

## Quantitative analysis of runoff reduction in the Laohahe basin

Liliang Ren, Xiaofan Liu, Fei Yuan, Jing Xu and Wei Liu

### ABSTRACT

In order to determine the reason for runoff reduction, daily natural runoff series were restored using a conceptual rainfall–runoff model. The period of 1970–1979 was regarded as a base period with little human activity; model parameters for each subcatchment within the Laohahe basin were calibrated for this period. The effects of human activity and climate change on runoff were quantified by comparing the observed runoff and the natural runoff simulated by the hydrological model. The results show that the observed annual mean runoffs in the 1980s and especially in the 2000s are smaller than those of the 1970s. Although runoff reduction in the 1980s and 2000s is mainly caused by climate change, human activity also plays an important role on the runoff reduction. Taking the 2000 as an example, human activity and climate change are responsible for 45.6 and 54.4% of the runoff reduction in Laohahe basin, respectively. The effect of human activity on runoff reduction in the Laohahe basin is increasingly intensive from the 1980s to the 2000s. Human activity in the Dianzi catchment has the most drastic effect within the Laohahe basin.

**Key words** | climate change, human activity, rainfall–runoff model, runoff reduction

**Liliang Ren** (corresponding author)

**Fei Yuan**

State Key Laboratory of Hydrology,  
Water Resources and Hydraulic Engineering,  
College of Hydrology and Water Resources,  
Hohai University,  
No. 1 Xikang Road, Nanjing 210098,  
China  
E-mail: RLL@nhu.edu.cn

**Xiaofan Liu**

Sichuan Communication Surveying & Design  
Institute, No. 35 Taishengbei Road,  
Chengdu 610017,  
China

**Jing Xu**

Department of Hydrosociences,  
Nanjing University,  
No. 22 Hankou Road, Nanjing 210093,  
China

**Wei Liu**

Shandong Hydrology and Water Resources Survey  
Bureau, No. 127 Lishan Road,  
Jinan 250013,  
China

### INTRODUCTION

Surface water resources are essential for agricultural irrigation, industrial production, ecological environment and human existence. With socioeconomic development, the amount of river runoff is to some extent influenced by human activity (Ren *et al.* 2007). In China, runoff reduction has been observed in many river basins, especially in the 20 years since 1990. Wang *et al.* (2008) analyzed the runoff record at the Houdacheng hydrological gauging station which is located in a first-order tributary of the Yellow River from 1958 to 2000. They detected that the runoff in Sanchuanhe River has markedly decreased over the past few decades, and that the annual mean runoff during 1990–2000 was less than half that from 1958–1969. Wang (2007) analyzed the changes of monthly runoff at five main hydrological stations in the upper reaches of the Yangtze River. It was found that the runoff at Gaochang station of the Minjiang River and Beibei

station of the Jialing River had decreased markedly (at the 95% confidence level).

It is well known that the variation of river runoff depends on climatic changes and human activity. The effect of human activity and climatic change on runoff of a river basin has therefore been of interest to hydrologists in recent years. Determining the reasons for runoff change will be extremely useful for planning and management of water resources in watersheds.

In the earlier studies, most investigations of runoff change in a river basin were mainly carried out through trend tests or empirical models (Zhang *et al.* 1998, 2006; Absalon & Matysik 2007). Although these methods can give the tendency for runoff change and the relationship between the hydrological variables and time, they rarely provide details of the precise factors which influence runoff change. Today, hydrological models are being

used to estimate the runoff changes of a river basin. Nützmann & Mey (2007) developed a composite lumped physically based model to determine the reasons for the decreasing runoff in a small lowland watershed of north-eastern Germany. The results showed that the occurrence of hydrological droughts in this area is mainly controlled by baseflow and that the decline of groundwater level has an increasing influence as stream-water leakage could seriously diminish the runoff. Ren *et al.* (2007) assessed the human impact on river runoff in the west Liaohe basin using the conceptual Xin'anjiang model. It was found that human activity caused river runoff to decrease by 1.02, 50.67, 58.06 and 97.2 mm in the 1960s, 1970s, 1980s and 1990s, respectively. Liu *et al.* (2009) used a semi-distributed hydrological model to quantify the effect of land use and land cover changes on evapotranspiration and runoff in the northern part of China. They found that if grassland had changed to forest and cropland in the Laohahe basin, the runoff during the period of 1964–1979 would have decreased by 8.71%.

The purpose of this study is to determine reasons for runoff reduction in the Laohahe basin. The main research work involved: (1) detecting the trend of precipitation, pan evaporation and runoff series of the Laohahe basin by Mann–Kendall trend analysis; (2) quantifying the effect of human activity and climatic change on runoff reduction of the Laohahe basin using a conceptual rainfall–runoff model; and (3) analyzing the spatial and temporal change

of the effect of human activity within the Laohahe basin by comparing observed runoff with natural runoff simulated by the hydrological model.

## STUDY AREA AND DATA

### Description of the study area

The Laohahe basin is located in the semi-arid region of northern China and has a drainage area of 7,720 km<sup>2</sup> with the Taipingzhuang hydrological station (42°12'N, 119°15'E) located at the basin outlet (Figure 1). Elevation within the basin ranges from 444 to 1,836 m above mean sea level, with elevation declining from the southwest towards the northeast. Annual average maximum (minimum) temperature is 14 °C (2 °C) ranging from –4 °C (–16 °C) in January to 29 °C (18 °C) in July. The average annual precipitation is approximately 464 mm, and the spatial and temporal distribution of precipitation is uneven. About 88% of the annual precipitation occurs during the months of May–September. The average annual runoff is about 30.8 mm.

### Data preparation

Data from 14 rain gauges and three hydrological stations from 1970 to 2006 were available for this basin. Taipingzhuang hydrological station is the basin outlet, and Dianzi

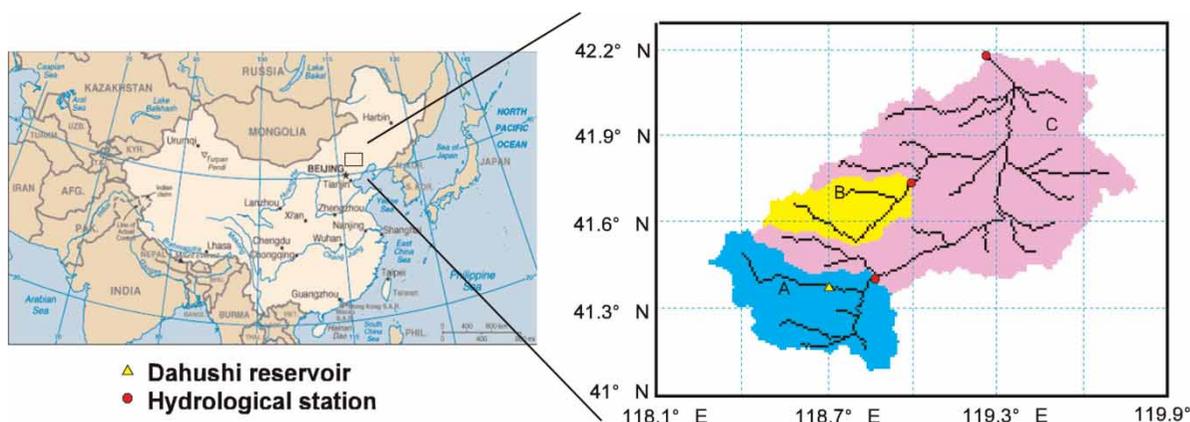


Figure 1 | The location of Laohahe basin.

(41°25'N, 118°50'E) and Xiaochengzi (41°45'N, 119°00'E) hydrological stations are two upstream control stations in the basin with drainage areas of 1,643 and 803 km<sup>2</sup>, respectively. Based on digital elevation data obtained from the Global Land One-km Base Elevation database, the topography of the river network and subcatchments within the basin was determined using the digital elevation drainage network model of [Martz & Garbrecht \(1992\)](#).

The notation  $D$ ,  $P$  and  $R$  in [Figure 2](#) represent observed runoff depth, precipitation and the correlation coefficient between annual precipitation and observed runoff, respectively. As shown in [Figure 2](#), the correlation coefficients between annual precipitation and observed runoff depth in 1970s, 1980s, 1990s and 2000s are 0.709, 0.925, 0.733 and 0.332, respectively. The correlation coefficient decreases gradually from 1970s to 2000s, which means that the linear relation between annual precipitation and runoff decreases. The slope of the regression equation is 0.2345, 0.1592, 0.2804 and 0.0208 in the 1970s, 1980s, 1990s and 2000s, respectively. The slope of the regression equation for the 2000s decreases by 86.94% from the 1980s value, meaning that the same quantity of precipitation produces less runoff in the 2000s than in the 1980s. It is therefore evident that the relation between precipitation and runoff has

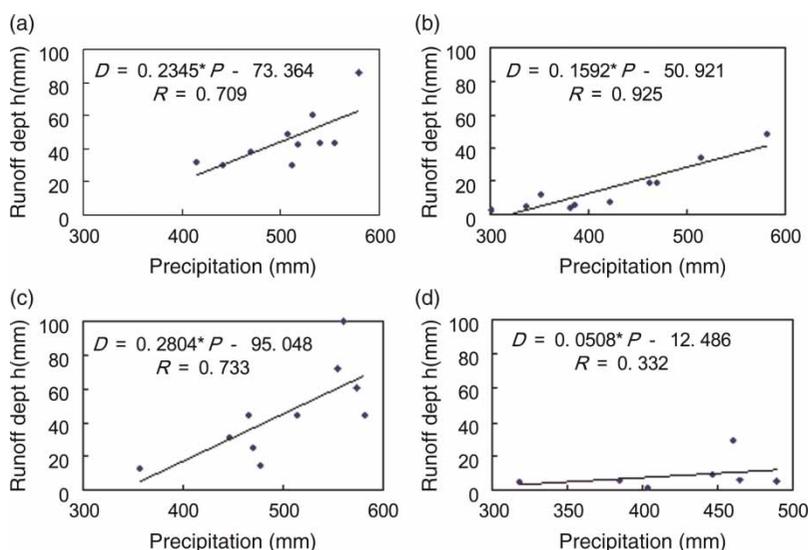
been changed in the Laohahe basin during the 20 year period since 1990.

## METHODOLOGY

### Method of trend significance test

The Mann–Kendall trend test is used in the study to detect trend and test its significance for annual precipitation, pan evaporation and runoff of the Laohahe basin. The Mann–Kendall test can show detailed changing trends of different periods in the analyzed time series and does not require the data to be normally distributed. The rank-based Mann–Kendall method ([Mann 1945](#); [Kendall 1975](#)) is a non-parametric and commonly used method to assess the significance of monotonic trends in hydrometeorological time series. This test has the advantage of not assuming any distribution form for the data and has the similar power as its parametric competitors. It is therefore highly recommended for general use by the World Meteorological Organization ([Zhang et al. 2006](#)).

The assumption (null hypothesis) of the Mann–Kendall trend test is formulated as follows: the sample  $(x_1, x_2, \dots, x_n)$  of the random variable  $X$  does not show the beginnings of



**Figure 2** | Scatter diagram of annual precipitation and observed runoff depth with regression line over the Laohahe Basin from 1970s to 2000s: (a) 1970s; (b) 1980s; (c) 1990s; and (d) 2000s.

a developing trend. The following test is carried out to prove or disprove the assumption. The number of allelomorphs in the sample  $(x_1, x_2, \dots, x_n)$  is calculated as:

$$p = \sum_{i=1}^{n-1} d_i \quad (1)$$

$$d_i = \sum_{j=i+1}^n r_j \quad (i = 1, 2, \dots, n-1) \quad (2)$$

$$r_j = \begin{cases} 1 & \text{if } x_j > x_i \\ 0 & \text{otherwise} \end{cases} \quad (j = i+1, i+2, \dots, n) \quad (3)$$

If  $x_j$  is always larger than  $x_{j-1}$  ( $j = 2, 3, \dots, n$ ) there is an upward trend in the samples and

$$p = (n-1) + (n-2) + \dots + 1 = n(n-1)/2$$

if  $x_j$  is always smaller than  $x_{j-1}$  ( $j = 2, 3, \dots, n$ ) there is a downward trend in the samples and  $p = 0$ . Under the null hypothesis of no trend, the statistic  $P$  is therefore distributed as a normal distribution with the expected value of  $E(p)$  and variance  $\text{Var}(p)$  as follows:

$$E(p) = n(n-1)/4 \quad (4)$$

$$\text{Var}(p) = n(n-1)(2n+5)/72 \quad (5)$$

Under the above assumption, the definition of the statistic index  $U$  is calculated as:

$$U = \frac{\tau}{\sqrt{\text{Var}(\tau)}} \quad (6)$$

$$\tau = \frac{4p}{n(n-1)} - 1 \quad (7)$$

$$E(\tau) = 0 \quad (8)$$

$$\text{Var}(\tau) = \frac{2(2n+5)}{9n(n-1)} \quad (9)$$

The statistic index  $U$  follows the standard normal distribution. In a two-sided test for trend, the null hypothesis is rejected at the significance level of  $\alpha$  if  $|U| > U_{\alpha/2}$ , where  $U_{\alpha/2}$  is the critical value of the standard normal distribution with a probability exceeding  $\alpha/2$ . A positive  $U$ -value denotes a positive trend and a negative  $U$ -value denotes a negative trend. In this paper, the significance level of  $\alpha = 0.05$  is used.

### Hybrid runoff model

In order to investigate the effect of human activity and climatic change on the runoff reduction in the Laohahe basin, the conceptual rainfall-runoff model of Hu (1993) was selected. The advantage of this hybrid runoff model over other rainfall-runoff models is that it combines the saturation excess (Dunne) and infiltration excess (Horton) runoff mechanisms by means of the combination of the spatial distribution curve of soil tension water storage capacity and that of infiltration capacity at the same time. Details of the concept and algorithm of the hybrid runoff model are given by Ren et al. (2008) and Liu et al. (2009).

In this study, pan evaporation data was an input to the hybrid runoff model. In order to use pan evaporation to estimate the potential evapotranspiration, the raw values must be multiplied by an evaporation conversion factor  $k_e$ . Besides  $k_e$ , 13 other parameters used in the model had to be optimized through model calibration against observed hydrological responses in the catchment. Based on the three hydrological stations, the Laohahe basin is divided into three catchments. As shown in Figure 1, part A is the Dianzi catchment with the Dianzi station at the catchment outlet and part B is the Xiaochengzi catchment with the Xiaochengzi station at the catchment outlet. Part C is the interzone catchment between Dianzi, Xiaochengzi and Taipingzhuang stations, with Taipingzhuang station at the catchment outlet. The drainage areas of the three catchments are 1,643, 803 and 5,274 km<sup>2</sup>, respectively. Each catchment is divided into several subcatchments with regard to area and terrain by the digital elevation drainage network model. The hybrid runoff model is applied to runoff calculation over each subcatchment, and sub-

sequently flow routing from the subcatchment outlet to the catchment outlet is achieved by using the Muskingum method to obtain the total catchment runoff. Parameters of the hybrid runoff model in each catchment were calibrated using daily runoff data for the corresponding hydrological station at the catchment outlet. It is necessary to point out that the observed runoff data of Dianzi and Xiaochengzi stations were used as the upstream incoming water to calibrate the model parameters for the interzone catchment C.

Assuming the Laohahe basin experienced little human disturbance in the 1970s, the observed hydrological data from 1970 to 1979 were selected for model calibration; the calibrated model parameters could therefore represent the hydrological characteristics of a natural basin. Model calibration is performed using the SCE-UA (Shuffled Complex Evolution, University of Arizona) optimization algorithm of Duan *et al.* (1992). The objective function used in this study is calculated as:

$$\text{Function} = 0.5 \times \frac{\sum_{i=1}^N (Q_{\text{obs}_i} - Q_{\text{sim}_i})^2}{\sum_{i=1}^N (Q_{\text{obs}_i} - \overline{Q_{\text{obs}_i}})^2} + 0.5 \times \left| \frac{\sum_{i=1}^N Q_{\text{sim}_i} - \sum_{i=1}^N Q_{\text{obs}_i}}{\sum_{i=1}^N Q_{\text{obs}_i}} \right| \quad (10)$$

where  $Q_{\text{obs}_i}$  is observed runoff at time-step  $i$ ,  $Q_{\text{sim}_i}$  is the simulated runoff at time-step  $i$ ,  $\overline{Q_{\text{obs}_i}}$  is the mean of the observed values and  $N$  is the number of data points.

The calibrated model is applied to runoff simulation in subsequent periods; the simulated runoff series represents the impact of climatic variation on runoff under the same situation of land surface characteristics as for the calibration period. Consequently, the effect of human activity on river runoff can be analyzed and discussed by comparing the simulated runoff with observed runoff.

## RESULTS AND DISCUSSION

### Hydrological series trend analysis

Annual precipitation, pan evaporation and runoff of Dianzi, Xiaochengzi and Taipingzhuang stations were analyzed using the Mann–Kendall trend analysis. The statistic  $U$ -values and their  $p$ -values were obtained. The  $p$ -value is the probability of rejecting the null hypothesis that there is no trend in the series. As shown in Table 1,  $U$ -values of annual precipitation for the three stations are all positive, whereas their  $p$ -values are larger than 0.05. This finding means that there is a slightly increasing trend in the annual precipitation series, but the increasing trend does not pass the significance test with the significant level of  $\alpha = 0.5$ . With regard to annual pan evaporation, the  $U$ -values for the three stations are all negative and their  $p$ -values are smaller than 0.05. There is therefore a remarkable decreasing trend in the series of annual pan evaporation in the Laohahe basin. The  $U$ -values of annual runoff for the three stations are all negative, and their  $p$ -values are smaller than 0.05 except Xiaochengzi station. There is therefore a remarkable decreasing trend in the series of annual runoff at the outlet of Laohahe basin. It is well known that evaporation plus runoff is equal to precipitation in the long-term water balance equation. However, runoff change in the Laohahe basin is contrary to that under the condition of invariable precipitation and decreasing pan evaporation. This situation implies that the observed runoff in the Laohahe basin has been disturbed by human activity.

### Hybrid runoff model calibration

The results of model calibration for the three catchments during the period 1970–1979 are shown in Table 2.

**Table 1** | Trend analysis of annual precipitation, pan evaporation and runoff

Station	Precipitation		Pan evaporation		Runoff	
	$U$ -value	$p$ -value	$U$ -value	$p$ -value	$U$ -value	$p$ -value
Dianzi	0.379	0.704	−5.711	0.000	−1.972	0.049
Xiaochengzi	1.471	0.141	−4.790	0.000	−1.827	0.068
Taipingzhuang	0.509	0.611	−4.237	0.000	−2.889	0.004

**Table 2** | Calibrated parameter values for the daily runoff simulation

Parameters	Descriptions	Catchment		
		A	B	C
WUM (mm)	Areal mean tension water capacity of upper soil layer	10.27	10.24	18.76
WLM (mm)	Areal mean tension water capacity of lower soil layer	82.61	73.16	83.14
WDM (mm)	Areal mean tension water capacity of deeper soil layer	30.20	70.00	61.95
$k_c$	Ratio of potential evapotranspiration to pan evaporation	0.999	0.952	1.211
$C$	Coefficient of evapotranspiration from deeper soil layer	0.090	0.090	0.129
$B$	Exponential value of the tension water storage capacity curve	0.350	0.161	0.178
$B_X$	Exponential of infiltration capacity curve	0.899	0.362	0.900
$f_0$ (mm h <sup>-1</sup> )	Maximum infiltration rate	8.74	7.43	17.00
$f_c$ (mm h <sup>-1</sup> )	Static infiltration rate	2.96	3.03	2.27
$K$	Decay coefficient with time	0.774	0.792	0.697
$k_g$	Recession constant of groundwater storage	0.873	0.870	0.945
Imp	Factor of impervious area	0.020	0.016	0.017
$K_c$ (h)	Ratio of storage to discharge within the stream segment	22	22	22
$X_c$	Proportional coefficient of discharge at upstream/downstream	0.203	0.165	0.256

The calibrated parameters for the three catchments are all within reasonable ranges and demonstrate some differences among catchments. In this study, the objective function of the optimization algorithm was composed by the difference between 1 and the Nash–Sutcliffe efficiency (DC) and the absolute value of runoff relative error (Bias) for the 10 years from 1970 to 1979. Thus, the annual mean Nash–Sutcliffe efficiency and annual mean runoff relative error during 1970–1979 have achieved the global

optimization. As shown in the last line of Table 3, the annual mean Nash–Sutcliffe efficiency is above 0.6 and the annual mean runoff relative error is less than 0.05% for the three catchments in the Laohahe basin.

Although model performance of the Xiaochengzi catchment in some years (e.g. 1978) is not good, the long-term water balance is the key point for this study. The annual mean runoff depth in each decade was used to analyze the runoff reduction in the Laohahe basin, which reduces the

**Table 3** | Model performance for 1970–1979 (DC is Nash–Sutcliffe efficiency; Bias is relative error;  $R_{obs}$  is observed runoff;  $R_{sim}$  is simulated runoff)

Period	Dianzi catchment				Xiaochengzi catchment				Interzone catchment			
	$R_{obs}$ (mm)	$R_{sim}$ (mm)	DC (-)	Bias (%)	$R_{obs}$ (mm)	$R_{sim}$ (mm)	DC (-)	Bias (%)	$R_{obs}$ (mm)	$R_{sim}$ (mm)	DC (-)	Bias (%)
1970	82.0	65.7	0.667	-19.8	35.8	43.4	0.526	21.0	38.3	40.0	0.775	4.4
1971	76.5	68.2	0.818	-10.9	27.7	19.3	0.616	-30.1	31.9	30.3	0.740	-5.2
1972	51.5	65.4	0.604	27.1	50.2	53.5	0.531	6.6	30.5	33.9	0.750	11.2
1973	118.9	112.6	0.862	-5.3	53.6	65.2	0.194	21.6	42.6	43.8	0.815	2.6
1974	105.5	103.6	0.761	-1.8	149.3	146.1	0.776	-2.1	59.8	57.6	0.906	-3.6
1975	121.3	124.9	0.804	3.0	64.2	54.3	0.537	-15.5	48.6	48.6	0.800	-0.1
1976	47.6	42.1	0.578	-11.5	29.6	19.7	0.572	-33.3	30.3	32.1	0.835	6.2
1977	98.9	84.6	0.809	-14.5	45.5	54.7	0.299	20.2	43.1	40.1	0.886	-7.2
1978	146.2	163.4	0.876	11.8	37.5	46.7	-0.316	24.4	43.4	47.5	0.868	9.5
1979	168.7	186.4	0.908	10.5	117.5	121.9	0.671	3.8	86.1	80.7	0.903	-6.2
1970–1979	101.7	101.7	0.828	0.0	61.1	62.5	0.673	0.0	45.5	45.5	0.852	0.0

effect of modelling uncertainty in each year. Possible reasons for the dissatisfactory model performance in the Xiaochengzi catchment are analyzed. Xiaochengzi catchment is located in the headstream of Laohahe catchment where the spatial distribution of elevation is very uneven; the inverse distance square precipitation interpolation method used in this study does not consider the effect of elevation on precipitation. The input data error could lead to an uncertainty in model results. In addition, the area of Xiaochengzi catchment is only 803 km<sup>2</sup>, and the amount of runoff is relatively small. The runoff absolute error is less than 10 mm, though the runoff relative error is larger than 30% in some years.

Taking the year 1979 as an example, Figure 3 shows the comparison between the observed and simulated runoff at Dianzi, Xiaochengzi and Taipingzhuang stations.

### Effects of human activity and climate change on runoff

Observed runoff series in the 1970s is regarded as the reference runoff in this study, thus decadal runoff change can be

obtained by comparing observed annual mean runoff in the 1980s, 1990s, and 2000s with that in the 1970s. As the model parameters calibrated using the 1970–1979 hydrological data might be regarded as the representation of hydrological characteristics of a less human-disturbed river basin, those parameters are used to perform hydrological simulations from 1970 to 2006. The simulated runoff series can be assumed to be the hydrological responses under a natural river system with less human disturbance. The effect of human activity on the runoff can therefore be quantified by comparing the simulated runoff time series with the observed runoff from 1980s to 2000s.

The effect of climate change on the runoff is obtained by subtracting the effect of human activity on the runoff from the runoff change. Table 4 shows the decadal mean values of hydrological components from the 1970s to the 2000s within three catchments of the Laohahe basin. The variables listed in Table 4 are defined as follows:  $P$  is annual mean precipitation (mm);  $E_{\text{pan}}$  is annual mean pan evaporation (mm);  $R_{\text{obs}}$  is observed annual mean runoff depth (mm);  $R_{\text{sim}}$  is simulated annual mean runoff depth (mm);  $\Delta R$  is

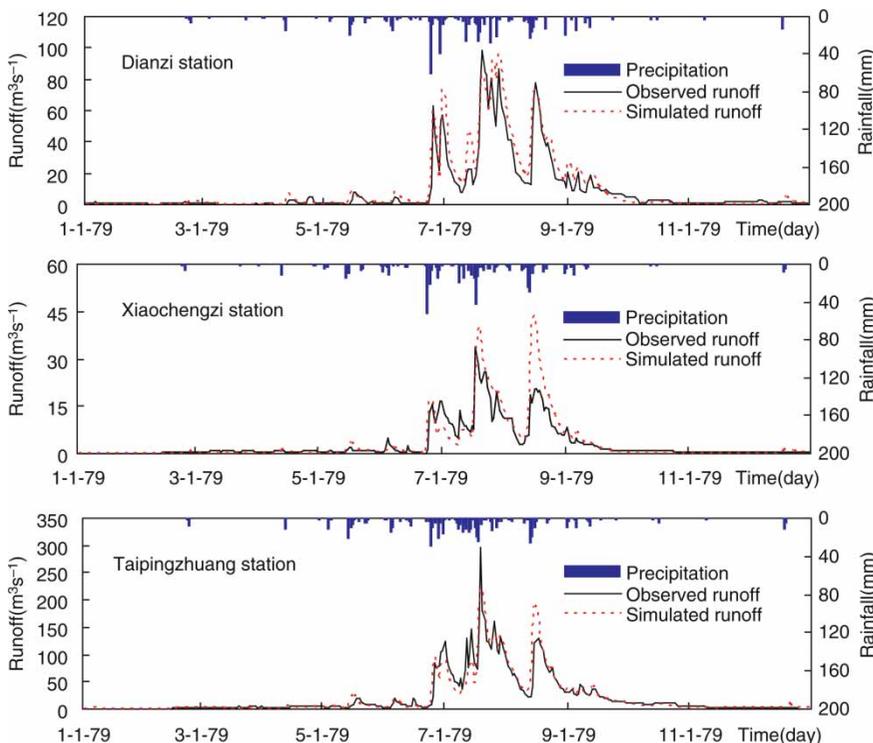


Figure 3 | Comparison of the observed and simulated runoff at Dianzi, Xiaochengzi and Taipingzhuang stations in 1979.

**Table 4** | Decadal mean values of hydrological components (mm)

Catchment	Decade	<i>P</i>	<i>E<sub>pan</sub></i>	<i>R<sub>obs</sub></i>	<i>R<sub>sim</sub></i>	$\Delta R$	HA	CC
Dianzi catchment	1970s	555.46	1,591.2	101.7	101.69			
	1980s	468.99	1,322.9	36.88	80.77	-64.82	-43.89	-20.93
	1990s	540.94	1,106.1	89.00	165.19	-12.70	-76.19	63.49
	2000s	479.74	1,235.4	30.42	81.25	-71.28	-50.83	-20.45
Xiaochengzi catchment	1970s	503.91	1,722.3	65.30	65.29			
	1980s	411.28	1,495.5	26.90	35.56	-38.40	-8.66	-29.74
	1990s	521.09	1,284.5	65.37	117.93	0.07	-52.56	52.63
	2000s	431.55	1,564.3	19.82	40.37	-45.48	-20.55	-24.93
Interzone catchment	1970s	454.53	1,773.0	45.47	45.46			
	1980s	378.73	1,639.8	16.01	23.19	-43.12	-10.51	-32.61
	1990s	470.64	1,318.0	45.12	54.94	-0.51	-14.37	13.86
	2000s	399.15	1,498.7	9.06	21.79	-53.30	-18.63	-34.66

the difference between observed annual mean runoff depth and reference runoff (mm); HA is the effect of human activity on runoff (mm); and CC is the effect of climate change on runoff (mm).

The observed runoff data of Dianzi station and Xiaochengzi station were used as the upstream incoming water when the hybrid model was applied in the interzone catchment C. The effect of human activity on runoff in the interzone catchment is therefore represented by the difference between simulated and observed runoff at Taipingzhuang station. However, the drainage area of Taipingzhuang station is 7,720 km<sup>2</sup> which is different from the drainage area of the interzone catchment of 5,274 km<sup>2</sup>.  $\Delta R$ , HA and CC in the interzone catchment were therefore calculated as:

$$\Delta R = \frac{7720}{5274}(R_{\text{obs}} - R_{\text{ref}}) \quad (11)$$

$$\text{HA} = \frac{7720}{5274}(R_{\text{sim}} - R_{\text{obs}}) \quad (12)$$

$$\text{CC} = \Delta R - \text{HA} \quad (13)$$

where  $R_{\text{ref}}$  is the reference runoff in the 1970s.

As shown in Table 4, the annual mean precipitation in the 1970s is almost equivalent to that of the 1990s, and the two periods are regarded as relatively humid periods in

the Laohahe basin. Similarly, the annual mean precipitations in the 1980s and 2000s are also equivalent, and the two periods are regarded as relatively dry periods in the Laohahe basin. Comparing the observed annual mean runoff in the 1970s and 1990s, the observed annual mean runoff in 1990s is almost equivalent to that of the 1970s, except that Dianzi station demonstrates a small reduction. However, observed annual mean runoffs of the three hydrological stations in the 2000s are all smaller than those in 1980s. Thus runoff reduction in the Laohahe basin is drastic in the 2000s. The role that human activity and climate change play on runoff is different among the three catchments in the Laohahe basin. Climate change is the dominant cause of the runoff change in the Xiaochengzi catchment and interzone catchment, while human activity is the dominant cause of runoff change in the Dianzi catchment.

The effects of human activity and climate change on runoff in the Laohahe basin are calculated by area-weighted averages of that in the three catchments. As shown in Table 5 for the Laohahe basin, although runoff reduction in the 1980s and 2000s is mainly caused by climate change (precipitation reduction and air temperature increment), human activity also plays an important role on runoff reduction. Taking the 2000s for example, human activity and climate change are responsible for 45.6 and 54.4% of the runoff reduction in Laohahe basin, respectively. Overall, the effect of human activity on runoff

**Table 5** | Effects of human activity and climate change on runoff within Laohahe basin (mm)

Decade	Dianzi catchment		Xiaochengzi catchment		Interzone catchment		Laohahe basin	
	HA	CC	HA	CC	HA	CC	HA	CC
1980s	-43.89	-20.93	-8.66	-29.74	-10.51	-32.61	-17.42	-29.83
1990s	-76.19	63.49	-52.56	52.63	-14.37	13.86	-31.50	28.46
2000s	-50.83	-20.45	-20.55	-24.93	-18.63	-34.66	-25.69	-30.63

reduction in the Laohahe basin increased from the 1980s to the 2000s, and the most drastic effect of human activity occurred in the 1990s due to an abundance of water resources.

Comparing the effect of human activity among the three catchments within the Laohahe basin, the value of HA in the Dianzi catchment is the largest from the 1980s to the 2000s. According to the field investigation carried out by this research group in August 2008, a reservoir by the name of Dahushi (41°23'N, 118°41'E) was built in the Dianzi catchment in 1980. Agricultural irrigation is the main function of Dahushi reservoir, as well as flood protection, electric power generation, fish culture and tourism. The existence of Dahushi reservoir offers strong supporting evidence for the effect of human activity on runoff in the Dianzi catchment.

## CONCLUSIONS

The results from applying the Mann–Kendall trend analysis indicate that there is an obvious decreasing trend in the observed annual runoff and pan evaporation series, while there is no remarkable trend towards a decrease in the annual precipitation series. The runoff change in the Laohahe basin is contrary to the conditions of invariable precipitation and decreasing pan evaporation. The purpose of this study was to determine the reason for the observed runoff reduction in the Laohahe basin. Based on three hydrological stations, the Laohahe basin was divided into three catchments. The observed hydrological data from 1970 to 1979 were selected for model calibration, and the calibrated model was applied to simulate the runoff from 1970 to 2006.

There is an obvious decreasing trend in the observed annual runoff, especially in the 2000s. Observed annual

mean runoffs for three hydrological stations in 2000s are all smaller than those in 1980s, though the annual mean precipitation in 2000s is almost equivalent to that of the 1980s. The roles that human activity and climate change play on runoff are different among the three catchments in the Laohahe basin. Climate change is the dominant cause of the runoff change in the Xiaochengzi catchment and interzone catchment, while human activity is the dominant cause of runoff change in the Dianzi catchment. Although runoff reduction in the 1980s and 2000s is mainly caused by climate change (precipitation reduction and air temperature increment), human activity also plays an important role on the runoff reduction. Considering the 2000s, human activity and climate change are responsible for 45.6 and 54.4% of the runoff reduction in Laohahe basin, respectively. The effect of human activity on runoff reduction in the Laohahe basin increased from the 1980s to the 2000s, and the most drastic effect of human activity arose in 1990s due to an abundance of water resources. The effect of human activity on runoff in the Dianzi catchment is the most drastic within the Laohahe basin, due to the Dahushi reservoir which was built in this catchment.

## ACKNOWLEDGEMENTS

This study was supported by the National Key Basic Research Program of China under Project No. 2006CB400502. This research is the result of the 111 Project under Grant B08048, Ministry of Education and State Administration of Foreign Experts Affairs, P. R. China. This work was also supported by the Program for Changjiang Scholars and Innovative Research Team in University under Grant No. IRT0717, Ministry of Education, China and the Grand Sci-Tech Research Project of Ministry of Education under Grant No. 308012.

## REFERENCES

- Absalon, D. & Matysik, M. 2007 [Changes in water quality and runoff in the Upper Oder River Basin](#). *Geomorphology* **92**, 106–118.
- Duan, Q., Sorooshian, S. & Gupta, V. 1992 [Effective and efficient global optimization for conceptual rain-runoff models](#). *Water Resour. Res.* **28** (4), 1015–1031.
- Hu, C. 1993 [Computational method of runoff generation in semi-humid and semi-arid regions](#). In *Proceedings of the Symposium on Hydrological Information and Forecasting*, China Water Power Press, Beijing, China, 57–62 (in Chinese).
- Kendall, M. G. 1975 *Rank Correlation Methods*. Griffin, London, UK.
- Liu, X., Ren, L., Yuan, F., Singh, V. P., Fang, X., Yu, Z. & Zhang, W. 2009 [Quantifying the effect of land use and land cover changes on green water and blue water in northern part of China](#). *Hydrol. Earth Syst. Sci.* **13**, 735–747.
- Mann, H. B. 1945 [Nonparametric tests against trend](#). *Econometrica* **13**, 245–259.
- Martz, W. & Garbrecht, J. 1992 [Numerical definition of drainage network and subcatchment areas from digital elevation models](#). *Comput. Geosci.* **18** (6), 747–761.
- Nützmann, G. & Mey, S. 2007 [Model-based estimation of runoff changes in a small lowland watershed of north-eastern Germany](#). *J. Hydrol.* **334**, 467–476.
- Ren, L., Nghi, V. V., Yuan, F., Li, C. & Wang, J. 2007 [Quantitative analysis of human impact on river runoff in west Liaohé basin through the conceptual Xin'anjiang model](#). In *Proceedings of Symposium HS3006 at IUGG2007*, IAHS Publication 315, Perugia, pp. 295–302.
- Ren, L., Zhang, W., Li, C., Yuan, F., Yu, Z., Wang, J. & Xu, J. 2008 [Comparison of runoff parameterization schemes with spatial heterogeneity across different temporal scales in semihumid and semiarid regions](#). *J. Hydrologic Eng.* **13** (5), 400–409.
- Wang, M. 2007 [Runoff changes in the upper reaches of the Yangtze River](#). *Research of Soil and Water Conservation* **14** (5), 115–117 (in Chinese).
- Wang, G., Zhang, J., He, R., Jiang, N. & Jing, X. 2008 [Runoff reduction due to environmental changes in the Sanchuanhe river basin](#). *Int. J. Sediment Res.* **23**, 174–180.
- Zhang, S., Li, Z. & Zhao, W. 1998 *Causes and Tendency of Runoff and Sediment Variation in Rich Coarse Silt Area of the Middle Yellow River*. Yellow River Press, Zhenzhou (in Chinese).
- Zhang, Q., Xu, C., Becker, S. & Jiang, T. 2006 [Sediment and runoff changes in the Yangtze River basin during past 50 years](#). *J. Hydrol.* **331**, 511–523.

First received 18 October 2009; accepted in revised form 14 July 2010. Available online December 2011