Analyzing the effects of climate variability and human activities on runoff from the Laohahe basin in northern China

Shanhu Jiang, Liliang Ren, Bin Yong, Congbin Fu and Xiaoli Yang

ABSTRACT

The runoff from the Laohahe basin in northern China has been greatly influenced by climate variability and human activities, and it is very important to quantitatively analyze these effects. Three methods, the Mann–Kendall test, ordered clustering and double cumulative curve were used to detect the trend and change points in annual precipitation and runoff for the period from 1964 to 2008, and the runoff series were divided into a 'natural period' (1964–1979) and a 'human-induced period' (1980–2008). Then the three-layer Variable Infiltration Capacity (VIC-3L) model was used to quantitatively evaluate the effects of climate variability and human activities on runoff. The results show that compared with the 'natural period', the annual precipitation varied by −10, 10 and −10% during the periods of 1980–1989, 1990–1999 and 2000–2008, respectively, while the corresponding yearly runoff changed by −57, 17 and −72%, respectively. It was found that the range of yearly runoff percentage change is much larger than the range of annual precipitation variation. Additionally, the computing effects of human activities on runoff decreasing are more evident during the two drier periods of 1980–1989 and 2000–2008 with the contribution of 70 and 78%, respectively, while that of the wetter period of 1990–1999 is only 21%. It is suggested that within the Laohahe basin human activities are the main reason that runoff decreased during the two drier periods of 1980–1989 and 2000–2008, while the increasing of the runoff during the wetter period of 1990–1999 is mainly attributed to the climate variability.

Key words | climate variability, human activities, hydrologic model, runoff

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INTRODUCTION

The global and regional hydrological cycles have been greatly influenced by climate variability and human activities in recent decades (IPCC 2007), especially in arid and semiarid regions. In many river basins of northern China, the runoff has obviously decreased (Ren *et al.* 2002; Liu & Xia 2004). It is very important to understand the effects of climate variability and human activities on runoff, and quantitatively evaluate these effects. In the past, the effect of human activities on runoff was estimated by investigating their impact on each item in the water balance equation (Ren *et al.* 2007). However, such a method is limited because it is difficult to calculate the water consumption directly generated by human activities such as implementation of soil conservation measures, improvement of farming techniques, population growth, and socioeconomic structure changes. Recently, some new approaches have been proposed to quantitatively separate the effect of climate variability and human activities on runoff. For example, Xu & Niu (2000) attempted to quantify the impacts by using an empirical method. Dooge *et al.* (1999), Li *et al.* (2007) and Ma *et al.* (2008) have analyzed the sensitivity of annual streamflow to precipitation and potential evaporation. Even more extensive, hydrologic models (Gleick 1987; Guo *et al.* 2002; Wang *et al.* 2008,

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2010) have been used to investigate the effects of climate variability and human activities on the hydrologic cycle. The hydrologic modeling approach could reconstruct regional time series of natural runoff, therefore it can easily quantitatively assess the effects of climate variability and human activities on runoff. In contrast to the empirical and sensitivity analysis methods, the hydrologic model has better representations of physical mechanisms.

This study attempts to quantitatively evaluate the effects of climate variability and human activities on runoff by using the three-layer Variable Infiltration Capacity (VIC-3L; Liang *et al.* 1994, 1996) model within the Laohahe basin in northern China. In this study, climate variability refers to the variations in precipitation and potential evapotranspiration resulting from the Laohahe basin's warming environment (Figure 1), while the human activities include direct withdrawal of water from river channel or ground for irrigation, industrial production, municipal utilization and national living consumption, and man-made land use changes and reservoir dam construction and so on. Firstly, the Mann–Kendall rank correlation test (MK) (Mann 1945; Kendall 1975), ordered clustering (OC) (Wang *et al.* 2010) and the precipitation–runoff double cumulative curve (DCC) (Huo *et al.* 2008) methods were employed to detect the trend and change points of the annual precipitation and runoff series. By the above three approaches, the runoff series of the Laohahe basin can be divided into a 'natural period' and a 'human-induced period'. Then the VIC-3L model was tentatively used to quantitatively evaluate the effects of climate variability and human activities on runoff.

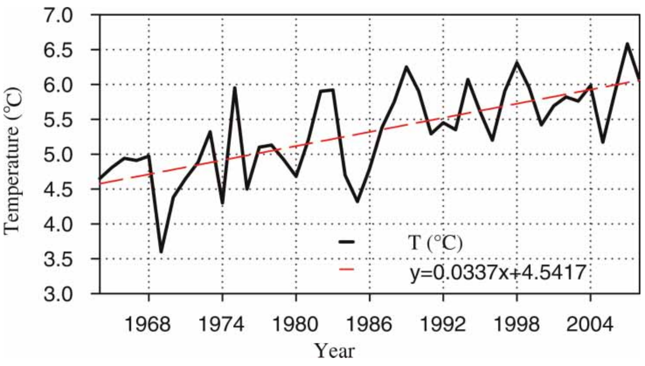

Figure 1 | Time series of annual mean temperature within the Laohahe basin which is coincident with global warming.

STUDY AREA AND DATA

Physical characteristics

The Laohahe basin, a tributary of the West Liaohe River, with a drainage area of 18,112 km^2 above the Xinglongpo hydrologic station, is located at the junction of the Hebei Province, Liaoning Province, and Inner Mongolia Region in northern China (Figure 2). The basin extends from 117.25° to 120° E longitude and 41° to 42.75° N latitude, and it is in the temperate semiarid continental monsoon climate. The elevation within the basin ranges from 427 to 2,054 m above average sea level, and the topography significantly descends from southwest to northeast. The basin's average annual temperature, precipitation and runoff during the period of 1964–2008 are about 7.5 °C, 424 and 28.3 mm, respectively. The spatial and temporal distribution of the precipitation within the Laohahe basin is uneven, and about 80% of the annual precipitation occurs between May and September.

Socioeconomic situation

In the Laohahe basin, agriculture, stock raising and mining industry are the three main activities in production, and the dominant types of land use are grassland and cropland. Chifeng City is the largest city within the Laohahe basin, whose GDP, population, food production and livestock numbers have increased markedly since 1964 (Figure 3) (Zhou *et al.* 2004; Wang *et al.* 2005, 2006; Liu *et al.* 2009). Food production and GDP accelerated at the start of the 1980s, which coincided with the policy of China's reform and opening to the world commencing in 1978 and the decision on acceleration of agricultural development in 1979. Agriculture within the basin developed quickly in the 1980s, and livestock numbers increased tremendously in 1989. There also are several reservoirs for agricultural irrigation and industrial consumption; for instance, Erdaohezi reservoir, Dahushi reservoir and Sanzuodian reservoir were built in 1971, 1982 and 2000,

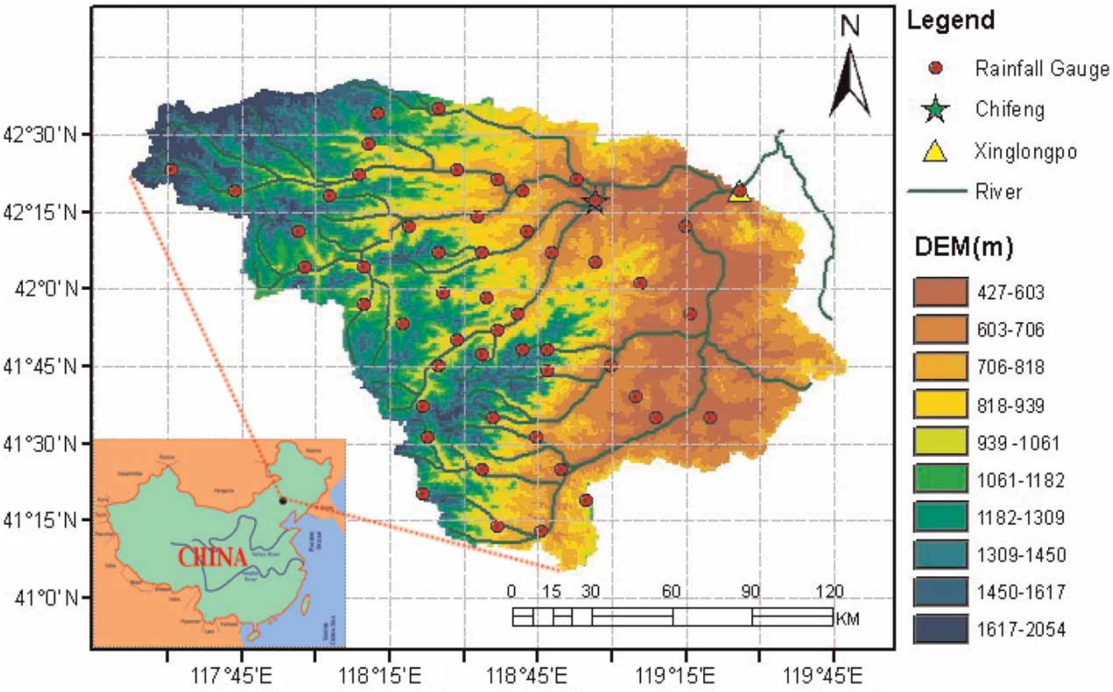

Figure 2 | Location of the study area and distribution of rain gauge and hydrologic stations.

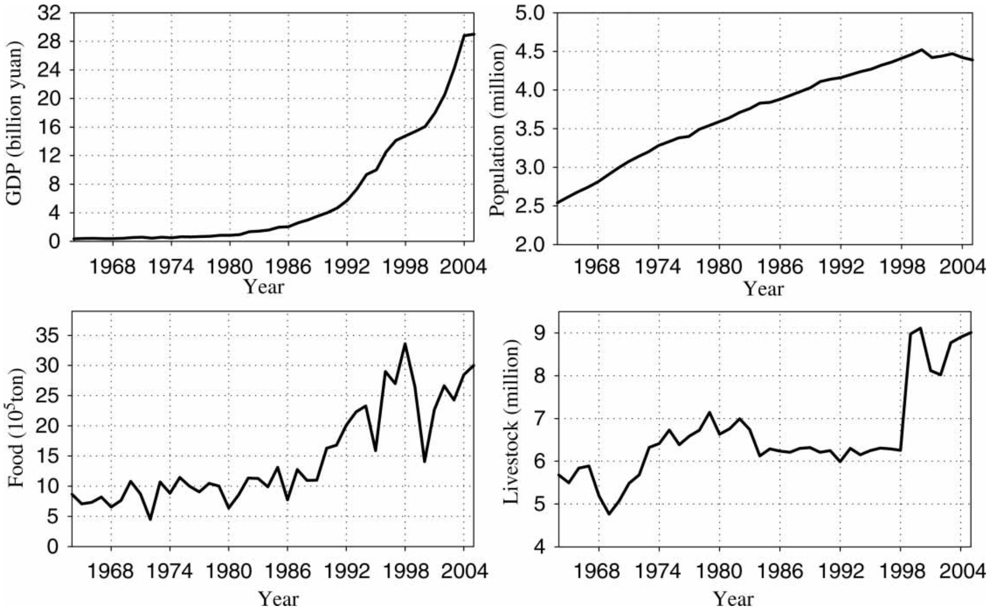

Figure 3 | Changes of GDP, population, food and livestock in Chifeng City for 1964–2005.

respectively, all of which have caused water use to increase within the Laohahe basin. Surface water and groundwater were drawn from rivers and aquifers for cropland irrigation, industrial production and city development. Over-exploitation and utilization of water resources has caused a decrease of runoff; especially, some tributaries of the Laohahe have dried-up since the beginning of the 1980s (Wang & Li 2007).

Data

There are two types of datasets used in this study.

1. The land surface datasets are mainly collected from local administrative agencies: for example, the soil types were derived from the Food and Agriculture Organization data set (FAO 1998), the vegetation types were obtained from the University of Maryland's (UMD) 1 km global land-cover production (Hansen *et al.* 2000); the 30 arc-second global digital elevation model (GTOPO30) data were obtained from the US Geological Survey (USGS) and resampled to $0.0625^\circ \times 0.0625^\circ$ resolution topography data to generate flow direction, basin mask and contributing area for running the VIC-3L model.
2. Meteorological data, including daily maximum and minimum air temperature, wind speed and sunshine duration, were obtained from four national standard meteorological stations. Daily precipitation data for 52 rain gauge stations for the period from 1964 to 2008 were used and the same time series daily runoff data of the Xinlongpo hydrologic station was prepared. The inverse distance weighting method (IDW; Bartier & Keller 1996) was used to obtain the spatially distributed precipitation database and the average precipitation for the basin.

METHODOLOGY

Trend and change point analysis

The MK trend test was used to analyze the trend and test the significance for the annual precipitation and runoff series, and the OC method and the precipitation–runoff DCC were adopted to detect the change points of the annual runoff series.

The rank-based nonparametric MK method is commonly used to assess the significance of monotonic trends in meteorological and hydrological series (Xu *et al.* 2003; Zhang *et al.* 2009). For a time series $X = \{x_1, x_2, \ldots, x_3\}$ that $n > 10$, the standard normal statistic Z is estimated by the following formula:

$$Z = \begin{cases} (S-1)/\sqrt{\mathrm{var}(S)}, & S > 0 \\ 0 & 0 \\ (S+1)/\sqrt{\mathrm{var}(S)}, & S < 0 \end{cases} \tag{1}$$

with

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

$$\mathrm{sgn}(\theta) = \begin{cases} +1, & \theta > 0 \\ 0, & \theta = 0 \\ -1, & \theta < 0 \end{cases} \tag{3}$$

$$\mathrm{var}(S) = [n(n-1)(2n+5) - \sum_t t(t-1)(2t+5)]/18 \tag{4}$$

in which t is the extent of any given tie, and $\sum_t$ denotes the summation of all ties.

The statistic Z follows the standard normal distribution, at the 5% significance level, and the null hypothesis of no trend is rejected if $|Z| > 1.96$. A positive value of Z denotes an increasing trend, and the contrary would correspond to a decreasing trend.

The OC analysis method can detect the change point τ_0 of long time series by making the sum of the similar series' deviation squares least. Given a time series $X = \{x_1, x_2, \ldots, x_n\}$, the OC method assumes the possible break point is τ, and then V_τ and $V_{n-\tau}$ are calculated as:

$$\begin{cases} V_\tau = \sum\limits_{t=1}^{\tau} (x_t - \bar{x}_\tau)^2 \\ V_{n-\tau} = \sum\limits_{t=\tau+1}^{n} (x_t - \bar{x}_{n-\tau})^2 \end{cases} \tag{5}$$

in which $\bar{x}_\tau$ and $\bar{x}_{n-\tau}$ are the average values of the two sub-series separated at τ. Then $S_n(\tau)$ is obtained as follows:

$$S_n(\tau) = V_\tau + V_{n-\tau} \tag{6}$$

The change point τ_0 will satisfy the objective function:

$$S_n(\tau_0) = \min_{2 \le \tau \le n-1} \{S_n(\tau)\} \tag{7}$$

The DCC can visually represent the consistency of the precipitation and runoff. Normally it should be a straight line. Once the curve has a change, we can judge that the characteristic of the precipitation or runoff has changed.

Separation method

Changes in river runoff can be attributed to two interacting reasons: climate variability and human activities. For a small basin, the variability of climate is controlled mainly by external forcing, so we regard these two factors as two independent variables in this study (Wang *et al.* 2008, 2010; Cong *et al.* 2009). Within the Laohahe basin, the runoff series from 1964 to 2008 was divided into two parts, a 'natural period' and a 'human-induced period', through the trend and change points analysis. The 'natural period' was taken as a baseline of the long-term runoff series and the VIC-3L model was calibrated in this baseline, then the calibrated model was used to reconstruct the natural runoff of the 'human-induced period'. The details of the method of quantification of the effects of climate variability and human activities on runoff are described as follows:

$$\Delta Q_{\mathrm{tot}} = Q_{\mathrm{h}} - Q_{\mathrm{b}} \tag{8}$$

$$\Delta Q_{\mathrm{human}} = Q_{\mathrm{hr}} - Q_{\mathrm{h}} \tag{9}$$

$$\Delta Q_{\mathrm{climate}} = \Delta Q_{\mathrm{tot}} - \Delta Q_{\mathrm{human}} \tag{10}$$

$$I_{\mathrm{human}} = \frac{\Delta Q_{\mathrm{human}}}{|\Delta Q_{\mathrm{tot}}|} \times 100\% \tag{11}$$

$$I_{\mathrm{climate}} = \frac{\Delta Q_{\mathrm{climate}}}{|\Delta Q_{\mathrm{tot}}|} \times 100\% \tag{12}$$

In which ΔQ_{tot} is the total change of runoff, $|\Delta Q_{\mathrm{tot}}|$ expresses the absolute value of the ΔQ_{tot}, Q_{b} means the baseline runoff, Q_{h} and Q_{hr} demonstrate the observed and reconstructed runoff during the 'human-induced period', $\Delta Q_{\mathrm{climate}}$ and $\Delta Q_{\mathrm{human}}$ indicate the impacts from climate variability and human activities, respectively, and I_{human} and I_{climate} show the impact percentages of human activities and climate variability effecting on runoff, respectively.

VIC-3L large-scale hydrologic model

The VIC-3L hydrological model has been successfully applied in many river basins in China during recent years (Liang & Xie 2001; Su & Xie 2003; Yuan *et al.* 2004; Xie *et al.* 2007; Yong *et al.* 2010). It is a grid-based land-surface processes scheme which considers the dynamic changes of both water and energy balances. A distinguishing characteristic of the model is its incorporation of subgrid spatial variability of precipitation and infiltration, with the land surface divided into different land-cover types and bare soil (Liang *et al.* 2004). The soil is partitioned into three layers: a thin top layer, a middle layer and a lower layer. The thin top layer represents quick-response evaporation from bare soil after small amounts of rain, the middle layer represents the dynamic response of the soil wetness to rainfall events, and the lower layer characterizes the seasonal soil moisture behavior (Xie *et al.* 2007). A variable infiltration curve is used to represent the subgrid variability of soil infiltration capability under different land cover and soil types (Zhao *et al.* 1980). There are seven parameters commonly calibrated in the VIC-3L model, of which B and d_2 are the two most sensitive (Su & Adam 2005). In this study, the three baseflow parameters and the two layer depth parameters (d_1, d_3) were used with minor revision during the calibration based on the default values (Su & Adam 2005; Xie *et al.* 2007), while the parameters B and d_2 were calibrated independently.

The VIC-3L model was implemented at 0.0625° spatial resolution and daily temporal resolution from 1964 to 2008. The routing model (Lohmann *et al.* 1996, 1998) was adopted to produce the model-simulated runoff at the Xinlongpo hydrologic station.

RESULTS AND ANALYSIS

Trend and change point analysis of precipitation and runoff

Figure 4 shows the trend of annual precipitation and runoff. From Figure 4 and the MK test (Table 1) we can see that the precipitation has no obvious increasing or decreasing trend within Laohahe basin, and the average precipitation of 1964 to 2008 is 424 mm, while the runoff demonstrates a remarkable decreasing trend (with a significance of 0.004) at 4.7 mm every 10 years, and the average observed runoff from 1964 to 2008 is only 28.3 mm, which is much smaller than average precipitation.

Table 2 shows the change of observed precipitation and runoff for different durations. It can be seen that, compared with the baseline, precipitation has decreased 10% during both the periods 1980–1989 and 2000–2008, while the observed runoff displayed a decrease much more than precipitation, i.e. 57 and 72%, respectively. During the period 1990–1999, precipitation and observed runoff increased by 10 and 17%, respectively.

The OC analysis shows that there are two change points (in 1979 and 1998) of the runoff series (Table 1). Figure 5 shows the cumulative annual precipitation and runoff within the Laohahe basin, from which we can see that before 1979 precipitation and runoff have a good uniformity, while after 1979 the characteristic of the precipitation or runoff has changed. These change points are consistent

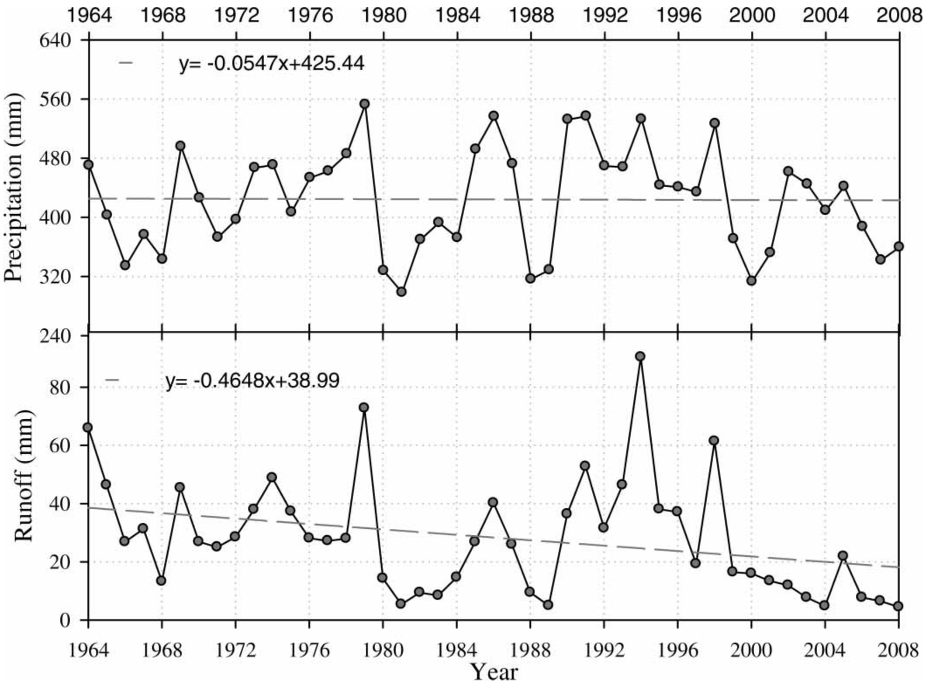

Figure 4 | Time series of annual precipitation and observed runoff 1964–2008.

Table 1 | Trend and change point analysis of annual precipitation and runoff

		Mann–Kendall test		**Average value**	**Change rate**	**Change point**
Factor	**Period**	***Z***	**Significance**	**mm**	**mm/10a**	**OC**
Precipitation	1964–2008	−0.42	–	424	−0.5	–
Runoff	1964–2008	−2.89	0.004	28.3	−4.7	1979, 1998

Table 2 | The change of observed precipitation and runoff

	Precipitation			Observed runoff (mm)		
Duration	mm/a	Change (mm/a)	Relative change (%)	mm/a	Change (mm/a)	Relative change (%)
1964–1979	432.3			36.9		
1980–1989	390.6	–41.7	–10	16.0	–20.9	–57
1990–1999	475.4	43.1	10	43.0	6.1	17
2000–2008	390.2	–42.1	–10	10.5	–26.4	–72

with the socioeconomic development situation. From the situation of socioeconomic development and the OC and DCC analysis, it is believed that 1979 could be the change point reflecting the effect of human activities on runoff. Therefore, we take the period from 1964 to 1979 as the baseline during which less effect of human activities on runoff was recognized, and we regard the period from 1980 to 2008 as the human-induced period which is divided into three durations based on the decades 1980–1989, 1990–1999 and 2000–2008.

Natural runoff reconstruction

During the 'natural period', i.e. 1964–1979, there was little human activity within the Laohahe basin, so the VIC-3L model is calibrated in this period. The year 1964 was regarded as the model's 'warm-up-time'. The period 1965–1974 was the calibration period and 1975–1979 was the validation period, and all the outputs (discharge/runoff) are in monthly time steps. A model efficiency criterion (NSCE; Nash & Sutcliffe 1970) and BIAS, given by Equations (13) and (14) respectively, are used to evaluate the model performance:

$$\mathrm{NSCE} = 1 - \frac{\sum_{i=1}^{n}(Q_{\mathrm{sim}}(i) - Q_{\mathrm{obs}}(i))^2}{\sum_{i=1}^{n}(Q_{\mathrm{obs}}(i) - \bar{Q}_{\mathrm{obs}})^2} \tag{13}$$

$$\mathrm{BIAS} = \frac{\sum_{i=1}^{n}(Q_{\mathrm{sim}}(i) - Q_{\mathrm{obs}}(i))}{\sum_{i=1}^{n} Q_{\mathrm{obs}}(i)} \tag{14}$$

in which $Q_{\mathrm{obs}}(i)$ is the observed runoff (mm/month) at time step i, $Q_{\mathrm{sim}}(i)$ is the simulated runoff (mm/month) at time step i, $\bar{Q}_{\mathrm{obs}}$ is the mean value of the observed values (mm/month), and n is the number of data points.

Figure 6 shows the comparison between the monthly observed and simulated runoff at Xinlongpo hydrologic station from 1965 to 1979. It can be seen that simulated and observed runoff are in good agreement. The values of NSCE and BIAS are 85 and 4.2% during the calibration period of 1965–1974, and 80 and 1.8% during the verification period of 1975–1979, respectively. Then the well calibrated hydrologic model was applied to reconstruct the natural runoff series of the three human-induced durations

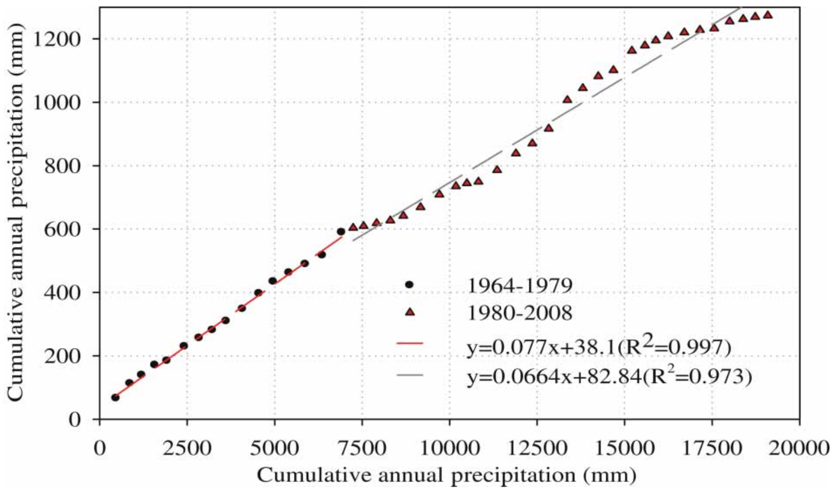

Figure 5 | Double cumulative curve of annual precipitation and observed runoff.

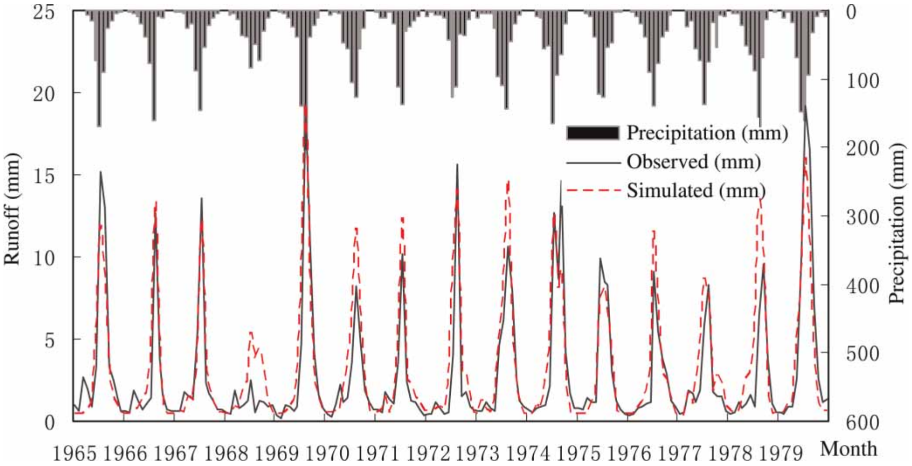

Figure 6 | Monthly observed and simulated runoff at Xinlongpo hydrologic station for the calibration (1965–1974) and validation (1975–1979) years.

of 1980–1989, 1990–1999 and 2000–2008 with the actual meteorological and hydrologic data as input.

Effects of climate variability and human activities on runoff

With the reconstructed runoff series of the 'human-induced period' and the coincident observed runoff series, it is possible to quantitatively analyze the effects of climate variability and human activities on runoff.

Figure 7 shows the comparison between the simulated and observed runoff at Xinlongpo hydrologic station from 1980–2008. It can be seen that the difference between the simulated and observed runoff is very small during the 1990s, while the differences are very large during the 1980s and after 2000. The observed and simulated runoff coefficients during the different durations are given in Table 3, which shows that the observed runoff coefficients during the 1980s and after 2000 were much smaller than the baseline, from which it emerges that there may be some activities affecting the runoff during these two durations, while the simulated runoff coefficients for the different durations are very similar to the baseline. From Figure 7 and Table 4 we can summarize that: (1) the runoff of 1980–1989 and 2000–2008 decreased compared

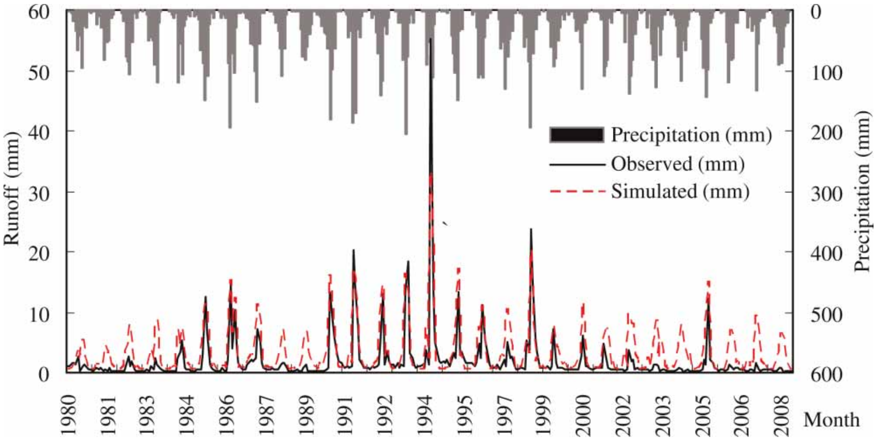

Figure 7 | Monthly observed and simulated runoff at Xinlongpo hydrologic station 1980–2008.

Table 3 | Observed and simulated runoff coefficient during different durations within the Laohahe basin

Duration	1964–1979	1980–1989	1990–1999	2000–2008
Observed runoff coefficient	0.09	0.04	0.09	0.03
Simulated runoff coefficient	0.09	0.08	0.10	0.09

with the baseline, with both climate variability and human activities playing the decreasing role, while runoff increased during the period of 1990–1999, and climate variability played the increasing role but human activities did the opposite; and (2) during the 'human-induced period', human activities always play the decreasing role with respect to runoff, while the effect of human activities on runoff is much less for the wetter period of 1990–1999 with a contribution of 21% than that for the two drier durations of 1980–1989 and 2000–2008 with contributions of 70 and 78%, respectively.

The decreasing effect of human activities on runoff within the Laohahe basin can be due to reservoirs and dams for water supply and power generation, the increase of irrigated area and industrial consumption, etc. In semiarid regions, runoff is significantly related to the quantity of precipitation, and it is more sensitive to human activities relative to wet regions. When precipitation is much less than average, more water is abstracted from streams and aquifers for production and life activities, and the river runoff will be significantly influenced by those activities. When precipitation is more than the average value, water demand trends to be relatively lower, and the effect of human activities on runoff will be less.

CONCLUSIONS

The objective of this study has been to quantitatively analyze the effects of climate variability and human activities on runoff from the Laohahe basin in northern China. Trend and change point analysis was applied to the annual precipitation and runoff from 1964 to 2008 by the three methods of MK, OC, and DCC. The results show that precipitation keeps a smooth trend during that period, while the runoff has a remarkable decreasing trend with 4.7 mm every 10 years. The year of 1979 is believed to be the break point of reflecting the effect of human activities on runoff. According to the trend and change points analyses, the period of 1964–1979 was assigned as a 'natural period' which was supposed to have little human effect, and the 'human-induced period' of 1980–2008 was divided into three durations: 1980–1989, 1990–1999 and 2000–2008. Then the VIC-3L model was used to quantitatively evaluate the effects of climate variability and human activities on the changes of runoff. The model was first calibrated for the period of 1964–1979. Then the calibrated model was used to reconstruct the nature runoff of the 'human-induced period'. The results reveal that during the drier periods of 1980–1989 and 2000–2008, the contributions of climate variability to the decrease in runoff were 30 and 22%, respectively, and the contributions of human activities to the decrease in runoff were 70 and 78%, respectively. During the wetter period of 1990–1998, the contributions of climate variability and human activities to the increase of runoff were 121 and –21%, respectively. The effects of human activities on runoff during the drier periods are much more serious than in the wetter period. It is suggested that the human activities are the main reasons for the runoff decrease during the two drier periods of 1980–1989 and 1999–2008 within Laohahe basin, and the

Table 4 | Effects of climate variability and human activities on runoff within the Laohahe basin

Duration	Observed runoff (mm) mm/a	Total change in runoff mm/a	Relative change (%)	Reconstructed runoff mm/a	Impact due to climate variability mm/a	%	Impact due to human activities mm/a	%
1964–1979	36.9							
1980–1989	16.0	−20.9	−57%	31.6	−6.2	−30	−14.7	−70
1990–1999	43.0	6.1	17%	46.9	7.4	121	−1.3	−21
2000–2008	10.5	−26.4	−72%	33.2	−5.9	−22	−20.5	−78

increase of runoff during the wetter period 1990–1999 is mainly attributed to climate variability. This quantitative evaluation of the effects of climate variability and human activities on runoff is useful for water resource assessment and management of the Lahohahe basin. This study also provides a demonstration of quantitative analysis of the runoff change under variational environment.

We should point out that there are some uncertainties involved in the hydrologic model approach for analyzing the effect of climate variability and human activities on runoff. Firstly, uncertainty may come from the definition of the 'natural period' in which there may be some effects of human activities on runoff. Secondly, there are some uncertainties in the model structure and the calibrated model parameters. Last but not least, uncertainty arises from observation errors of hydrometeorological variables and uneven spatial distribution of precipitation. Those uncertainties will definitely have an effect on the computational results. Thus more work should be done in order to reduce these uncertainties in the future.

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