respectively, which are similar to our findings. The contribution of human activities is 52.91% in the 1980s, so the primary driving factor for the runoff change in this period is human activities rather than climate changes. The land reform of China in the early 1980s may account for this phenomenon, which greatly promoted the enthusiasm for production of Chinese farmers, which resulted in a rapid increase of agricultural water.

As regards the basin above Linjiacun, climate changes are the primary driving factor on the runoff decrease in 1970s, 1980s, 1990s and 2000s compared with that in the 1960s, and the contributions are 59.66%,

Table 2 Contribution of human activity and climate change to runoff change compared with 1960s

Region	Period	Q	ΔQ	Contribution of climate change		Contribution of human activity	
				ΔQ_{clim}	$\Delta \eta_{clim}$	ΔQ_{hum}	$\Delta \eta_{hum}$
Basin above Linjiacun	1960–1969	95.86	–	–	–	–	–
	1970–1979	52.28	–43.58	–26.00	59.66	–17.58	40.34
	1980–1989	51.95	–43.91	–28.56	65.04	–15.35	34.96
	1990–1999	25.17	–70.69	–47.61	67.35	–23.08	32.65
	2000–2005	28.24	–67.62	–37.25	55.09	–30.37	44.91
Basin above Zhangjiashan	1960–1969	42.96	–	–	–	–	–
	1970–1979	30.48	–12.48	–8.32	66.67	–4.16	33.33
	1980–1989	32.72	–10.24	–5.91	57.71	–4.33	42.29
	1990–1999	32.96	–10.00	–6.06	60.60	–3.94	39.40
	2000–2005	36.37	–6.59	–3.25	49.32	–3.34	50.68
Whole basin	1960–1969	91.30	–	–	–	–	–
	1970–1979	56.46	–34.84	–18.90	54.25	–15.94	45.75
	1980–1989	75.14	–16.16	–7.61	47.09	–8.55	52.91
	1990–1999	41.57	–49.73	–30.01	60.35	–19.72	39.65
	2000–2005	45.11	–46.19	–26.51	57.39	–19.68	42.61

Notes: Q and ΔQ denote runoff and the change of runoff, respectively; ΔQ_{clim} and ΔQ_{hum} stand for the variation of runoff induced by climate change and human activities, respectively; $\Delta \eta_{clim}$ and $\Delta \eta_{hum}$ represent the contribution of climate change and human activities to the runoff change, respectively

65.04%, 67.35% and 55.09%, respectively, while human activities play a subordinate role in these periods, whose contributions to the runoff decrease are 40.34%, 34.96%, 32.65% and 44.91%, respectively.

Similarly, in the basin above Zhangjiashan, climate changes are also the main driving factor on the runoff decrease in 1970s, 1980s and 1990s compared with that in the 1960s, whose contributions are 66.67%, 57.71% and 60.60%, respectively, while human activities play a subordinate role in these periods. The reasons are that the population and economy in the two sub-basins is in low-density, thus, the influence of human activities on the runoff change is relatively small. The results are consistent with the findings of the combined water-energy budgets analysis in Section 4.3.

It is a common knowledge that climate changes impact runoff mainly by means of the variation of precipitation and PET. Since the calculated PET denotes the integrated influences of meteorological variables, a further analysis is made to estimate the contribution of meteorological variables to the decreasing trend of PET in the Weihe River Basin (Fig. 6). The major driving factors on the decreasing trend of PET are wind speed and sunshine duration, which have a great effect on PET, thus affecting runoff in a catchment. The analysis results are similar to those from Xu *et al*. (2006) and Ye *et al*. (2013), who pointed out that the main driving factors on the downward tendency of PET in the Changjiang (Yangtze) River and the Poyang Lake catchments were wind speed and net radiation, respectively.

The values of measured and simulated runoff based on the VIC model are shown in Fig. 7. The Nash-Sutcliffe efficiency coefficients of the 1960s, 1970s, 1980s, 1990s and 2000s are 0.89, 0.92, 0.91, 0.88, 0.86, respectively, implying that the VIC model has a good performance of simulating hydrological processes. The contributions of climate changes and human activities in the 1970s, 1980s, 1990s, and 2000s compared with that in the 1960s are 65.32%, 48.92%, 55.64%, 51.82% and 34.64%, 51.08%, 44.36%, 48.18%, respectively, whereas those of simulated by the VIC model are

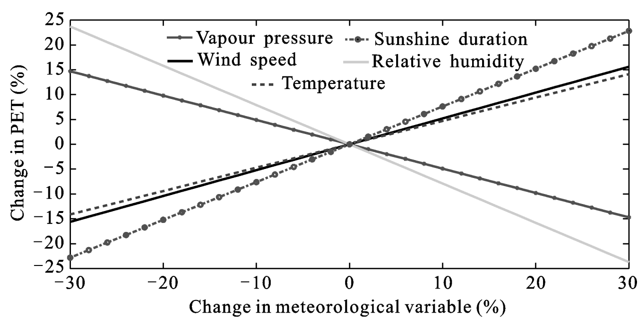

Fig. 6 Sensitivity analysis of five major meteorological variables to potential evapotranspiration (PET)

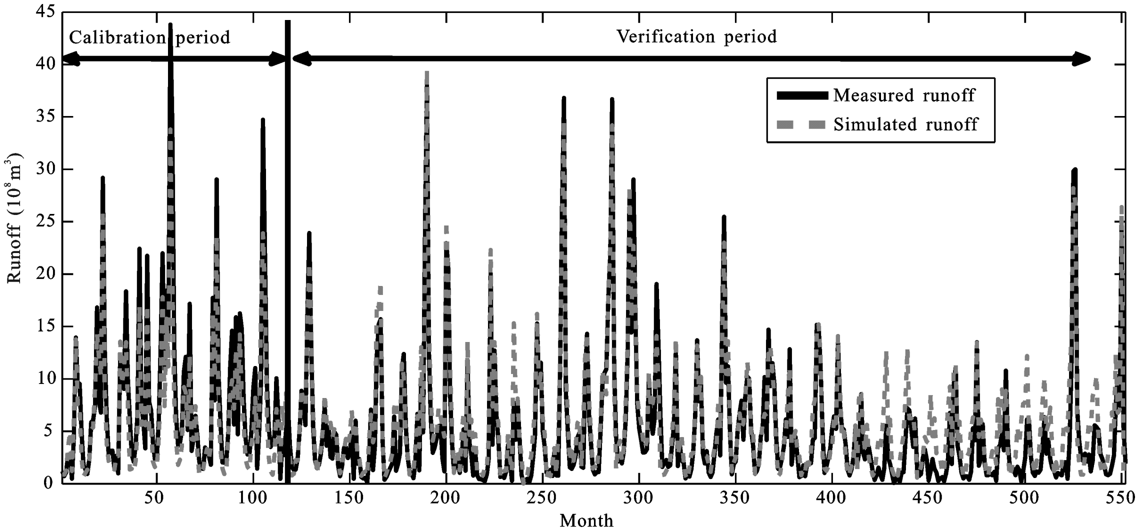

Fig. 7 Measured and simulated runoff based on Variable Infiltration Capacity (VIC) model

54.25%, 47.09%, 60.35%, 57.39% and 45.75%, 52.91%, 39.65%, 42.61%, respectively. It shows that the contributions calculated by the two models are similar except the 1970s, and the contribution of climate changes and human activities are consistent. Therefore, in terms of the relative amount, the results calculated by the two models are extremely consistent. Note that all of the contributions of climate changes and human activities to runoff change in each decade are relatively high, thus, the runoff change in the Weihe River Basin was affected by the joint influence of climate changes and human activities. Because of the different mechanism and data type of the two models, the detailed results calculated by the two models have a little difference. However, we believe that the difference is reasonable through the comparative analysis. In general, the results based on the VIC model are similar to those of this study to a great extent, and the contributions calculated in this study therefore are reliable.

4.5 Uncertainty analysis

The performance of the hydrological sensitivity analysis is determined by the runoff data of the long-term baseline period which is based on the assumption that the runoff in this period is not affected by human activities. In fact, it is extremely difficult to obtain the long-term observation data without any influences by human activities, even for the baseline period of 1960s, which was also disturbed by human activities including land use changes, farm irrigation as well as the construction of water conservancy projects. Furthermore, whether the calibrated available water coefficient (w) is optimized or not will directly influence the calculation results.

5 Conclusions

Under the background of changing environment, the climate changes and human activities are regarded as two major driving factors on the runoff decrease in the Weihe River Basin. An investigation was made to estimate the influences of human activities and climate changes on runoff change in the basin during the past several decades in this study. The modified Mann-Kendall trend test method was employed to detect the trend of meteorological variables and runoff in the basin. Furthermore, the impact of climate changes and human activities was initially qualitatively distinguished through a coupled water and energy budgets analysis, and then the effect was further separated by means of a quantitative estimation based on hydrological sensitivity analysis. The conclusions obtained in this study are as follows:

(1) Generally, the hydro-meteorological variables in the Weihe River Basin changed with different extents. Precipitation, wind speed, potential evapotranspiration and runoff have a significantly decreasing trend, while temperature has a remarkably increasing tendency in the Weihe River Basin on the annual scale. On the seasonal scale, precipitation has a positive trend in summer and winter and a negative trend in spring and autumn, while PET has a non-significantly increasing trend in spring and autumn and a non-significantly decreasing trend in

summer and winter. Both temperature and vapor pressure increase significantly in spring and summer, but they have no-significant trends in other seasons except that temperature in winter significantly increases at the 0.01 significance level. For relative humidity, it has a statistically decreasing trend in autumn at the 0.95 significance level. Similarly, sunshine duration have a statistically decreasing trend in summer at the 0.95 significance level.

(2) On the whole, the annual runoff in the Weihe River Basin has a dramatically decreasing trend. The Linjiacun and Huaxian stations have a remarkably downward tendency which is significant at the 0.99 significance level. The runoff in 12 months at Linjiacun and Huaxian stations has a decreasing trend, and most of the trends are significant at the 0.95 significance level. Amongst the three stations, only the runoff at Zhangjiashan station in January, February, March, April, June and December has an increasing tread.

(3) With regard to the whole basin, climate changes are the major driving factor on the runoff decrease in the 1970s, 1990s and 2000s compared with that in the 1960s, whose contributions are 54.25%, 60.35% and 57.39%, respectively, and human activities play a subordinate role in these periods, whose contributions to the runoff decrease are 45.75%, 39.65% and 42.61%, respectively. Nevertheless, human activities are the main driving factor on the runoff decrease in the 1980s due to its high contribution of 52.91%. Regarding the basin above Linjiacun, climate changes are the primary driving factor on the runoff decrease in the 1970s, 1980s, 1990s and 2000s compared with that in the 1960s, whose contributions are 59.66%, 65.04%, 67.35% and 55.09%, respectively, while human activities play a subordinate role in these periods, whose contributions to the runoff decrease are 40.34%, 34.96%, 32.65% and 44.91%, respectively. Similarly, in the basin above Zhangjiashan, climate changes are also the main driving factor on the decreased runoff in the 1970s, 1980s and 1990s compared with that in the 1960s, whose contributions are 66.67%, 57.71% and 60.60%, respectively, while human activities play a subordinate role in these periods.

In this study, we assume that human activities have no effect on climate change. However, in practice, human activities have an interactive influence with climate, and this interactive effect is very complex. Therefore, we should try to separate the impact of human activities on climate in further study, in order to separate the contribution of climate changes and human activities to the runoff change more accurately.

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