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# Impact of climate change and human activities on runoff in the Weihe River Basin, China

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ABSTRACT

Runoff has been in decline in most river basins in China during the last 50 years. The Weihe River, the largest tributary of the Yellow River, has experienced runoff declines as large as 35% in the last century. Little is known regarding the relative contributions of climate and human impact to the observed hydrological trends in the Weihe River Basin. In the present paper, data from seven hydrological stations and 21 meteorological stations are used to analyze the long-term trends of precipitation, temperature, and streamflow. Using the daily climatic data, a Variable Infiltration capacity (VIC) hydrological model is calibrated and verified to a baseline period from 1956 to 1970. Subsequently, natural runoff for the following years (1971–2006) is reconstructed using the VIC model without considering local human impacts. On the basis of observed meteorological data and runoff and the reconstructed runoff data from 1971 to 2006 in the Weihe River Basin, we quantified long-term trends and decadal and annual variations. The results showed that precipitation and runoff have decreased since the baseline decade. We further estimated the relative contributions of human activity and climate change to the hydrological response of the Weihe River Basin and determined that human activity (such as large-scale soil conservation practices and large irrigation areas) has a greater impact on basin runoff than do climate change factors. The percentages in change of runoff due to climate change (*PC*) are 36%, 28%, 53% and 10% in the 1970s, 1980s 1990s and 2000s, respectively. The percentages in change of runoff caused by human activity (*PH*) are 64%, 72%, 47%, and 90%, respectively.



## 1. Introduction

Investigations on regional and global environment changes and their subsequent impacts on society have received considerable attention in recent years. Environmental changes can be grouped into two categories: changes driven by climate change and changes as a result of human alterations to land and water bodies, such as land use/cover change (LULC) due to cropland expansion or urbanization, water consumption for human use, and damming of rivers, which alters natural flow (Labat et al., 2004; Fraiture, 2007; Milliman et al., 2008; Liquete et al., 2009). In hydrological research, there has been growing interest in identifying the driving factors and impacts on hydrological change in the last decade (Zalewski, 2000; Sankarasubramanian and Vogel, 2001; Drogue et al., 2004; Andreo et al., 2006; Novotny and Stefan, 2007).

Much of this attention has been focused on analyzing climate changes in China (Guo et al., 2002; Wang et al., 2005; Zhou and Yu, 2006; Li et al., 2012). The Yellow River, the second largest river in China, is a source of freshwater for approximately 107 million people within the river basin. It is now under great stress due to climate change and a growing water demand in the basin. Studies on the Yellow River basin (YRB) have reported warming trends at a rate of 1.28C°/50 years, while the average precipitation has dropped approximately 8.8% over the second half of the 20th century. Variations in precipitation and temperature play an important role in the runoff change of the YRB, especially in the upper stream, where human impacts are minimal (Zhen et al., 2007; Xu et al., 2009; Liu et al., 2011). However, human activity, including land use change, increased water diversion, strengthened soil and water conservation measures and artificial water intake in the YRB, has also

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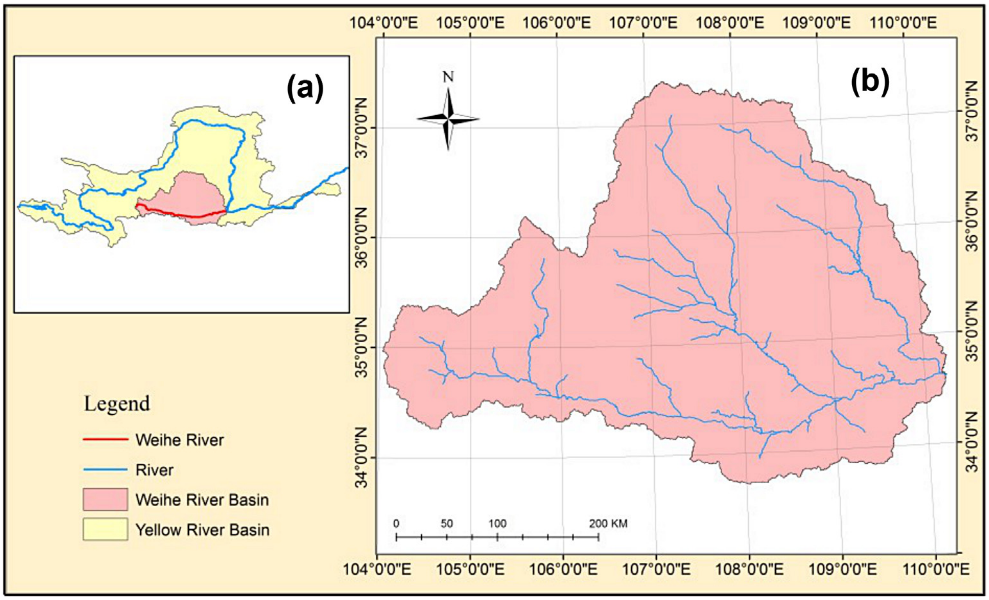


**Fig. 1.** The location maps of (a) the Yellow River Basin and (b) the entire Weihe River Basin.

impacted the hydrology of the YRB, especially in the middle and lower streams (Saito et al., 2001; Liu, 2004; Lu, 2004; Wang et al., 2004). Different values of the change in runoff have been reported across the YRB. Zheng et al. (2009) reported that changes in land use during the course of the 1990s were responsible for more than 70% of the decrease in streamflow of some headwater subcatchments of the Yellow River Basin. Li et al. (2007) reported that soil conservation measures from 1972 to 1997 accounted for 87% of the total reduction in mean annual streamflow in the Wuding River, a sub-basin of the Yellow River with an area of 30,000 $km^2$. Ma et al. (2008) estimated that climate variability accounted for over 64% of the reduction in mean annual streamflow in the Shiyang River basin, located in an arid region of Northwest China.

In this study, we concentrate on the Weihe River Basin (WRB), the largest tributary of the Yellow River (135,000 $km^2$), which has substantial runoff decline across the basin. Changes in the Weihe River hydrology greatly affect the Guanzhong area of the Shaanxi Province; approximately 85% of the water supply of Xi'an City and the water supply for several smaller cities (such as Baoji, Weinan, and Xianyang) are derived from the river. In this region alone, over 22 million people rely on the Weihe River. Studies have shown that runoff from the Weihe River has decreased significantly in recent decades (Wang et al., 2006; Wei et al., 2008; Hou et al., 2011). Due to its vital national (cultural, environmental, functional) importance and delicate hydrological balance, quantitative assessments of climate change and human impact on the WRB will have a critical role in determining a sustainable plan for future water resource utilization projects. What is the major driving factor of streamflow decrease in the WRB? The answer to this question is very important for future water resource planning and management decisions to ensure sustainable water resource utilization. If climate variability is the major driving factor, it is essential to study the impact of climate variability on future water resources under different climate change scenarios. However, if human activity contributions more, water resource management by policymakers is more important.

The primary aim of this study is to examine the relative contributions of climate and LULC on the hydrology of the WRB. Du and Shi (2012) investigated the relationships between climatic factors, human activity, and measured runoff in the Weihe River drainage basin using a statistical method. In this study, we begin by examining trends in temperature, precipitation, and annual runoff throughout the latter half of the 20th century and the early 21st century, during which a sufficient number of detailed hydro-climatological records were collected for analysis. Hydrological models have been widely used to assess water resources (Whitehead and Robinson, 1993; Xiong and Guo, 1999; Wilby et al., 2002; Gao et al., 2007). A model known as VIC, which is driven by daily hydrometeorological data, is used to identify the relative influences of climate change and human impact on the runoff of the WRB from 1956 to 2006. Following model calibration, the VIC model is first used to simulate runoff under natural conditions without any human impact on LULC and water use. Based on observations and the model simulation results, impact percentages from local human activity and climate change are calculated.

## 2. Study area

The study area, the Weihe River, which originates from the Gansu province and passes through the Shaanxi province, is the largest tributary of the Yellow River in China (Fig. 1). It is asymmetric and fan-shaped, and the terrain of the river basin is high in the western area and low in the eastern area. The basin drainage area is 135,000 $km^2$, and the main stream length is 818 km. The average annual natural runoff of the river is 10.4 billion $m^3$, which is 17.3% of the Yellow River's total discharge. The Weihe River's two largest tributaries are the Jing River and Beiluo River, and the Huaxian station is the most downstream hydrometric station on the main stream of the Weihe River.

The Weihe River valley is the main grain-yielding area and an important industry and commerce area in Northwestern China. The Weihe River is a major source for drinking water, industrial water, and irrigation in the central plain. The basin hosts 76 major cities with a total population of 22 million. The climate in the region is characterized by temperate continental monsoon with a mean annual precipitation of approximately 610 mm, 80% of which falls between June and October. The mean annual temperature is between 7.8 and 13.5 °C across the basin. The extreme maximum and minimum temperatures, 42.8 °C and −28.1 °C, are observed in July and January, respectively. Both precipitation and runoff have strong inter-annual and intra-annual variability; the seasonal variation in

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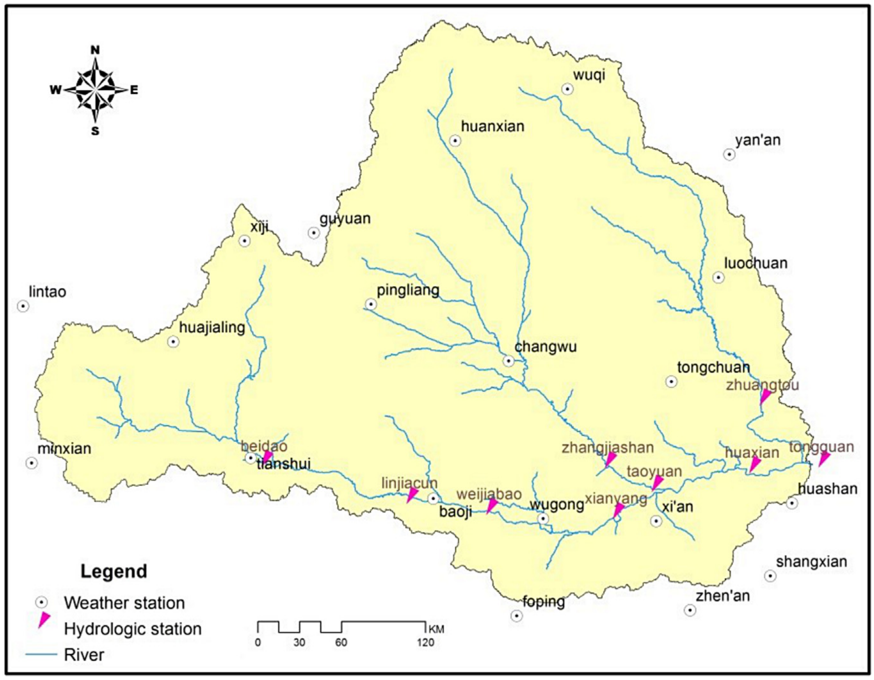


**Fig. 2.** Location of hydrological and meteorological stations.

runoff is similar to that of precipitation. The runoff between July and October is approximately 65% of the mean annual runoff. The mean annual potential evaporation ranges from 800 mm in the south to 1200 mm in the north.

Human activity has become extensive in the WRB over the last several decades. Due to the increase in population, industry, and farmland area, the amount of surface water withdrawal and groundwater exploitation has been increasing rapidly. From 1978 to 1985, China's land reform motivated farmers to increase agricultural production; however, increased agricultural activity results in increased agricultural water use. According to statistical data from the Ministry of Water Resources, hyper-irrigation using water taken from the WRB occurred in an approximately 9500 $km^2$ area in 2008. Hyper-irrigation directly reduces the regional water discharge due to water consumption by irrigation fields. In addition, approximately 130 reservoirs were built after 1949 with a total storage capacity of 1.67 billion $m^3$ (Xin et al., 2007). The construction of these reservoirs lead to increased evaporation due to the increase in water surface area and affected the inter-annual distribution of streamflow. Moreover, due to the thick and highly erodible loess, sparse vegetation, unevenly distributed rainfall, and relatively high intensity of rainstorms, soil erosion in the WRB is significant. Since the 1970s, soil and water conservation measures have been funded by the Central Government. As a result of these projects, there has been an increase in vegetation coverage and significant LULC in the WRB since the 1970s, leading to an increase in the canopy interception, soil regulation effect, and soil moisture capacity. Eventually, there will be a decrease in the direct runoff and an increase in the amount of baseflow (Li et al., 2002; Wang et al., 2010). Several studies have shown that runoff has been decreasing since the 1970s due to human activity in the WRB (Xu and Niu, 2000; Hou et al., 2011).

## 3. Methodology and data

### *3.1. Data sources and site selection*

There are 22 standard meteorological stations that take daily precipitation and mean temperature data in the WRB. The longest available data period is from 1951 to 2012, and 21 of the 22 stations have data for a 51 year period (1956–2006). These 21 stations (Fig. 2), having high-quality data, are maintained according to the standard methodology of the China Meteorological Administration. In this paper, the monthly and annual precipitations were established from the collected data. Air temperature data were prepared by calculating monthly mean and annual maximum, minimum, and mean air temperature values from the daily data. Daily precipitation amounts were summed to obtain monthly and annual values. The annual mean precipitation and temperature for the whole basin were derived using the precipitation distribution map within the corresponding drainage area of each section. The daily streamflow data were gathered for the same period from the Shaanxi Hydrometric and Water Resource Bureau for 7 streamflow gauges, most of which were on the main stem of the basin (Fig. 2, Table 1). Data from these selected weather and streamflow stations were examined for trends from 1956 to 2006. The soil data were extracted from the FAO two-layer 5-min 16-category global soil texture maps. The DEM data were obtained from the SRTM 90 m Digital Elevation Data.

**Table 1**
Locations of hydrological stations whose data records were analyzed in this study.

| Site name | Latitude (N) | Longitude (E) | Elevation (m) | Drainage area ($km^2$) |
|---|---|---|---|---|
| Linjiacun | 34.21 | 107.00 | 615 | 32,850 |
| Weijiapu | 34.15 | 107.45 | 507 | 40,600 |
| Xianyang | 34.17 | 108.42 | 390 | 49,822 |
| Lintong | 34.26 | 109.12 | 328 | 97,299 |
| Huaxian | 34.44 | 109.42 | 342 | 105,350 |
| Zhangjiashan | 34.35 | 108.35 | 342 | 41,800 |
| Zhuangtou | 35.02 | 109.50 | 1082 | 25,645 |

### *3.2. Quantifying the influences of climate change and human activity on runoff*

Observed runoff shows the combined impacts of climate change (lower precipitation and increased temperatures) and increased human activity, such as direct river withdrawals. While trend analysis of hydroclimatological variables would give us an idea of how the hydrological system changed over the last 50 years, identifying the cause of this change is the true challenge. In an attempt to disentangle the role of climate change from human impact in the last 40 years, we took the 1956–1970 data as the baseline for this study. We used a numerical model of hydrology (VIC) calibrated using the 1956–1970 period and ran the model with fixed land use and land cover (LULC) conditions until 2006. This fixed LULC simulation was used as the baseline case, reflecting the influence of climate change alone (precipitation and temperature). The runoff difference between the baseline and recorded data recorded during the human-disturbed period consists of two parts; we define one describing the changes from human activity as $\Delta R_h$ and the other describing changes from climate conditions as $\Delta R_c$. Thus, the difference between the observed runoff for the assessment period, $R_i$, and the runoff for the baseline period represents the runoff response under climate change and human activities, or the sum of $\Delta R_h$ and $\Delta R_c$.

$$\begin{aligned} \Delta R_h + \Delta R_c &= R_i - R_b \\ \Delta R_h &= R_i - R_m \\ \Delta R_c &= R_m - R_b \end{aligned} \tag{1}$$

where $\Delta R_h$ (m$^3$) and $\Delta R_c$ (m$^3$) are the changes in runoff impacted by human activity and climate conditions, $R_b$ is the observed annual runoff for the baseline period (m$^3$), $R_i$ is the observed annual runoff for the assessment period (m$^3$), and $R_m$ is the reconstructed annual runoff estimated by the hydrological model for the assessment period (m$^3$).

The relative change in observed runoff (*PR*) for the assessment period can be attributed to the combined impacts of human activity and climate change.

$$PR = \left(\frac{R_i}{R_b} - 1\right) \times 100\% \tag{2}$$

where *PR* is the relative change in observed runoff during the baseline period (%).

The impact percentages from local human activity (*PH*) and climate change (*PC*) can then be stated as

$$PH = \frac{\Delta R_H}{\Delta R_H + \Delta R_C} \times 100\% \tag{3}$$

$$PC = \frac{\Delta R_C}{\Delta R_H + \Delta R_C} \times 100\% \tag{4}$$

Using Equations (3) and (4), we can separate the percentage of climate change impact from the summation of combined impacts. Equation (3) calculates the proportional runoff change brought by human activity over the total observed runoff change. Equation (4) represents the percentage of runoff change due to climate variation.

Equations (1)–(4) can be used to quantitatively separate the impacts of climate change and human activity on runoff in the study basin from 1956 to 2006. The next step is to reconstruct natural runoff using the VIC hydrological model.

### 3.3. Brief introduction of the VIC (variable infiltration capacity) model

Hydrological models are used for various applications, ranging from the estimation of catchment water yield to the estimation of land use and climate change impacts on runoff characteristics (Porter and McMahon, 1971; Drogue et al., 2004). In this paper, a VIC hydrological model is used. The VIC (variable infiltration capacity) model (Liang et al., 1994, 1996; Nijssen et al., 1997) is a large-scale gridded hydrological model that was developed to simulate the water and energy balance for large-scale applications (Zhao et al., 1980; Cherkauer and Lettenmaier, 1999). Each grid cell solves a full energy and water balance using three soil layers. The top thin soil layer represents quick bare soil evaporation following small rainfall events; the middle soil layer represents the dynamic response of the soil to rainfall events; and the lower layer characterizes the seasonal soil moisture behavior (Liang and Xie, 2001). The VIC model represents sub-grid cell variation in both vegetation cover and infiltration. It uses a mosaic-type method that allows multiple vegetation types and bare soil to be specified within a grid cell using fractional coverage areas. A full energy and water balance is computed for each vegetation fraction, and the ET from each vegetation type is characterized using a Penman–Monteith formulation. Distinguishing features of the VIC model include the sub-grid variability in soil moisture, land surface vegetation, precipitation, and topography using the elevation band. In the VIC model, The ARNO baseflow formulation is used to represent subsurface runoff generation from the deepest soil layer. Fundamentally, the baseflow is specified as a function of soil moisture in the lowest soil layer that is non-linearly related to high soil moisture content and linearly related to low soil moisture content of the deepest soil layer. The total runoff is the sum of the direct runoff and baseflow of each grid cell (Christensen and Lettenmaier, 2007).

Having simulated streamflow well, the VIC model has been tested and applied in various basins (Abdulla et al., 1996; Lohmann et al., 1998; Wood et al., 1998; Bowling et al., 2003; Su et al., 2005). Su and Xie (2003) applied the VIC-3L model to assess the effects of climate change on runoff in arid and semi-arid regions of China with encouraging results.

## 4. Results and discussion

### 4.1. Mean precipitation and temperature trends

Fig. 3 is the spatial map of precipitation and temperature (January and July) in the WRB. Precipitation decreases going from the southeast to the northwest. In the summer, the temperature in the north and south sections is higher than in the east and west, and, in the winter, the temperature decreases from south to north. The time series of the WRB precipitation and temperature in the study basin (from 1956 to 2006) are shown in Figs. 4 and 5, respectively. In the period, the annual observed precipitation decreased, and the temperature increased. The regression slopes for precipitation and temperature were −1.58 and 0.02, respectively. The annual precipitation reached a maximum of 842 mm in 1958 and a minimum of 367 mm in 1997. The decadal variability of precipitation indicated that 1956–1970 was a wet period. The WRB suffered a long dry period from 1991 to 2000 and another dry period from 1971 to 1980. Precipitation from 1981 to 1990 fluctuated near the long-term average value. Between 2001 and 2006, there was another wet period; 2003 had the second highest annual precipitation in the last 50 years. The result of a Mann–Kendall–Sneyers test showed a decreasing trend for annual precipitation in the WRB from 1956 to 2006; however, the trend was insignificant at $a = 0.05$ level (Fig. 4). Furthermore, a significant step change point for precipitation in the WRB was not observed.

The climate of the WRB has become warmer during the last 50 years (Fig. 5). The coldest year over the last 50 years was 1984. After 1994, the annual temperature was always higher than the long-term mean temperature. The result of a Mann–Kendall–Sneyers

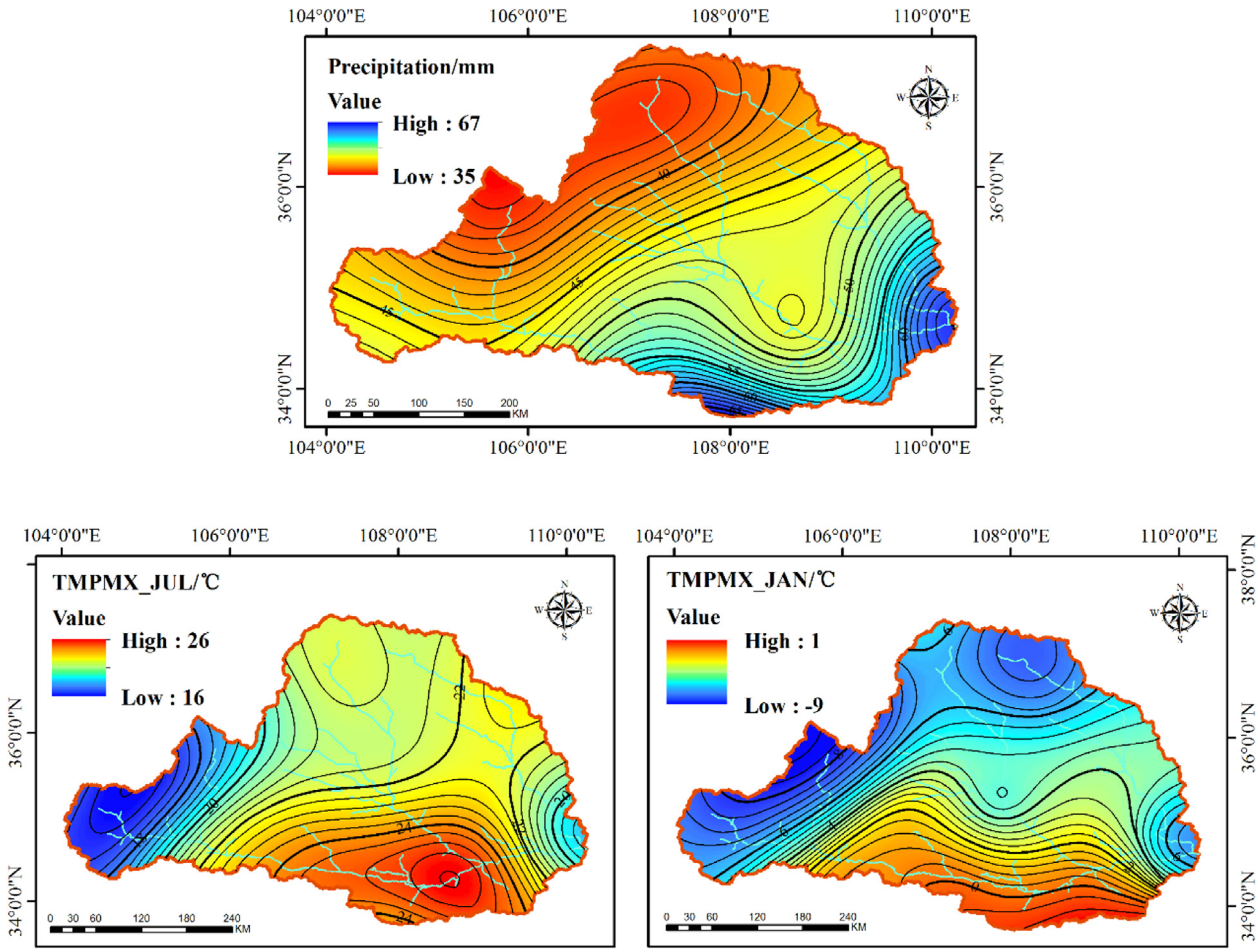


**Fig. 3.** The spatial map of precipitation and temperature (January and July).

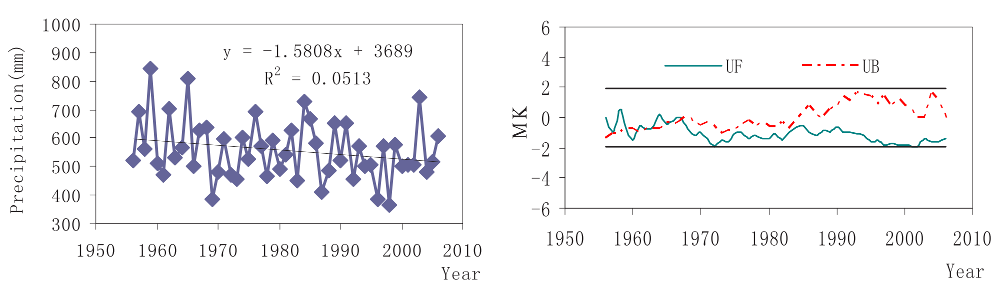


**Fig. 4.** Observed annual precipitation and Mann–Kendall–Sneyers test.

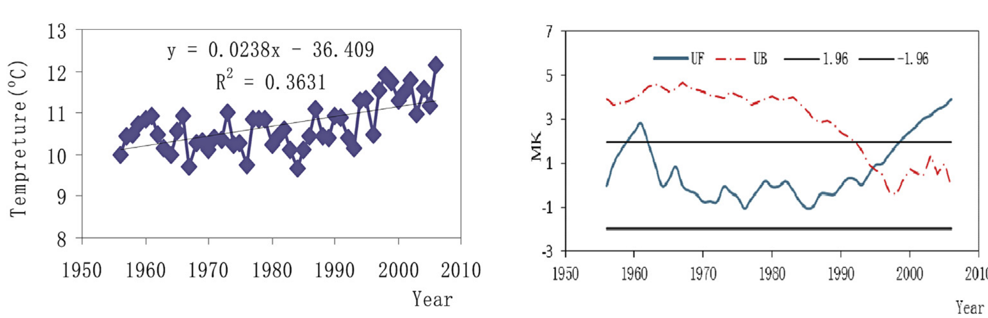


**Fig. 5.** Observed annual temperature and Mann–Kendall–Sneyers test.

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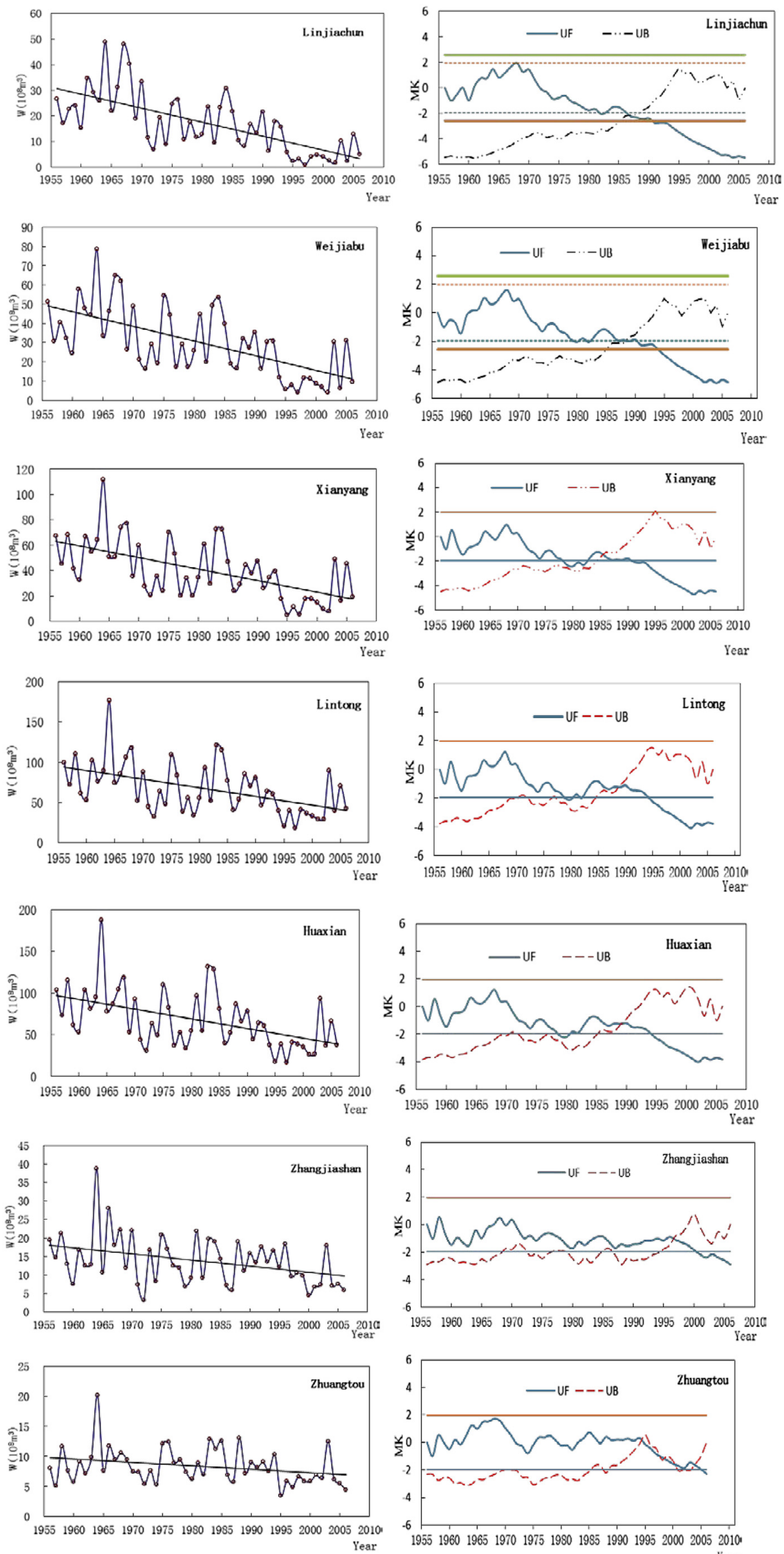


**Fig. 6.** Variation in annual runoff (1956–2006) for the seven hydrological stations in the study area.

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test showed the same increasing trend for annual mean temperature in the WRB from 1956 to 2006 (Fig. 5). There was a statistically significant increasing trend from 1994 to 2006 ($a = 0.05$ level), and the step change point of the annual mean temperature was in 1999. Over the whole period, the MK value was 4.0, which indicates a high amount of warming.

### 4.2. Streamflow trend

Fig. 6 depicts the recorded annual streamflow for six hydrological stations: the Linjiacun, Weijiapu, Xianyang, Lintong, Huaxian, Zhangjiashan and Zhuangtou stations (for 1956–2006). Overall, for the whole available period, the Mann–Kendall–Sneyers test results showed a significant decreasing trend in annual streamflow for all of the seven hydrological stations of the WRB; of these, five were statistically significant at $a = 0.05$ level, and 2 were statistically significant at $a = 0.01$ level. Significant step change points for streamflow at Linjiacun and Weijiapu were not observed and the step change point at Xianyang, Lintong, Huaxian, Zhangjiashan and Zhuangtou stations was ca.1986, 1988, 1990, 1996, and 1995 respectively.

### 4.3. Model calibration and verification

The VIC model was used to simulate streamflow in the WRB at a 0.5°spatial and daily temporal resolution. The model has six parameters that need to be calibrated, three baseflow parameters, Dm, Ws, Ds; the variable soil moisture capacity curve parameter, b; and two parameters that control the thickness of the second and third soil layers, d2 and d3. These parameters are optimized to minimize the objective function defined as the sum of squares of the difference between the modelled and recorded monthly runoffs.

$$OBJ = \sum_{i=1}^{N} \left(Q_{obs,i} - Q_{sim,i}\right)^2 \quad (5)$$

where $Q_{obs}$ and $Q_{sim}$ are the observed and simulated monthly runoffs, respectively, and $N$ is the number of months in the record.

Two criteria are used to assess the model using observed data and model estimates: the Nash and Sutcliffe efficiency criterion (NSE) and the relative Water Balance Error percentage (WBE), which are defined as

$$\text{NSE} = 1 - \frac{\sum_{i=1}^{N} \left(Q_{obs,i} - Q_{sim,i}\right)^2}{\sum_{i=1}^{N} \left(Q_{obs,i} - \overline{Q_{obs}}\right)^2} \quad (6)$$

$$\text{WBE} = \frac{\sum_{i=1}^{N} \left(Q_{sim,i} - Q_{obs,i}\right)}{\sum_{i=1}^{N} Q_{obs,i}} \quad (7)$$

where $\overline{Q_{obs}}$ is the mean monthly recorded streamflow during the calibration period.

NSE expresses the proportion of variance of the recorded flows that can be accounted for by the model. The value of *WEB* should be close to zero for a good simulation of the total volume of the observed runoff series.

To use the VIC model, a baseline period must be selected. In recent years, the double mass curve of runoff and precipitation has been widely used in studies on hydrology, water resources and fluvial geomorphology (Yue et al., 2003). When only the precipitation changes, the double mass curve should become a straight line, and the curve will shift when affected by other factors, such as human activity. Thus, the inflexion point obtained from the double mass curve could reflect the time when runoff change begins to be affected by human activity. The degree of deviation of the curve also reflects the intensity of the effect of the activity. Therefore, the double mass curve of precipitation and runoff can reveal the impact of human activity on runoff changes periodically. Fig. 7 shows the double mass curve of runoff and precipitation at the Huaxian station in the WRB and the two inflexion points for the runoff change (at 1970 and 1990) obtained using the curve. The inflexion points are distinct, and the relationships between the accumulative precipitation and runoff in different intervals separated by the points are significant. In the WRB, the runoff change before 1970 was mainly influenced by precipitation change. Since 1971, human activity has gradually intensified and somewhat influenced the runoff change. We therefore took 1956–1970 as the baseline period for this study. We reconstructed the natural runoff for subsequent years (1971–2006) with no consideration of local human activity effects on the basin (i.e., land use change and artificial water intake).

The observed daily climatic and streamflow data from 1956 to 1967 were used for calibration, and the data from 1968 to 1970 were used for verification of the Huaxian station. Fig. 8 shows simulated and recorded runoff for the calibration and validation periods on a monthly basis, demonstrating that the recorded and simulated data fit well. In addition, statistical analyses indicate that the calibrations were generally satisfactory; the relative Water Balance Error percentage was approximately 2.3%. Furthermore, the Nash and Sutcliffe efficiency for the calibration period (1956–1967) was 0.72, with slight underestimation of the higher peaks. For the validation period (1968–1970), the NSE and WBE were 0.76 and 0.7%, respectively, showing underestimation of runoff particularly for the high peaks.

Overall, the calibration and verification accuracies of the model were acceptable for inter-annual runoff analysis. The application results show that the conceptual daily rainfall runoff model is capable of simulating the monthly runoff series well and has the same efficiency in simulating monthly water balance as other more complicated models.

### 4.4. Runoff reconstruction for the impacted period

After the VIC hydrological model was benchmarked using the hydrometeorological conditions of the baseline period, the

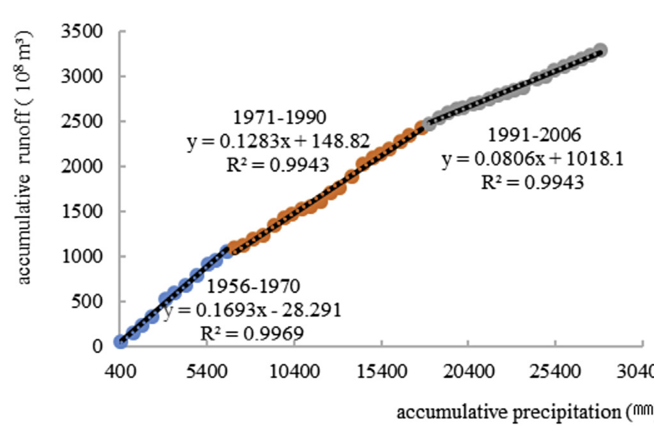


**Fig. 7.** Variation trend of the double mass curve of precipitation and runoff and inflexion points at the Huaxian station.

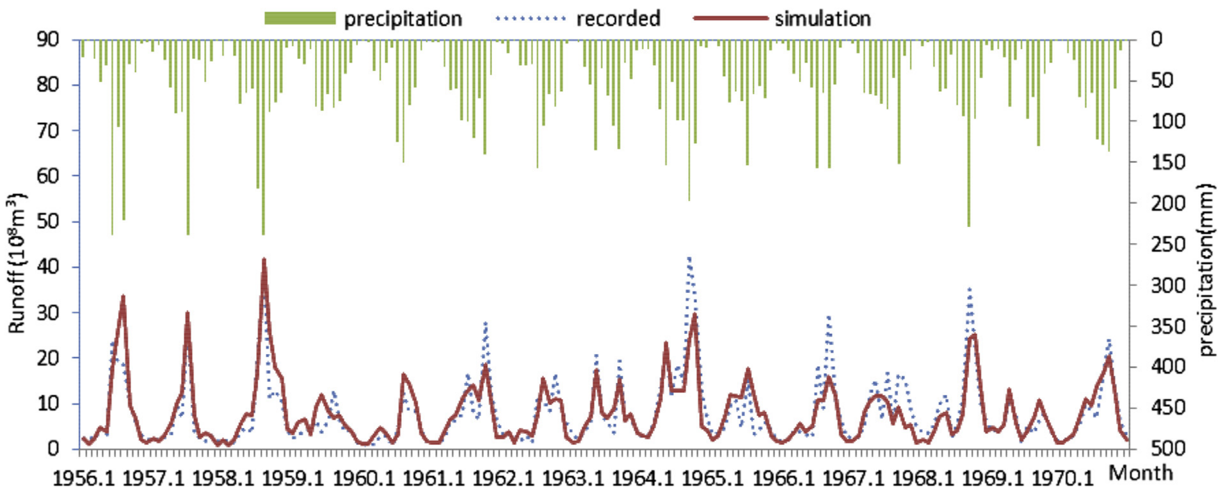


**Fig. 8.** Monthly time series of precipitation, observed runoff and simulated runoff for the period 1956–1970 at the Huaxian station.

calibrated VIC model and meteorological data were used to estimate the natural runoff for the later years, from 1971 to 2006, with no consideration of land use changes or artificial water intake (i.e., no impacts from local human activity) (Fig. 9).

On average, human activity and climate change were found to be responsible for 66% and 34% of the total reduction in runoff, respectively. Human activity is the primary cause of the decreased runoff that has been recently observed in the Weihe River.

**Table 2**
Impacts of climate change and human activities on runoff at Huaxian station in the WRB.

| Periods | Recorded runoff ($10^8$ m$^3$) | Reconstructed runoff ($10^8$ m$^3$) | Total change | | Impact by climate Change | | Impact by human activities | |
|---|---|---|---|---|---|---|---|---|
| | | | ($10^8$ m$^3$) | *PR*(%) | ($10^8$ m$^3$) | *PC*(%) | ($10^8$ m$^3$) | *PH*(%) |
| Baseline | 93.86 | 94.66 | | | | | | |
| 1971–1980 | 55.60 | 79.97 | 38.26 | 40% | 13.89 | 36% | 24.37 | 64% |
| 1981–1990 | 81.55 | 90.43 | 12.31 | 13% | 3.43 | 28% | 7.88 | 72% |
| 1991–2000 | 39.52 | 64.95 | 54.34 | 58% | 28.91 | 53% | 25.43 | 47% |
| 2001–2006 | 47.91 | 89.34 | 45.95 | 49% | 4.52 | 10% | 39.89 | 90% |
| 1971–2006 | 56.15 | 81.17 | 37.71 | 40% | 12.69 | 34% | 19.23 | 66% |

Total change is the value compared with the value in baseline periods.

### 4.5. Quantification of the impacts

Given the recorded runoff and reconstructed natural runoff data (Fig. 8), the impacts of climate change and human activity on runoff during the human-impacted period were analyzed and summarized in Table 2. Four observations can be made from the data shown in Table 2. (1) The average annual runoff for 1971–2006 was less than that of the baseline period, which means the recorded runoff at the Huaxian station in the WRB markedly decreased over the past few decades. The absolute and relative combined impacts of climate change and human activity on runoff were 37.71 $\times$ $10^8$ m$^3$ and 40%, respectively. The most significant impact was 54.34 $\times$ $10^8$ m$^3$ and 58%, appearing in the 1990s. (2) The difference between the reconstructed natural runoff and the runoff of the baseline period represents the runoff reduction due to climate change. Human activity contributes much more to changes in the hydrological series in most years. The percentages in change of runoff due to climate change (*PC*) were 36% and 28% in the 1970s and 1980s, respectively. For the same years, the percentages in change caused by human activity (*PH*) were 64% and 72%, respectively. (3) The relative impact of human activity on runoff has increased. For example, runoff was reduced by 24.37 $\times$ $10^8$ m$^3$ and 39.89 $\times$ $10^8$ m$^3$, and the percentages of runoff changes increased from 64% to 90% from 1971 to 1980 and 2001 to 2006, respectively, due to human activity. (4)

### 4.6. Discussion

Large-scale human activity, including hyper-irrigation and water and soil conservation, is the direct cause for the change of runoff in the WRB. To meet the food requirements of the growing population, a large amount of uncultivated land was converted into irrigation areas in the WRB, especially in the 1970s and 1980s, when irrigation areas were extended outside the basin. According to statistical data from the Ministry of Water Resources, irrigation occupies approximately 9500 km$^2$. Table 3 shows the nine hyper-irrigation areas in the WRB, which are approximately 5924 km$^2$ in Shannxi province. The Baojixia irrigation district is the largest, and the Baojixia diversion project has been in service since 1972. Its annual average water diversion is 0.58 billion m$^3$ with uneven distribution throughout the 12 months. Table 4 shows the monthly water diversion of the Baojixia irrigation district; water diversion in dry seasons is more than that in wet seasons, especially in January, February, March and December because having enough water from February to May is critical to crop growth (Lin and Li, 2010). Hyper-irrigation directly reduces the regional water discharge due to water consumption by irrigation fields. In addition, because rainfall often does not meet crop water demands, approximately 130 reservoirs with a total storage capacity of over 1.67 billion m$^3$, and 3290 pump projects were built to supplement agricultural water supply in the WRB. These projects not only redistribute the

**Table 3**
Hyper-irrigation areas in the Weihe River Basin.

| Irrigation name | Began to irrigation time | Irrigation water source | Irrigation area (km$^2$) | Reservoir number | Pump station number | Length of channel (km) |
|---|---|---|---|---|---|---|
| Baojixia | 1972 | Wei river | 1948 | 4 | 97 | 1109 |
| Jinghuiqu | 1972 | Jing river | 894 | | 19 | 370 |
| Jiaokou | 1963 | Wei river | 798 | | 123 | 343 |
| Taoqupo | 1980 | Ju river | 212 | | 3 | 230 |
| Shitouhe | 1981 | Shitou river | 247 | | 24 | 112.6 |
| Fenfngjiashan | 1974 | Qian river | 909 | 6 | 164 | 690 |
| Yangmaowan | 1978 | Qishui river | 213 | 4 | 751 | 246 |
| Luohuiqu | 1950 | Luo river | 496 | | 11 | 236 |
| Shibaochuan | 1975 | Shibaoschuan | 207 | | 13 | 235 |

**Table 4**
Ratio of water withdrawn to natural flow in the Baojixia diversion works (%).

| Month | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Water withdrawn/ natural flow | 87 | 81 | 74 | 57 | 42 | 49 | 37 | 39 | 35 | 36 | 54 | 88 |

seasonal water discharge within any given year but also adjust inter-annual distribution.

In the study area, soil loss is severe: thus, soil conservation practices (e.g., afforestation, grass-planting, creation of level terraces, and building check dams) have been implemented since 1970. Table 5 and Fig. 10 show that the soil conservation area has expanded with time. These soil conservation practices change local microtopography, intercept precipitation, improve the infiltration rate of water flow, slow down or retain runoff, and, consequently, reduce runoff. After land terracing, the slope of cultivated land becomes very gentle, which greatly enhances rainfall infiltration. According to observations in the field, when daily rainfall is less than 50 mm and uniformly distributed, all the rainfall can infiltrate the soil, and no river flow is generated from the terraced land (Xu, 2011). After planting trees and grass on bare hill slopes, the runoff generation process may change. After several years, when the vegetation cover is sufficient, a considerable proportion of rain can be intercepted by the canopy and evaporate into the atmosphere. Thus, the effective rainfall for runoff generation is reduced. As the mechanisms of different measures for water reduction are different, the runoff reduction per unit area of different measures is also different. Some plot experiments conducted in the study area showed that land terracing can reduce surface runoff by 65% as compared with sloping cultivated land. Table 6 shows the runoff reduction effect of different measures (Xu and Niu, 2000). The impact of human activity on the hydrological cycle in the WRB exceeds that of climate change in all periods except from 1991 to 2000 (Table 2). Therefore, it is very important to effectively and reasonably utilize, manage, and control river flow for local human survival and development.

**Table 5**
Area of soil conservation practices in study area.

| Time | Area of soil conservation practices (km$^2$) | | | | |
|---|---|---|---|---|---|
| | Level terrace | Afforestation | Grass-planting | Check dam | Total |
| 1960 | 172 | 327 | 47 | 6 | 552 |
| 1970 | 974 | 1309 | 193 | 24 | 2500 |
| 1980 | 2918 | 3886 | 446 | 64 | 7314 |
| 1990 | 4758 | 8468 | 2320 | 78 | 15,624 |
| 2000 | 9088 | 14,924 | 3648 | 134 | 27,794 |
| 2006 | 11,779 | 17,157 | 4265 | 143 | 33,344 |

**Table 6**
Soil and water conservation slope measures runoff reduction efficiency coefficient.

| Item | Wet years | Moderate years | Dry years | Average |
|---|---|---|---|---|
| Level terrace | 45% | 70% | 80% | 65% |
| Afforestation | 25% | 30% | 45% | 33% |
| Grass-planting | 10% | 20% | 30% | 20% |

Climate change in the WRB primarily results from changes in precipitation. As shown in Fig. 4, annual precipitation in the basin has generally decreased; the average annual precipitation prior to 1970 was 641 mm, decreasing by 7.95%, 1.4%, 15.6%, and 4.99% in the 1970s, 1980s, 1990s, and 2000s, respectively. From 1991 to 2000, precipitation was reduced 100 mm/y as compared to the baseline period; the relative change is approximately 15.6%. The percentage

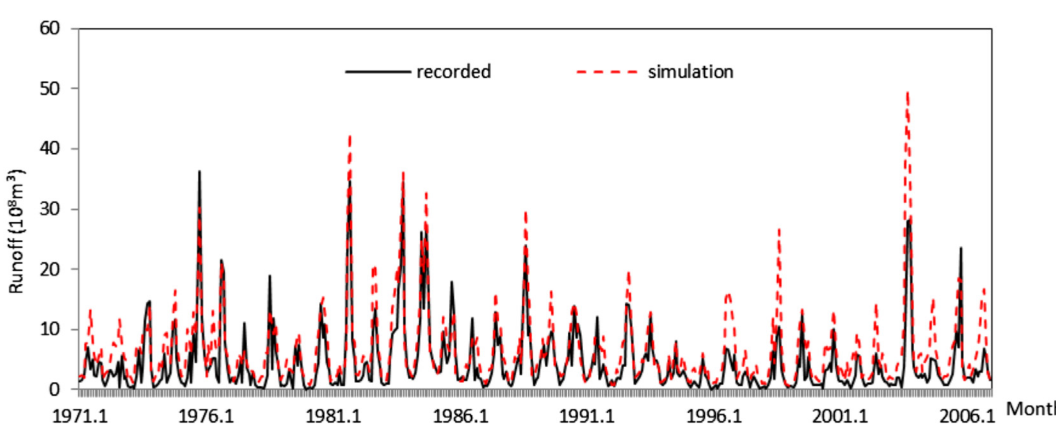


**Fig. 9.** Monthly time series of observed runoff and simulated runoff for the period 1971–2006 at the Huaxian station.

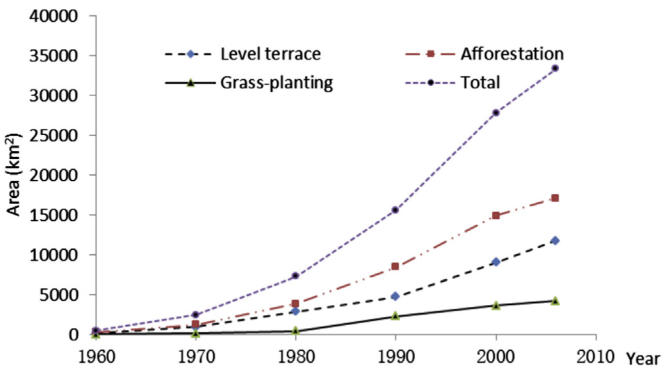


**Fig. 10.** Accumulative area affected by soil conservation practices in the Weihe River Basin from 1960 to 2006.

change in runoff due to climate change (*PC*) was 53% which exceeds that of human activity (Table 2) in the 1990s.

## 5. Conclusions

Previous studies have identified climate changes (mainly precipitation) and local human activity (e.g., river water withdrawals for irrigation, land use changes) as the two primary factors impacting the hydrological cycle. In this study, we estimated the relative contributions each to the hydrological response of the WRB by simulating the natural runoff that occurred during the human-disturbed period (Equations (1)–(4)). The VIC hydrological model was calibrated and verified to a baseline period (1956–1970) as a benchmark (Fig. 8). We simulated the natural runoff for subsequent years (1971–2006) using the VIC model with no consideration of local human activity (Fig. 9). The difference between the reconstructed natural runoff and the runoff of the baseline period represents the runoff reduction due to climate change. Thus, the difference between the reconstructed natural runoff and the observed runoff represents the runoff reduction resulting from human activity ($\Delta R_h$).

The long-term trend and decadal variations of observed precipitation and runoff both show a decreasing trend (Fig. 4). The observed runoff at the Huaxian station from 1956 to 2006, influenced by both climate change and local human activity, decreased 1.22% per year. However, the reconstructed natural runoff (impacted by climate change only) decreased at a rate of 0.14% per year, implying that changes in the natural runoff are controlled by decreasing precipitation and increasing temperatures. Large-scale soil conservation practices (e.g., afforestation, grass-planting, creation of level terraces, and the building of check dams) and large irrigation areas play an important role in the regulation of runoff and water conservation; they may successfully delay or even reduce runoff.

The percentages in change of runoff due to climate change (*PC*) were 36%, 28%, 53% and 10% in the 1970s, 1980s 1990s and 2000s, respectively. The percentages in change of runoff caused by human activity (*PH*) were 64%, 72%, 47%, and 90%, respectively. It can thus be concluded that human activity has greater impacts on basin runoff than do climate change factors.

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