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Quantitative contribution of climate change and human activities to runoff changes in the Wei River basin, China

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Abstract

Surface runoff from the Wei River basin, the largest tributary of the Yellow River in China, has dramatically decreased over last 51 yr from 1958 to 2008. Climate change and human activities have been identified as the two main reasons for the decrease in runoff. The study period is split into two sub-periods (1958–1989 and 1990–2008) using the Mann–Kendall jump test. This study develops an improved climate elasticity method based on the original climate elasticity method, and conducts a quantitative assessment of the impact of climate change and human activities on the runoff decrease in the Wei River basin. The results from the original climate elasticity method show that climatic impacts contribute 37 % ~ 40 % to the decrease in runoff, while human impacts contribute 60 % ~ 63 %. In contrast, the results from the improved climate elasticity method yield a climatic contribution to runoff decrease of 22 % ~ 29 % and a human contribution of 71 % ~ 78 %. A discussion of the simulation reliability and uncertainty concludes that the improved climate elasticity method has better mechanism and can provide more reasonable results.

1 Introduction

Climate change is expected to extensively alter global hydrological cycles (Legesse et al., 2003; Milly, 2005; Piao et al., 2007) by primarily changing the pattern of precipitation (IPCC, 2013; Sun et al., 2012). After precipitation falling into a basin, human activities including land use change, dam construction, river diversion, and other engineering and management practices will modify hydrological cycles locally and therefore temporal and spatial distribution of water resources (Govinda, 1995; Milly et al., 2005). Quantitatively assessing the influence of climate change and human activities on surface runoff is vital for sustainable water resources management.

Quantitative evaluation of the effects of climate change and human activities on runoff has yielded significant results, but with complex regional patterns. For instance, Zhang et al. (2008) used the sensitivity of runoff to precipitation and potential evaporation to study the response of runoff to changes in climate and land use/cover in the Loess Plateau of China and pointed out that LUCC (Land Use and Land Cover Change) accounted for over 50 % of the reduction in mean annual runoff in 8 out of 11 catchments. Bao et al. (2012) discussed the reasons for runoff changes in Haihe River Basin, and analyzed the influence of human activities through the VIC model and then proved human activities were the main driving force for the reduction of water resources. Wang et al. (2009) established a distributed monthly water balance model (DTVGM) to analyze the Chaobai River Basin upstream of Miyun Reservoir in north China, and concluded that human activities were therefore the main cause of runoff changes. Ma et al. (2008) estimated that the effects of climate change accounted for over 64 % of the mean annual runoff reduction in the Shiyang River in the arid region of Northwest China. For the same basin, human activities and climate change may have different influences on runoff for different periods. For example, Qiu et al. (2012) analyzed the influence of climate change and human activities on water resources in North China and found that in the 1970s–1980s the effects of climate change were dominant, but in the late 1980s and early 1990s the effects of the two factors were similar, and since the 90s the influence of human activities has been slightly higher at around 55 %. Guo et al. (2008) employed the SWAT model to analyze the annual and seasonal runoff variability caused by climate change and human activities and found that the main influencing factor on annual runoff was climate change, but that changing land use was the main influence on seasonal runoff changes.

So far, there are many different methods used to evaluate and separate the effects of the two factors. One such method is based on physical processes or physical mechanisms. This method controls the evolution of the various elements and analyzes the changes in driving factors and contributions in a physical process simulation. The approach may be physically sound but requires major efforts on model calibration and can lead to remarkably different results because of uncertainty in model structure and parameter estimation (Nash and Gleick, 1991; Revelle and Waggoner, 1983; Schaake, 1990; Vogel et al., 1999). Other methods can be classified as statistical data analysis methods, such as the climate elasticity method used in this paper. The statistical data analysis methods are based on mean annual change trend in long time series, and provide generalized relationships which do not consider species differences. This approach incorporates measured or observed data via a variety of data validation techniques, and analyzes the contributions of different factors on different processes. The method is relatively simple, but requires a large volume of high-quality data (Risbey and Entekhabi, 1996).

Many studies have proved that the climate elasticity method is reasonable and credible. Chiew (2006) evaluated rainfall elasticity of streamflow in 219 catchments across Australia using the nonparametric climate elasticity estimator and compared the estimates with results obtained from the conceptual rainfall-runoff model SIMHYD, showing a consistent relationship between climate elasticity values estimated using the rainfall-runoff model and the nonparametric estimator. Ma et al. (2010) used a distributed hydrological model (GBHM) and a climate elasticity model to conduct a quantitative assessment of the impacts of climate change and human activities on inflow into a reservoir. The GBHM simulation and climate elasticity model showed that climate change accounts for about 55 and 51 % of the reservoir inflow reduction, respectively. Hu et al. (2012) analyzed the impacts of climate change and human activities on the Baiyangdian upstream runoff, using two assessment methodologies (climate elasticity and hydrological modeling). The climate elasticity method was implemented at the annual scale and was computationally relatively simple; it needed fewer data and parameters to calculate the impacts of climate change on annual runoff. The hydrological model was implemented at the daily scale, and therefore needed more data and parameters but yielded more detailed, high temporal resolution results. These two independent methods based on different time scales could obtain consistent results. Thus, the climate elasticity method is considered to be an important indicator for quantifying the sensitivity of runoff to climate change and for separating the effects of natural and anthropogenic factors at a catchment scale (Dooge et al., 1999; Fu et al., 2007; Milly and

Dunne, 2002; Sankarasubramanian et al., 2001; Schaake, 1990; Zheng et al., 2009). However, the main poor point for the climate elasticity method previous research indicates is that the method is used to separate the sensitivity of runoff to climate change without considering the human activities directly, and furthermore the accuracy of the original climate elasticity method should be improved.

In this paper we improve the climate elasticity approach by adding the influence of human activities to evaluate the hydrological consequences of climate change and human activities. To compare the original and improved climate elasticity approaches, we choose the Wei River basin as a case study. The application results have a great strategic meaning in the regional economic development and the development of West China (Song et al., 2007). The rest of the paper is structured as follows: Sect. 2 describes the study area and data; Sect. 3 presents the methodology; Results and discussion are in Sect. 4.The conclusions are presented in Sect. 5.

2 Study area and data

2.1 Study area

The Wei River is the largest tributary in the Yellow River. It originates from Niaoshu Mountain, and runs into the Yellow River at Tongguan. The basin is located between 104°00′ E to 110°20′ E and 33°50′ N to 37°18′ N with a length of 818 km and a drainage area of 1.35×10^5 km^2.

The Wei River basin is located in temperate continental monsoon climate region. The climate is cold, dry and rainless in winter controlled by the Mongolia high, while hot and rainy in summer affected by the West Pacific subtropical high. The mean air temperature is 7.8 to 13.5 °C (decrease from the main channel towards the north and south tributaries), the mean annual precipitation is 400 to 800 mm (decrease from south to north), and the mean annual potential evapotranspiration is 800 to 1000 mm (decrease from east to west). The mean annual runoff in depth is 450 to 550 mm with the coefficient of variation falling within 0.1 to 0.2 (He et al., 2009).

2.2 Data description

This study uses the continuous daily series data from 1958 to 2008 at 7 national meteorological observatory stations in and around the Wei River basin. Observed daily mean air temperature, precipitation and solar shortwave radiation could largely reflect climatic change in the region (Fig. 1). In addition, observational runoff data of 1958–2008 comes from Hua Country hydrological station which located in the outlet of river downstream.

The potential evapotranspiration within the watershed can be calculated using Hargreaves method, Hargreaves formula is an empirical formula which was derived using the permeameter by Hargreaves and Samani (1982) to estimate potential evapotranspiration, and the expression is as follows:

$$E_0 = 0.0135(T + 17.8)\frac{R_s}{\lambda} \tag{1}$$

where E_0 represents potential evapotranspiration, mm day^{-1}; T represents mean air temperature, °; R_s represents solar shortwave radiation, MJ m^{-2} day^{-1}; λ represents latency for vapouring water, $\lambda = 2.45$ MJ kg^{-1}. Hargreaves formula is the best method of all the radiation and temperature estimation methods (Luo and Rong, 2007). So in this paper, the Hargreaves formula with less parameter is chosen and it can also give the optimal results.

3 Methodology

3.1 Detection of hydrologic changes

3.1.1 Trend analysis

In this study, the Mann–Kendall trend test is used to test the long-term trends of precipitation, evaporation and runoff in the Wei River basin. The Mann–Kendall trend test is a non-parametric statistical test method. It does not need the sample to follow any particular distribution, and is not subject to interference from a small number of outliers. Moreover, the required calculations are relatively simple (Mann, 1945; Kendall, 1975).

For a time series X which has n samples, construct variable S:

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

where x_i and x_j represent the values in years i and j, $i > j$, n is the record length of the series, and $sgn(x_i - x_j)$ is a characterization of the function.

The statistical test value Z_c is calculated by the following formula:

$$Z_c = \begin{cases} \frac{S-1}{\sqrt{\mathrm{Var}(S)}}, & S > 0 \\ 0, & S = 0 \\ \frac{S+1}{\sqrt{\mathrm{Var}(S)}}, & S < 0 \end{cases} \tag{3}$$

when $|Z_c| \leq Z_{1-\alpha/2}$, we accept the null hypothesis, which indicates the sequence does not have a trend. If $|Z_c| > Z_{1-\alpha/2}$, we reject the null hypothesis and conclude that the sequence does have a significant trend. $Z_{1-\alpha/2}$ is obtained from standard normal distribution function, and α is the significance level of the test.

To test the trend of the sequence in the Mann–Kendall test, it is usually necessary to estimate the slope of the monotonic trend, estimated as follows:

$$\beta = \mathrm{Media}\left(\frac{x_i - x_j}{i - j}\right), \ (\forall j < i,\ 1 \leq j < i \leq n). \tag{4}$$

A positive value of β indicates a rising trend (positive rate of change with time), and vice versa for negative β.

3.1.2 Change-point analysis

Under the hypothesis that the time series is independent and stochastic, we can compute the following statistics:

$$UF_k = \frac{S_k - E(S_k)}{\sqrt{\mathrm{Var}(S_k)}} \ (k = 1, 2, \ldots, n) \tag{5}$$

where $E(S_k)$ and $\mathrm{Var}(S_k)$ represent the mean and variance of S_k, respectively.

Next, the time series order is reversed (i.e., $x_n, x_{n-1}, \ldots, x_1$), and the above process is repeated to yield the statistical variables UB_k ($k = n, n-1, \ldots, 1$), such that

$$UB_k = -UF_k. \tag{6}$$

Next, we draw curves of UB_k and UF_k, and if the two curves have an intersection point and if the value of U at this point satisfies $|U| < 1.96$, then that point is regarded as a change point, with a confidence level α of 0.05.

Because the time series length in this study is 51 yr, a significance test is needed, for which we use the t test.

3.2 Original climate elasticity method

Runoff (Q) can be expressed as a function of climate variables (C) and other characteristics (H) (Hu et al., 2012):

$$Q = f(C, H) \tag{7}$$

while the parameter H represents the combined results of terrain, soil, land use/land cover and human activities (such as artificial water transfer). If the topography and soil in the study area remain constant during the study period, then H can represent human activities. So the runoff change can be expressed as:

$$\Delta Q = \Delta Q_\mathrm{C} + \Delta Q_\mathrm{H} \tag{8}$$

while the parameter ΔQ represents the total runoff change; and ΔQ_C, ΔQ_H represent the runoff changes caused by climate change and human activities, respectively.

The total runoff change can be obtained from the formula $\Delta Q = Q_\mathrm{obs1} - Q_\mathrm{obs2}$, where Q_obs1 and Q_obs2 represent the measured runoff before and after the change point, respectively.

Schaake (1990) first introduced the climate elasticity method to analyze the sensitivity of runoff to climate change. Climate elasticity of runoff (ε_X) can be defined as the proportional change in runoff (Q) relative to the change in climatic variables (X) (such as changes in precipitation or potential evapotranspiration) (Fu et al., 2007):

$$\varepsilon_X = \frac{\partial Q/Q}{\partial X/X}. \tag{9}$$

According to the long-term water balance equation ($Q = P - E$), we assume that the runoff response to climate factors is mainly caused by the precipitation and potential evapotranspiration. According to the theory of total differential equations, the differential form is as follows:

$$\Delta Q_\mathrm{C} = \varepsilon_\mathrm{P} \frac{Q}{P} \Delta P + \varepsilon_{E_0} \frac{Q}{E_0} \Delta E_0 \quad \text{and} \quad \varepsilon_\mathrm{P} + \varepsilon_{E_0} = 1 \tag{10}$$

where ΔQ_C represents runoff change caused by climate change, ΔP and ΔE_0 are the change of precipitation and potential evapotranspiration, and ε_P and ε_{E_0} are the precipitation and potential evapotranspiration elasticities of runoff, respectively.

According to the Budyko hypothesis, actual evapotranspiration (E) is a function of the dryness indices ($\phi = E_0/P$), specifically $E = P \cdot F(\phi)$, and the precipitation and potential evapotranspiration elasticities of stream flow can be expressed as:

$$\varepsilon_\mathrm{P} = 1 + \phi F'(\phi)/(1 - F(\phi)) \quad \varepsilon_{E_0} = -\phi F'(\phi)/(1 - F(\phi)). \tag{11}$$

The following formulae (one with a parameter and the others without) for the Budyko hypothesis are often used to estimate $F(\phi)$, as shown in Table 1.

According to Table 1, the precipitation elasticity (ε_P) and potential evapotranspiration elasticity (ε_{E_0}) can be determined, allowing the runoff change caused by climate change (ΔQ_C) to be calculated, and thus the contribution of climate change can be assessed. Calibration of Zhang's (2001) formula using land cover and land use conditions yielded a parameter value of 1.5.

3.3 Improved climate elasticity method

At the catchment scale, and over a long time period, the water balance equation can be simplified as $P = E + R$. Here we extended the framework based on the Budyko hypothesis by assuming the Budyko curve can precisely estimate the mean annual evaporation and therefore the mean annual runoff caused by climate variation (precipitation and potential evaporation). It follows that any departure from that curve would be caused by human activities over the land as defined above. Therefore the mean annual runoff R can be divided into observed runoff and changing runoff caused by human activities, i.e. $R = R_\mathrm{obs} + R_\mathrm{H}$, so that the water balance equation can be expressed as $P = R_\mathrm{obs} + R_\mathrm{H} + E$ which in differential form is:

$$\mathrm{d}P = \mathrm{d}R_\mathrm{obs} + \mathrm{d}R_\mathrm{H} + \mathrm{d}E \tag{12}$$

where R_obs is observed runoff, and R_H is the water consumption by human activities.

Meanwhile, according to the Budyko hypothesis $E = PF(\phi)$, $\phi = E_0/P$, the total differential form can be expressed as:

$$\mathrm{d}E = [F(\phi) - \phi F'(\phi)]\mathrm{d}P + F'(\phi)\mathrm{d}E_0. \tag{13}$$

When substituted into Eq. (12), this leads to:

$$\mathrm{d}R_{\mathrm{obs}} = [1 - F(\phi) + \phi F'(\phi)]\mathrm{d}P - F'(\phi)\mathrm{d}E_0 - \mathrm{d}R_{\mathrm{H}}. \tag{14}$$

After dividing Eq. (14) by R_{obs}, we obtain the following equation:

$$\frac{\mathrm{d}R_{\mathrm{obs}}}{R_{\mathrm{obs}}} = [1 - F(\phi) + \phi F'(\phi)]\frac{P}{R_{\mathrm{obs}}}\frac{\mathrm{d}P}{P} - F'(\phi)\frac{E_0}{R_{\mathrm{obs}}}\frac{\mathrm{d}E_0}{E_0} - \frac{R_{\mathrm{H}}}{R_{\mathrm{obs}}}\frac{\mathrm{d}R_{\mathrm{H}}}{R_{\mathrm{H}}}. \tag{15}$$

The climate and anthropic elasticities are calculated as follows:

$$\begin{aligned} \varepsilon_{\mathrm{P}} &= [1 - F(\phi) + \phi F'(\phi)]\frac{P}{R_{\mathrm{obs}}} \\ \varepsilon_{E_0} &= -F'(\phi)\frac{E_0}{R_{\mathrm{obs}}} \\ \varepsilon_{\mathrm{H}} &= -\frac{R_{\mathrm{H}}}{R_{\mathrm{obs}}} \end{aligned} \tag{16}$$

which satisfy $\varepsilon_{\mathrm{P}} + \varepsilon_{E_0} + \varepsilon_{\mathrm{H}} = 1$.

From Table 1 and Eq. (16), the elastic coefficients ε_{P}, ε_{E_0}, ε_{H} which represent the precipitation, evapotranspiration, and human activities elasticities, can be calculated. Next, the runoff change R_{H} caused by human activities is computed. The contribution of human activities to runoff can be expressed by P_{H}, where $P_{\mathrm{H}} = R_{\mathrm{H}}/\Delta Q$, thus the contribution of climate change can also be calculated.

4 Results and discussion

4.1 Detection of hydrologic changes

In this study, the Mann–Kendall trend test is adopted to determine the significance of the trends in runoff, precipitation and potential evapotranspiration, and to analyze the trends in meteorological factors and corresponding runoff changes over nearly 50 yr. Figure 2 shows time series of precipitation, potential evapotranspiration and runoff from 1958–2008, and the runoff series are observed at the hydrological gauging station located the river basin outlet. Qualitative inspection shows that the trends in precipitation and potential evapotranspiration are not obvious, while runoff notably decreases. The fluctuation range of potential evapotranspiration is not obvious in different years, but the fluctuation range of precipitation is significant, and its overall trends are stable. Thus, the decrease of runoff implies that precipitation and potential evapotranspiration are not the only influencing factors on runoff, and instead human activities may have had the main influence on the decreasing runoff.

The Mann–Kendall test is also used to analyze the change point of the runoff in the Wei River basin, at a confidence level set to $\alpha = 0.05$. The normal distribution shows that the critical value was $U_{\alpha/2} = 1.96$. The result of change point test is presented in Fig. 3. It can be seen in Figure 3 that the two curves intersect in 1990, and the intersection is within the critical value range $U_{\alpha/2} = \pm 1.96$. The result illustrates that an abrupt change of runoff occurred in 1990.

According to the results of trend analysis and change-point analysis, the monthly runoff data in the periods of 1958–1990 and 1990–2008 is used to plot the Flow Duration Curve (FDC) that indicates the runoff change of the basin in different periods, and the monthly runoff series are observed at the hydrological gauging station located the river basin outlet. Vogel and Fennessey (1994) provides the details of FDC method, which represents the relationship between the magnitude and frequency of runoff, providing an estimate of percentage of time a given runoff is equal or exceeded over a historical period. The relationship between the magnitude and frequency of monthly average runoff are shown in Fig. 4, which indicates the percentage of time runoff is exceeded in the period of 1958–1990 is larger than that in 1990–2008, and the runoff relative change for the two periods only have a large fluctuations at the percentage that is less than 10 % and more than 90 %. The Fig. 4 also implies the decrease of runoff in 1990–2008 has the correlations with human activities, and the influence on the decreasing runoff is easier to happen in the high-flow and low-flow periods at which the percentage time runoff is exceeded is less than 10 % and more than 90 %.

4.2 Results of the original and improved climate elasticity methods

4.2.1 Original climate elasticity method

In order to evaluate the influence on runoff caused by climate change, firstly, Eq. (11) is used to calculate the elasticities of precipitation and potential evapotranspiration for 1958–2008, which can be expressed as ε_P and ε_{E_0}, respectively, as shown in Table 2. These results reveal that if precipitation decreases by 10 %, runoff will decrease by 25.8 % ~ 27.7 %, and if potential evapotranspiration decreases by 10 %, runoff will increase by 15.8 % ~ 17.7 %. Then, according to the calculated ε_P, ε_{E_0} and Eq. (10), the runoff decrease caused by climate change can be computed. The total contribution of precipitation and potential evapotranspiration to the runoff decrease is 32.1 mm. Therefore, the contribution of climate change to the runoff decrease is 37 % ~ 40 %, and the contribution of human activities is 60 % ~ 63 %.

4.2.2 Improved climate elasticity method

In order to evaluate the influence on runoff caused by human activities, firstly, Eq. (16) is used to calculate the elasticities of precipitation, potential evapotranspiration and human activities for 1958–2008, which can be expressed as ε_P, ε_{E_0} and ε_H, respectively, as shown in Table 3. We realize that if annual runoff decreases by 32.1 mm, the decrease caused by human activities is 22.9 ~ 24.9 mm. So the contribution of human activities to runoff decrease is 71 % ~ 78 %, and the contribution of climate change is 22 % ~ 29 %.

4.2.3 Comparison of the simulation results

In this paper, two methods are used to analyze the causes of the runoff decrease in the Wei River basin. One is the original climate elasticity method, and the other is the improved climate elasticity method. Each method adopts two formulas based on the Budyko hypothesis (noting that one formula includes parameters and the other does not). Results are compared with each other and with those calculated by other methods, and the precision of the two methods is analyzed. Both methods are implemented at the annual time scale, and require relatively simple computation. The contributions of climate change and human activities to runoff variability can thus be computed by fewer data and parameters compared with other methods. The results of the original climate elasticity method show that the contributions of climate changes and human activities to runoff variability are 37 % ~ 40 % and 60 % ~ 63 %, respectively. Meanwhile, corresponding contributions calculated using the improved climate elasticity method are 22 % ~ 29 % and 71 % ~ 78 %, respectively. Early studies showed that during 1970–1995 the contribution of human activities to runoff decrease was 58.3 % in the Wei River basin (Zhang and Wang, 2007). In recent years, human activities have intensified, so by 2008 the contribution of human activities should have increased, and may now exceed 60 %. Gao et al. (2013) found that the contribution of human activities to reduced stream flow in the Wei River basin was even as high as 82.80 %. The results of the improved climate elasticity method are closer to the existing results than those of the original, suggesting that the improved climate elasticity method, which is more adaptable and easier to implement, is much more reliable and practical.

Moreover, it is important to note that the improved climate elasticity method is the first to introduce human activities elasticity ε_{H}. Without the trend analysis and change-point test, the strength of the influence of human activities on runoff changes can be calculated. When calculating the contribution of human activities to runoff changes, the change-point test is needed so that the total runoff decrease can be calculated.

The improved climate elasticity method broadens the concept of climate elasticity, and provides more intuitive and practical formula for calculating the contribution of human activities to runoff changes. Compared with the hydrological simulation method, the climate elasticity method not only needs fewer data and parameters, and is more reliable and easier to implement, but can also be easily extended. However, its temporal resolution is low and it lacks a physical basis. There is a trend towards coupling hydrological simulations with the more reliable hydrological and meteorological statistical methods, to quantitatively study hydrological responses to climate change and human activities.

4.3 Discussion

The impacts of human activities on runoff are reflected in land use and land cover changes. Land use and land cover change is a gradual process, and the impacts on runoff also accumulate gradually. We can decrease the uncertainty of quantitative predictions by analyzing the LUCC changes in the Wei River basin in 1980, 1990, 2000, 2005 and 2007, and then checking whether the results are reasonable. The main type of land cover in the Wei River basin is cultivated land, which covers more than 50 % of the total area, followed by woodland and grassland.

By analyzing the changing areas of cultivated land and woodland and grassland in the Wei river basin in 1980, 1990, 2000, 2005 and 2007, it can be concluded that the year 1990 is the turning point in cultivated land area, since the area decreases during 1980–1990, and then begin to increase again after 1990. The year 1990 is also the turning point in the area of woodland and grassland area, but the corresponding trends are opposite to those of the cultivated area. Because the area of cultivated land and woodland and grassland reaches 90 %, and considering the turning points of the three types of land, the year 1990 can be regarded as a more general turning point in surface characteristics. This decreases the uncertainty regarding 1990 as the runoff change point.

Major sources of uncertainty in the simulation associated with the climate elasticity may arise from the input data, classification of the stages, and the parameter in the Zhang (2001) formula. Precipitation data used in the models are from 7 rain gauges and meteorological stations in and around the study catchment. The flow data are measured during 1958–2008 from the Hua County hydrological station, which is located at the downstream end of the basin, but may not sufficiently represent the whole basin. Even though the breakpoint test is found to be reasonable, there remain some uncertainties which may be caused by the test method and artifacts when reading the results in the chart. The parameter which is very sensitive in the Zhang (2001) formula is calibrated according to the land cover and land use conditions.

Furthermore, it is essential to point out that climate change and human activities are supposed to be two mutually independent variables when separating their impacts on runoff; however, we note that land use and land cover can be influenced by both climate change and by human activities.

5 Conclusions

Decreasing runoff in many rivers in China has been reported in recent years, and the Wei River basin is one of the most serious cases. This paper is aiming at developing a new approach to quantifying the impact of climate variations and human activities on this decreasing runoff in the Wei River basin. The man-made changes here include land use, vegetation, and other land surface conditions, while climate change and climate variability are reflected in precipitation and potential evapotranspiration. This study uses the Mann–Kendall test to assess the temporal trends in precipitation, potential evapotranspiration and runoff, and also analyzes the point of abrupt change. On this basis, the original climate elasticity method and improved climate elasticity method are used to analyze the quantitative hydrological effects of climate change and human activities; these findings are then compared to existing results from the hydrological simulation method. The study shows as following:

In the last 50 yr, the runoff from the Wei River basin has obviously decreased, but the precipitation and potential evapotranspiration have shown no clear trend. Therefore it can be seen that climate factors have not obviously contributed to the runoff decrease.

From 1958 to 2008, the runoff in the Wei River basin shows an abrupt change in 1990, effectively dividing the total runoff into natural runoff process and runoff process affected by human activities. At the same time, this change shows that human activities have significant effects on runoff.

Human activities resulted in a shift in land use and land cover in 1990, and the type of land use and land cover has a great influence on runoff. This illustrates that human activities, especially those causing land use and land cover change, are the main reason for the runoff decrease.

The original climate elasticity method shows that the contributions of climate change and human activities to runoff decrease are 37 % ~ 40 % and 60 % ~ 63 %, respectively, but the improved climate elasticity method indicated that the contributions of climate change and human activities to runoff decrease are 22 % ~ 29 % and 71 % ~ 78 %, respectively. The result of the improved climate elasticity method is closer to those existing results concluded based on comprehensive hydrological models, thereby demonstrating that human activities are the main reason for the runoff decrease in the Wei River basin.

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Table 1. Different formulae for the Budyko hypothesis.

Expression	$F(\phi)$	$F'(\phi)$
Turc (1954); Pike (1964)	$\left(1+\phi^{-2}\right)^{-0.5}$	$1/\left[\phi^{3}\left(1+(1/\phi)^{2}\right)^{1.5}\right]$
Zhang (2001)	$(1+w\phi)/(1+w\phi+1/\phi)$	$\left(w+2w/\phi-1+1/\phi^{2}\right)/(1+w\phi+1/\phi)^{2}$

Table 2. Results of the original climate elasticity method.

Period	Formula	P/mm	E_0/mm	ε_p	ε_{E_0}	ΔQ_c/mm	ΔQ_c/%	ΔQ_H/%
1958–2008	Turc (1954); Pike (1964)	569.3	923.1	2.77	−1.77	11.9	37	63
1958–2008	Zhang (2001)	569.3	923.1	2.58	−1.58	12.9	40	60

Table 3. Results of the improved climate elasticity method.

Period	Formula	P/mm	E_0/mm	ε_p	ε_{E_0}	ε_H	ΔQ_H/mm	ΔQ_C/%	ΔQ_H/%
1958–2008	Turc (1954); Pike (1964)	569.3	923.1	3.53	−2.16	−0.37	22.9	29	71
1958–2008	Zhang (2001)	569.3	923.1	3.89	−2.49	−0.40	24.9	22	78

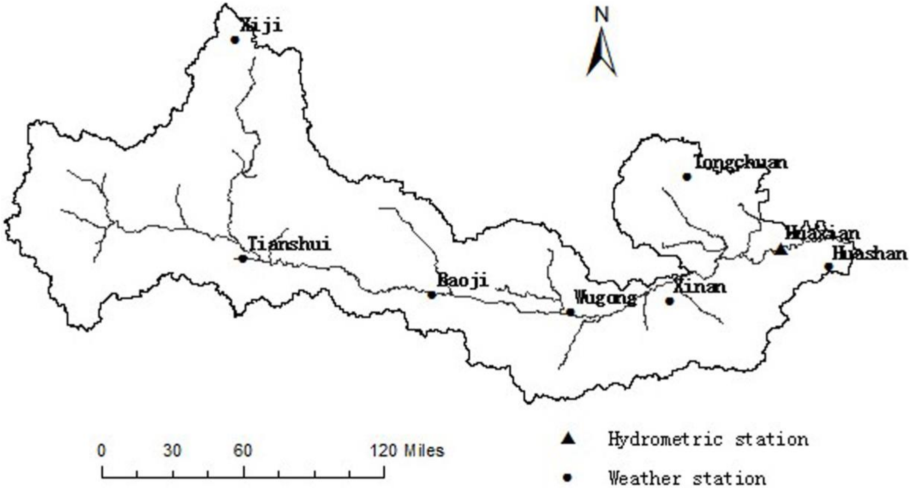

Fig. 1. Location of the meteorological and hydrological stations used in this study.

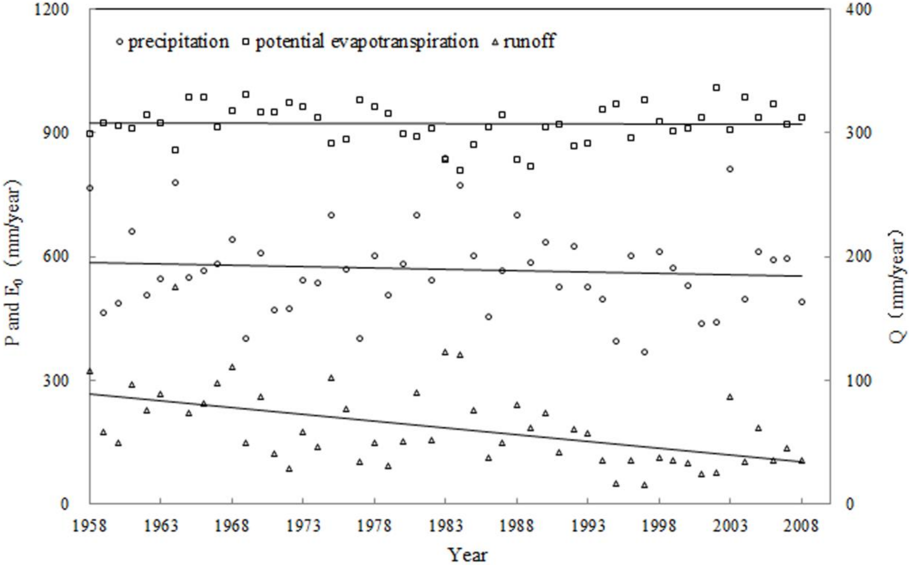

Fig. 2. Time series of annual precipitation, annual potential evapotranspiration and annual runoff in the Wei river basin from 1958–2008.

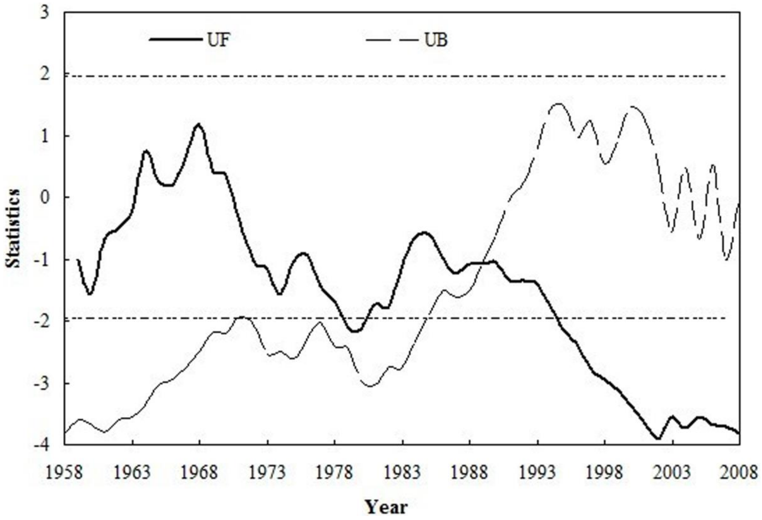

Fig. 3. The result of the abrupt change point test in the Wei river basin.

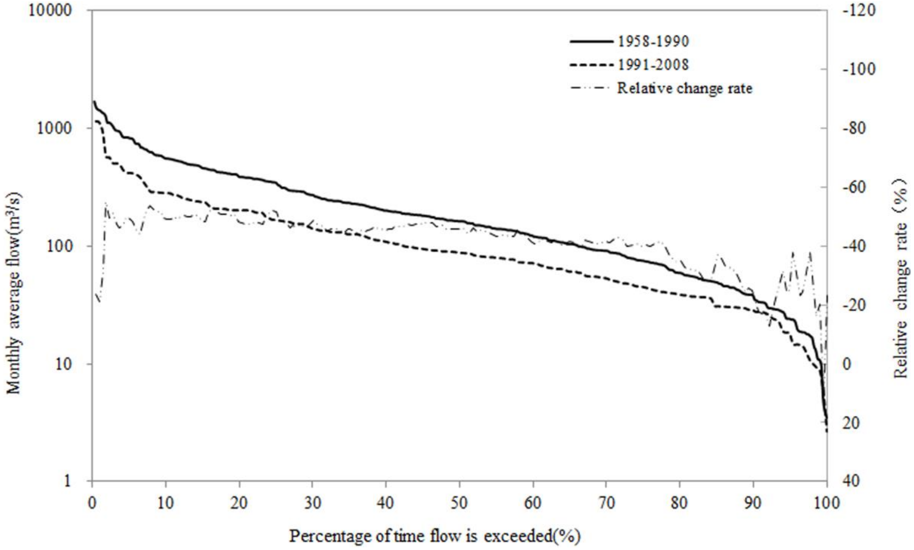

Fig. 4. Flow duration curves under different periods in the Wei river basin.