

# Characteristics and causes of changes in annual runoff of the Wuding River in 1956–2009

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**Abstract** The Yellow River is the second largest river in China. Its runoff experienced rapid changes in the past decades. The trend and driving forces of change of the river's runoff has been a hot topic in some academic fields in China in recent years, due to its importance in solving the contradiction between supply and demand of water resources, reasonable exploitation and utilization of water resources and its significance in promoting the social, economic and ecologically sustainable development. The Wuding River is one of the large tributaries in the Middle Yellow River and soil and water conservation measures have been implemented in the tributary much earlier. It can be a good example for investigating the trend and causes of changes of runoff of the Yellow River. In this paper, the variation trend and abrupt change are determined in the time series of annual runoff of the Wuding River recorded at a hydrological station near its outlet during the period from 1956 to 2009 using several time series analysis methods. Secondly, the influences of climate change and human activities are estimated through calculating the amount of runoff reduction due to climate change in different periods. Results show that the annual runoff was continually decreasing, the drought trend was aggravating, and abrupt change in runoff series appeared in 1971 and 1997 as a result of large scale water and soil conservation measure after 1971 and ecosystem restoration program

since 1997. It is also found that human activities were the main influence factor for runoff reduction during the period from 1972 to 2009. The contributions from climate change increased from about 23 to 30 %, and those from human activities decreased from 77 to 70 % from the period of 1972–1996 to the period of 1997–2009. Finally, a formula is built to reveal the relation of runoff with both climate factors and each main kind of human activities.

**Keywords** Middle Yellow River · Wuding River basin · Abrupt changes · Drought trend · Human activities · Soil and water conservation measures

## Introduction

In recent decades, because of the influences of both climate change and human activities, runoff reduced so rapidly that a series of problems emerged in the middle and lower reaches of the Yellow River, such as serious contradiction between supply and demand of water resources and sharply deteriorated natural environment (Xu 2005; Cao et al. 2008; Wang et al. 2008; Liu and Liu 2010). For alleviating the serious environmental problems, the Chinese government brought forward several policies in 1997, which include returning farmland to forest or grass, contracting out rural land to individuals, and protecting natural forests in the Loess Plateau. The Wuding River is a large tributary of the Middle Yellow River and water and soil conservation measures were implemented in the basin as early as the 1950s and further expanded in the 1970s. In addition, the policy of restoration of natural environment was carried out in this basin after 1997. Therefore, clarification of the changing trend of runoff and the impact of climate change and human activities plays an important role in promoting

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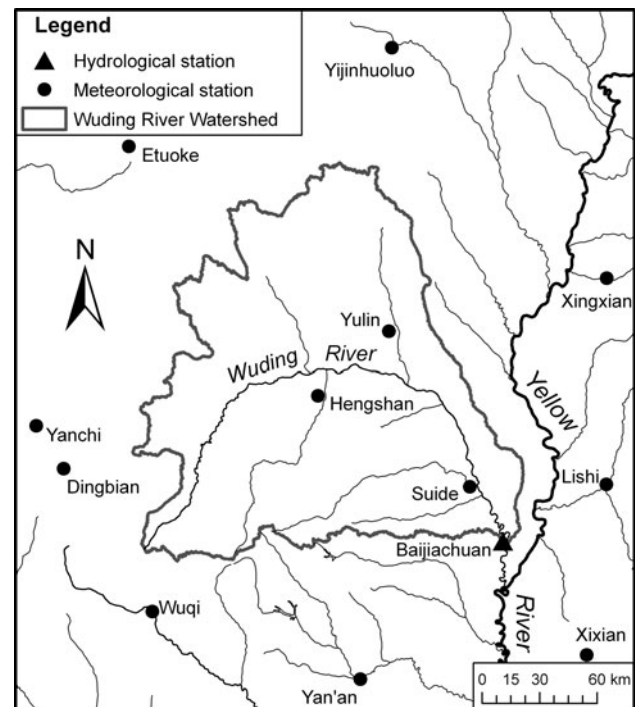
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the sustainable development of the economy, ecology and society in the basin. In addition, it can provide reference for reasonable development and effective utilization of water resources, and help to solve the contradiction between supply and demand. The literature abounds with studies on estimate of the influences on runoff from climate change and human activities (Li et al. 2007; Webber et al. 2008, 2011; Chen et al. 2009; He et al. 2010; Zarghami et al. 2011; Ling et al. 2011). On the one hand, considering the influences of climate change, previous studies in this field in China focused on constructing the correlativity between meteorological factors (usually only precipitation being considered) and runoff by statistical analysis or mechanical model simulations (Zhang et al. 2009; Wang et al. 2006; Liu and Cui 2011; Xu 2011). However, although the drought trend is an important feature of climate change in the northwest China and many related research results had been published about the Middle Yellow River, such as Yu and Lin (1996), and Yang et al. (2003), the influence of drought trend on runoff has rarely been investigated so far. Therefore, to investigate the contribution of climate change on runoff of the Wuding River, the drought index is used as a climate factor instead of other meteorological factors in this paper. On the other hand, in the Wuding River, the main human activities which have influences on runoff are soil and water conservation measures as argued by many studies (Xu 2004; Wang et al. 2006; Ran 2006; Zhang et al. 2010), but different results about the contributions of these measures to runoff change have been produced by different scholars. Hence, based on the previous researches, this essay systematically analyzed the characteristics and the causes of changes in runoff with statistical methods in order to make more reasonable results. The main aspects of investigation in the paper include: (a) the variation trends of the annual runoff, rainfall, temperature and humidity of the Wuding River basin, the drought trend and abrupt change of runoff series; (b) the influence of the drought trend on runoff; (c) the relation of runoff with both the drought index and water and soil conservation measures.

## Study area, data sources and methods

### Outline of study area

The Wuding River is located in the northern Loess Plateau. It is a first order tributary of the Yellow River. The most downstream hydrological station of the river has been set at Baijiachuan, above which the river has a drainage basin area of 29,662 km<sup>2</sup> and a length of 491 km. An average annual precipitation of 491.1 mm fell in the river basin, and a mean annual runoff of  $1.53 \times 10^{10}$  m<sup>3</sup> was recorded at Baijiachuan station. The river is a major sediment source



**Fig. 1** The map of the study region and distribution of hydrological and meteorological stations

of the Yellow River with a mean annual sediment discharge of about  $3 \times 10^9$  tons. The northwest part of its drainage basin is deserts and the rest is covered by thick loess. Figure 1 shows the map of the study region and the locations of hydrological and meteorological stations.

Due to sparse vegetation, thick and highly erodible loess, uneven seasonal distribution of rainfall, relatively high intensity of rainstorms and irrational human activities, soil and water loss in the Wuding River basin is serious. Since the 1950s, water and soil conservation measures have been undertaken in the Wuding River basin. Up to 1996, 96,600 ha of terracing land and 11,710 check dams had been built, 485,000 ha of forests land and 188,400 ha of grass had been planted. The total sediment detaining capacity of these measures was  $2.18 \times 10^9$  m<sup>3</sup>. Besides, there were 74 reservoirs of storage capacity larger than  $1 \times 10^6$  m<sup>3</sup>. The land applied with water and soil conservation measures had an area of 8,364 km<sup>2</sup>, which accounted for 36.4 % of soil erosion area (Wang et al. 2003; Xu and Wang 2010; Ma et al. 2010).

### Data sources and methods

The annual runoff used in this study was obtained from The Yellow River Water Yearbook and The Yellow River Water Resources Bulletin issued by The Yellow River Water Conservancy Commission. The rainfall, temperature and humidity recorded at meteorological stations were

provided by The National Meteorological Information Center, China Meteorological Administration. The original Kriging method in the tools of ArcGIS was used to interpolate and extract the annual rainfall, temperature and humidity of the Wuding River basin. Areas of farmland irrigation and water and soil conservation measures, which include terraces, check dams, forestation, grass sowing, came from the study by Wang and Fan (2002).

Mann–Kendall (Mann 1945; Kendall 1975) test and trend line method were used to examine the changing tendencies of runoff, rainfall, temperature, humidity and drought as well as the significance of these tendencies in past 54 years. Moreover, abrupt change in runoff series was diagnosed by seven methods, which include double mass analysis, sequential cluster (Ding 1986), Pettitt (Pettitt 1979), Yamamoto (Yamamoto et al. 1986), Lee-Heghinian (Lee and Heghinian 1977) optimal information partition (Xia et al. 2001) and Spearman (Lehmann 1975). A multiple regression model was built and used to estimate the impacts of climate change and human activities on runoff. At last, a model was constructed to show the relation of runoff with drought index and each kind of main human activities.

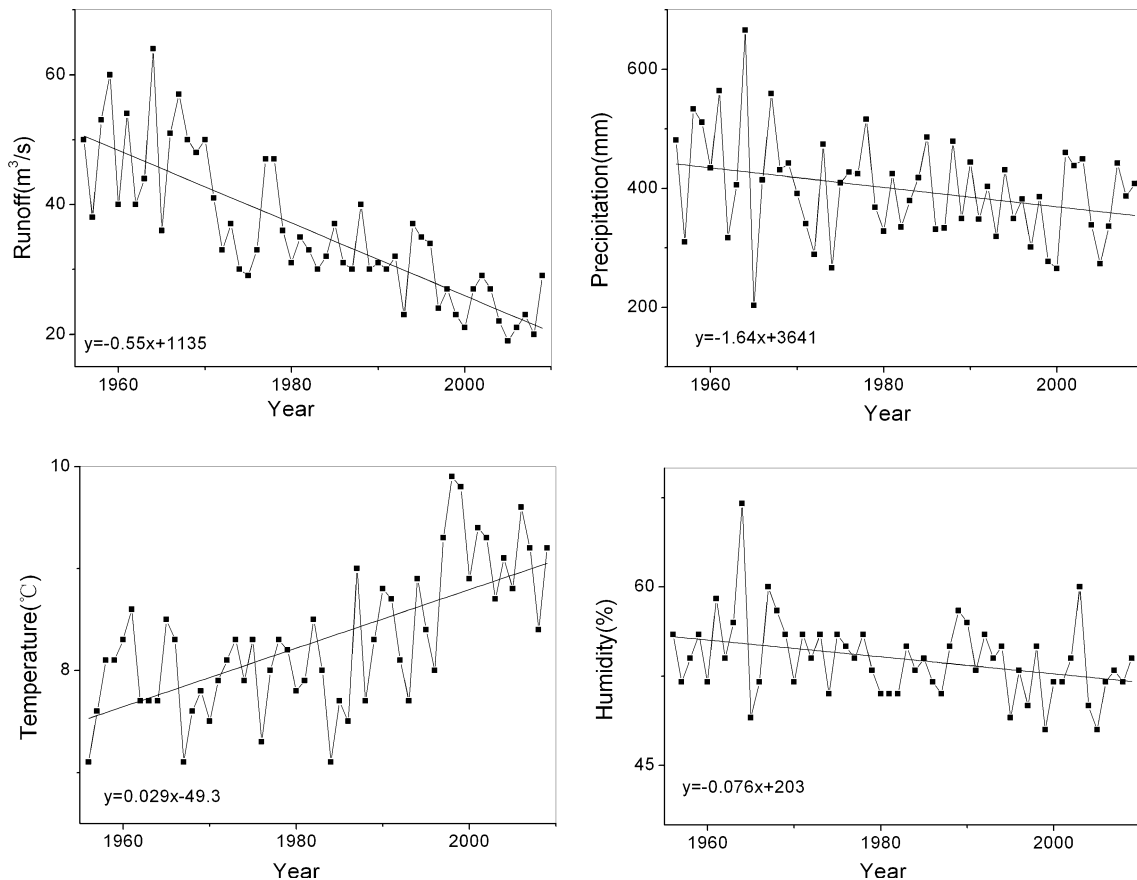
## Results and discussion

### Trend analysis and significance test

#### *Trends of meteorological factors and runoff*

As shown in Fig. 2, runoff, rainfall and humidity showed a downtrend, but temperature showed an uptrend from 1956 to 2009. The trend lines were added to the four variables. Their slopes represented their average change rates in the given periods, showing that runoff, rainfall, humidity reduced by  $0.57 \text{ m}^3/\text{s/a}$ ,  $1.83 \text{ mm/a}$  and  $0.08 \text{ %/a}$ , respectively, and temperature rose by  $0.03^\circ \text{ C/a}$  during the period 1956–2009.

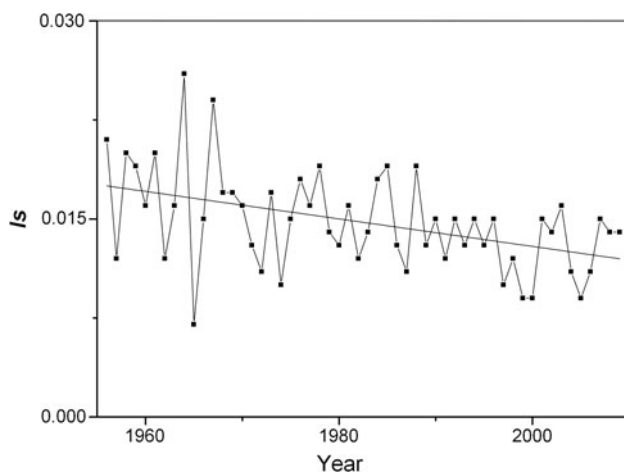
For investigating the phasic changes of the four variables, the 54 years from 1956 to 2009 were divided into six periods and the mean of each variable in each period was calculated (Table 1). The results indicate that the runoff was less than the average of 54 years and declined substantially in the three 10-year periods after 1981. Temperature exceeded the average of 54 years in the two 10-year periods after 1991, and had been risen continuously since 1956. After 1971, rainfall in four 10-year



**Fig. 2** Trend of runoff, precipitation, temperature and humidity during 1956–2009

**Table 1** Changes of runoff, temperature, rainfall, and humidity in six periods

Periods	Runoff (m <sup>3</sup> /s)	Temperature (°C)	Rainfall (mm)	Humidity (%)
1956–1960	48	7.8	454	54
1961–1970	49	7.8	439	56
1971–1980	36	8.0	384	54
1981–1990	33	8.1	398	54
1991–2000	29	8.8	346	52
2001–2009	24	9.1	392	53
Average of 54 years	36	8.3	398	54

**Fig. 3**  $I_s$  trend of Wuding River basin during 1956–2009

periods was less than the average of 54 years. Humidity was less than the average of 54 years in the three ten-year periods after 1981.

#### Trend of drought

Precipitation-temperature standardization index  $I_s$  is used here to show the drought trend. It is the different between standardized rainfall and temperature:

$$I_s = \frac{P - \bar{P}}{\sigma_P} - \frac{T - \bar{T}}{\sigma_T} \quad (1)$$

where  $P$  is the precipitation,  $T$  is the temperature,  $\sigma_p$  is the standard variation of precipitation, and  $\sigma_T$  is the standard variation of temperature. The smaller  $I_s$  is, the more drought of climate is. As a function of both precipitation and temperature, it is better than precipitation only in reflecting climate change. Figure 3 shows that the decreasing trend of  $I_s$  is clear, revealing the aggravation of drought in the Wuding River basin in the past 54 years.

#### Significance test

Mann–Kendall test was used to find the significance of the trend given above. If the test statistic is higher than 1.96 or lower than  $-1.96$  (a significance level of 0.05), the trend is deemed to be significant and vice versa. Moreover, the tendency is positive if the test statistic is over zero, or else it is negative.

The Mann–Kendall test statistic is  $-7.2$  for runoff,  $5.08$  for temperature, and  $-2.54$  for  $I_s$ , suggesting that there are a significant decreasing tendency both in runoff and  $I_s$  and a significant increasing tendency in temperature. The test statistics of rainfall and humidity are  $-1.93$  and  $-1.5$ , respectively, that means that there are no statistically significant trends in these two factors. In sum, the runoff was significantly reduced, and the climate exhibited a significant trend of drought in the Wuding River basin.

#### Abrupt change analysis

The abrupt change in runoff recorded at Baijiachuan hydrological station during 1956–2009 is examined using seven diagnostic methods as follows, and the results are given in Fig. 4.

#### Double mass curve

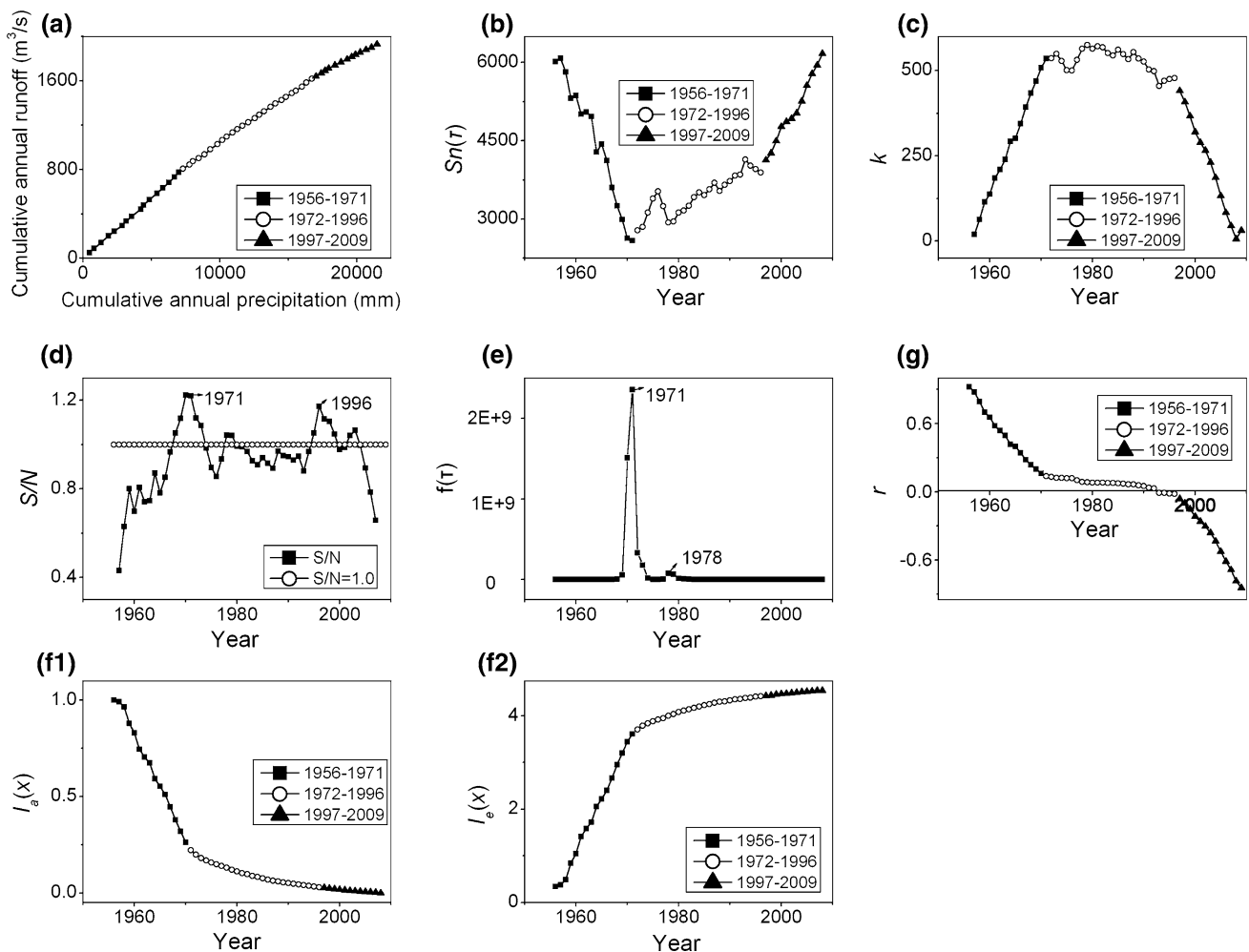
The double mass curve provides a means of detecting breaks in the consistency of runoff, and has been used by many previous studies for identifying the breaks resulting from the effect of human activities.

Figure 4a shows the relation between cumulative precipitation and runoff. Abrupt change can be found in 1971 and 1997. The slope of the relation fell sharply during the period from 1971 to 1996, and further declined during the period from 1997 to 2009. It should keep unchanged throughout all the survey time if rainfall is the only influencing factor to runoff. Thus, the two falls of the slope imply that human activities increased after 1971 and further enhanced after 1997.

#### Sequential cluster

Sequential cluster is based on the orderly classification approach. In essence, it is to estimate the optimal dividing point, which has the smallest sum of squared residuals, expressed as  $S_n(\tau)$ , in the two groups before and after the point.

Figure 4b shows the changes in  $S_n(\tau)$  during the period 1956–2009. The point in 1971 is the lowest point, so that it should be recognized as an abrupt change. Applying the



**Fig. 4** Statistical results of abrupt change. **a** Double mass analysis; **b** Sequential cluster- $S_n(\tau)$ ; **c** Pettitt- $K$ ; **d** Yamamoto- $S/N$ ; **e** Lee-Heghinian- $f(\tau)$ ; **f1** Optimal information partition- $I_a(x)$ ; **f2** Optimal information partition- $I_e(x)$ ; **g** Spearman- $r$

Sequential Cluster method to the series between 1971 and 2009, the minimum  $S_n(\tau)$  occurred in 1997 as shown in Fig. 4b, so that it is another abrupt change. It is clear that the abrupt changes identified by the Sequential Cluster are same as those by the Double Mass Analysis.

*Pettitt*

Through analyzing the changes of average of sequence, Pettitt test constructs the statistic  $U$  before and after the abrupt change. The abrupt change is the point of maximum of  $K$  which is the absolute value of the statistic  $U$ .  $P$  is used to estimate the significance of the change. The point is considered to be an abrupt change at the significance level of 0.05 if  $P \leq 0.5$ .

Figure 4c shows the changes of  $K$  statistic during the period 1956–2009. Obviously, abrupt changes appeared, respectively, in 1971 and 1997 dividing the curve into three sections, e.g., 1956–1971, 1972–1996 and 1997–2009.

These two points are statistically significant dividing points with  $P$  values of  $4.47 \times 10^{-5}$  and  $1.36 \times 10^{-5}$ , respectively.

*Yamamoto*

The Yamamoto formula computes Signal-to-Noise ratio ( $S/N$ ) to determine abrupt change. A ratio of  $>1.0$  indicates a distinct abrupt change in the sequence, and a ratio of  $>2.0$  reveals a mighty abrupt change in the sequence. The  $t$  test is used to estimate the significance. The point is considered to be a significant abrupt change at the significance level of 0.05 if the  $t$  statistic is larger than 2.0.

Figure 4d shows the changes of  $S/N$  during the period 1956–2009. The slope of  $S/N$  curve changed by two times, respectively, in 1971 and 1997, dividing the curve into three sections. The value of  $S/N$  reached its first peak in 1971 and the second peak in 1997. The value of  $S/N$  was much smaller during the period from 1972 to 1996. The

abrupt changes in 1971 and 1997 have a  $t$  statistic of 9 and 6, respectively, which are much higher than 2.0.

### Lee-Heghinian

Lee-Heghinian is based on the theory of Bayes. It is assumed that population distribution is Gaussian distribution and the prior distribution of abrupt change is Uniform distribution. Through calculating posterior distribution  $f(\tau)$  of all possible points in a given period, abrupt change can be identified by the peaks of curve of  $f(\tau)$ .

Figure 4e shows the posterior distribution curve of  $f(\tau)$  during the period 1956–2009. The curve changed dramatically around 1971. Another abrupt change appeared in 1978, but it had a much lower  $f(\tau)$  value than that in 1971, so that it could be ignored. Thus, the abrupt change in 1971 is the only significant one detected by Lee-Heghinian diagnostic method.

### Optimal information partition

This method is based on the theory of gray information and information differences. The information entropy  $I_e(X)$  and the relative measure of information differences  $I_a(x)$  are calculated for every point. A point is considered to be the significant abrupt change when it is a turning point on the curve of  $I_e(x)$  or  $I_a(x)$ .

Figure 4f shows the statistic changes of  $I_e(x)$  and  $I_a(x)$  during the period 1956–2009. Both of curves are divided obviously into three sections by the years 1971 and 1997.

### Spearman

Spearman is an effective method for analyzing the stationarity and testing trend of times series. It calculates the correlation coefficient ( $r$ ) of rank and time and uses the coefficient to judge the trend of a sequence.

The changes of correlation coefficient ( $r$ ) during the period 1956–2009 in Fig. 4g show two abrupt changes, respectively, in 1971 and 1997.

### Causes for the occurrence of abrupt changes

It can be seen that six out of seven diagnostic methods have detected same two abrupt changes at the same time, i.e., 1971 and 1997, in the runoff series recorded at Baijiachuan station during the period from 1956 to 2009. Using Bayes for the runoff series of the same station during the period 1950–2007, Fan and Yang (2010) obtained same findings. Some other studies only found an abrupt change around 1971 in the runoff series at Baijiachuan station in the 1950s–1990s (Yang et al. 2005; Wang et al. 2006). Hence,

the existence of the two abrupt changes in the runoff series recorded at Baijiachuan station during the period from 1956 to 2009 can be regarded as an approved fact.

Since the 1950s, soil and water conservation measures have been undertaken in the Wuding River basin to control soil erosion. Much more investment has been put in soil erosion control since the 1970s. These measures reduced soil losses but also changed the runoff of the river directly or indirectly. Thus, this might be the reason for the runoff of the river changed abruptly in 1971.

In order to promote restoration of the local ecosystems, the program of returning farmland to forests/grass and protecting natural forests was launched in the Loess Plateau region in 1997. This program also has a great impact on soil erosion control and runoff generation. The second abrupt change in 1997 given above should be a reflection of the effects of ecosystems restoration program on the runoff of the Wuding River basin.

### The impact of climate change and human activities on runoff

In general, climate change and human activities are considered the influence factors of runoff. In the case of the Middle Yellow River, human activities which have impacts on runoff of the river mainly refer to soil erosion control practices and water use for irrigation. As mentioned above, soil erosion control practices were carried out on a large scale after 1971, which coincided with the abrupt change being detected by this study. Therefore, in the period before the first abrupt change in runoff series, climate change could be considered the only factor, and this period is termed as the reference period here. After the first abrupt change, runoff was influenced by the combination of climate variation and human activities, so that this period is termed as the measure period. By regression analysis, the runoff is related with meteorological factors for the reference period. Based on the regression relation of the reference period and meteorological data of the measure period, the influence of climate change in the measure period is estimated by the difference between the calculated runoff and actual measured runoff. The amount of variation of annual runoff due to human activities is the difference between the total amount of variation of annual runoff and that due to climate change. They can be expressed as:

$$\begin{aligned}\eta_h &= \Delta W_h / \Delta W \times 100\% \\ &= (W_{hr} - W_{hn}) / (W_{hr} - W_n) \times 100\%\end{aligned}\quad (2)$$

$$\begin{aligned}\eta_c &= \Delta W_c / \Delta W \times 100\% \\ &= (W_{hn} - W_n) / (W_{hr} - W_n) \times 100%\end{aligned}\quad (3)$$

where  $\Delta W$  is the difference of runoff between measured annual runoff in the reference period and in the measure

period;  $\Delta W_h$  is the amount of variation of annual runoff due to human activities;  $\Delta W_c$  is the amount of variation of annual runoff due to climate change;  $W_n$  is the measured annual runoff of the reference period;  $W_{hr}$  is the measured annual runoff of the measure period;  $W_{hn}$  is the natural annual runoff of the measure period calculated using the relation between runoff and meteorological factors for the reference period;  $\eta_h$  and  $\eta_c$  are the percentages of contributions from human activities and climate change, respectively.

The drought index is a good measure of the climate characteristic of the arid and semiarid areas in northwestern China where the Wuding River is located. Hence,  $I_s$  is used to estimate the influence of climate change on runoff. Based on the diagnosis results of abrupt change, the time series of annual runoff is divided into the reference period from 1956 to 1971 and the measure period from 1972 to 2009. The relation between runoff and meteorological factors is usually not linear according to the studies by Fu and Liu (1991), Yu et al. (2008) and Lan et al. (2010), so an exponential regression equation is established by multiple regressions, and  $F$  statistic is used for testing the significance level. The results suggest that  $I_s$  was related with runoff both in the reference period and in the measure period on the significance level of 0.05. The regression equation is:

$$Q_{RP} = 346.7 \times I_{s1}^{0.482} (r_1^2 = 0.747, F = 41, p < 0.05) \quad (4)$$

$$Q_{MP} = 543.3 \times I_{s2}^{0.674} (r_2^2 = 0.428, F = 26, p < 0.05) \quad (5)$$

where  $Q_{RP}$  is the annual runoff of reference period,  $Q_{MP}$  is the annual runoff of measure period. The squared correlation coefficient was 0.75 in the reference period and 0.43 in the measure period. The lower squared correlation coefficient in measure period indicates that the impacts of human activities on runoff in the measure period are larger than those in the reference period.

To estimate the changes of impacts of human activities in the measure period, the time series of annual runoff is further divided into the first measure period (MP1) from 1972 to 1996 and the second measure period (MP2) from 1997 to 2009. Using Formula (1)–(4), the influences of human activities and climate change on runoff in measure periods are quantified and given in Table 2.

Table 2 shows that human activities were the dominant influencing factor in both the two measure periods. The contributions from climate change increased from about 23 % in the first measure period to 30 % in the second measure period and those from human activities decreased from 77 to 70 %. The changes in the contributions of the two kinds of causes may result from the relatively enhancing of climate change comparing with the impacts of human activities. With the aggravation of drought in the

**Table 2** The influences of human activities and climate change on runoff

Period	Mean runoff (m <sup>3</sup> /s)	The total change of runoff (m <sup>3</sup> /s)	Contribution rate of $I_s$ (%)	Contribution rate of human activities (%)
Reference	48	/	/	/
MP1	34	−15	23	77
MP2	24	−24	30	70

second measure period, the amount of its contribution to runoff increased by over one time from −3 m<sup>3</sup>/s in the first measure period to −7 m<sup>3</sup>/s in the second measure period. In contrast, the contribution of human activities increased only by 54 % from −11 to −17 m<sup>3</sup>/s. The relatively low escalation of contribution of human activities in the second measure period result partly from the decrease of retaining water function of part measures built in the first measure period, such as check dams being filled with sediment, as revealed by Xu (2005, 2010).

As mentioned above, some previous studies have reported the impacts of human activities and climate change on runoff of the Wuding River. Xu (2004) found that human activities were the main cause for runoff reduction during the period 1970–1996 in light of the decrease of coefficient of determination of the relation between runoff and precipitation. The study by Zhang et al. (2010) reported that the runoff reduction by human activities accounted for 80.3 % during the period from 1973 to 1996. Wang et al. (2006) argued that it was 52 % for the period from 1973 to 2000. In this study, the effect of human activities and climate change was objectively estimated in two measure periods defined by statically determined abrupt change in runoff series, showing that the role of human activities in runoff reduction was important and was increasing but the impact of climate change was also noticeable and enlarged in recent over ten years.

#### A relation of the runoff with climate change and water and soil conservation measures

In the last section, the human activities are demonstrated to be the main causes for runoff reduction after 1971. It is based on the records of runoff and meteorological data. To predict the future impacts of human activities on runoff, a relation directly associating the runoff with factors representing human activities is needed. This is the purpose of this section.

On the Loess Plateau, soil conservation measures and water use for irrigation are the main human activities, which affect the processes of runoff generation. The soil

conservation control measures primarily include terraces, check dams, forestation, and grass sowing. They alter the processes of runoff generation by increasing infiltration capacity on slopes and intercepting runoff in river channels. Because the areas of all the measures have been increased with time, they are highly correlated with each other and their real contributions to runoff cannot be revealed in the regression analysis. Therefore, a weighted area is used in this paper instead of the area of each soil erosion control measure. So far, many studies about contributions of single measure to runoff decreasing have been done. Hao (1993) found that the contributions on runoff from terraces, forestation and grass sowing were 86.0, 63.5 and 33.7 %, respectively, through analyzing experimental data from the Suide experiment station. Miao et al. (2011) gave a regression relation between the runoff and areas of terraces, forestation and grass sowing, in which the regression coefficients before these three factors are 3.8, 2.5 and 1.3, respectively. According to Zhang et al. (1994), the capacity of runoff interception of terraces, sediment check dams, forests and grass on the Loess Plateau is 700.5, 4,500, 199.5 and 150 m<sup>3</sup> ha<sup>-1</sup>, respectively. Thus, assuming the efficiency of water reduction by terraces to be  $\varepsilon$ , those by check dams, forests and grass will be  $6.4\varepsilon$  ( $4,500/700.5\varepsilon$ ),  $0.28\varepsilon$  ( $199.5/700.5\varepsilon$ ) and  $0.21\varepsilon$  ( $150/700.5\varepsilon$ ), respectively. Withdrawing water for farmland irrigation from the river directly reduces the runoff and its dimension is related with the irrigation area, so the irrigation area is used here as an independent variable.

With the foregoing analysis results, we can relate the runoff with the climate factor and the factors representing soil erosion control measures and irrigation in a model as follow:

$$Q = \alpha \times I_s^\beta + \gamma \times (\varepsilon \times At + 6.4\varepsilon \times Ad + 0.28\varepsilon \times Af + 0.21\varepsilon \times Ag) + \delta \times Ai \quad (6)$$

where  $Q$  is the annual runoff;  $\varepsilon$  is the efficiency of water reduction of terraces;  $At$  is the area of terraces;  $Ad$  is the area of dams;  $Af$  is the area of forestation;  $Ag$  is the area of grass;  $Ai$  is the irrigation area;  $\alpha$ ,  $\beta$ ,  $\gamma$ , and  $\delta$  are coefficients.

The data of soil erosion control measures and irrigation during the period 1956–1996 are available. They are used to determine model parameters' values. By nonlinear regression in SPSS, the relation is:

$$Q = 105.6 \times I_s^{0.46} - 0.00086 \times (At + 6.4 \times Ad + 0.28 \times Af + 0.21 \times Ag) - 0.0046 \times Ai \quad (7)$$

It has a squared correlation coefficient of 0.76. Using Formula (1), this model can also be express as follows:

$$Q = 105.6 \times \left( \frac{P - \bar{P}}{\sigma_P} - \frac{T - \bar{T}}{\sigma_T} \right)^{0.46} - 0.00086 \times (At + 6.4 \times Ad + 0.28 \times Af + 0.21 \times Ag) - 0.0046 \times Ai \quad (8)$$

This model represents the influences of climate change including precipitation and temperature changes and main kinds of human activities on runoff. The power of  $I_s$  is positive, suggesting that the rise of  $I_s$  increases runoff. The power of area of soil erosion control measures and irrigation land are negative, implying that an increase of the areas of measures and irrigation land will result in a decrease of runoff. Therefore, this formula is reasonable according to the mechanisms of impacts of these factors on runoff generation.

With the data of soil erosion control measures and irrigation during the period 1956–1996 and Formula (7), the effects of climate change and each kind of main human activities can be evaluated for the first measure period mentioned in the last section. The results are 22 % of contribution from climate change to the total runoff reduction, the difference between the runoff in the period of 1972–1996 and in the period before 1971, and 78 % from main human activities. The effect of main human activities can be further divided into 11 % by terraces, 19 % by sediment check dams, 13 % by forestation, 5 % by growing grass, and 30 % by irrigation. Clearly, irrigation was the first cause for runoff reduction in all the main human activities, and sediment check dam was the first one in soil erosion control measures during the period 1956–1996.

## Conclusions

It is found that the annual runoff of the Wuding River was reducing significantly and the climate in the drainage basin exhibited a significant trend of aridification during the recent decades. Two abrupt changes, which occurred in 1971 and 1997, respectively, are identified in the annual runoff series by six common diagnostic methods. These two abrupt changes coincide with the commencement of extensive soil erosion control practices in the 1970s and ecosystem restoration program after 1997. Results of the analysis of causes for the changes of runoff suggest that human activities have been the main influence factor for the decrease of runoff of the river since the 1970s and the climate change has also a certain contribution. The runoff and influence factors including rainfall, temperature, soil erosion control measures and farmland irrigation can be well related in a regression equation.



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