The impacts of climate variability and human activities on streamflow in Bai River basin, northern China

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ABSTRACT

Both the time series analysis method and hydrological modeling approach are integrated to analyze the streamflow response to climate variability and human activities in the Bai River basin, northern China using data from 1986 to 1998 in this study. Also, the quantification and separation of effects from climate variability and human activities is investigated. First, the Fu formula based on Budyko hypothesis was applied to explore the integrated underlying surface characteristics in the whole basin, and then the SIMHYD model was calibrated and validated using the data from 1986 to 1990 (pre-treatment period). The calibrated model was then used to simulate streamflow in the period 1991 to 1998 (testing period) and obtain quantitative assessment on the impacts of climate variability and human activities. The difference of observed streamflows between the pre-treatment period and the testing period reflects the combined influence of climate variability and human activities in the basin, while the difference between simulated and observed streamflow during the testing period reflects the impact of human activities in the catchment. The results show that the contribution rate of climate to the streamflow change in the basin is 37.5 and 62.5% for human activities. Human activities exerted a dominant influence upon streamflow change in the Bai River basin.

Key words | climate variability, human activity, hydrologic response, northern China, streamflow

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INTRODUCTION

The large-scale hydrological cycle of a catchment is a complex process influenced by climate, physical characteristics of the catchment, and human activities (Rind *et al.* 1992; Green *et al.* 2007; Ma *et al.* 2008). With worsening of water shortage problems and increasing numbers of water-related disasters globally (Song *et al.* 2011a), the study of the impact of climate change/variability and human activities (e.g. human-induced land use change) on hydrology and water resources has become a hot issue in hydrology in the 21st century (e.g. Vorosmarty *et al.* 2000; Kang *et al.* 2004; Milly *et al.* 2005; Fu *et al.* 2007; Scanlon *et al.* 2007; Barnett *et al.* 2008; Piao *et al.* 2010; Wu & Jiang 2010; Liu & Cui 2011). Some studies indicated that the impact of human activities exert a dominant influence upon runoff change in northern China compared to climate change (Li & Li 2008; Wang *et al.* 2009; Zhan *et al.* 2011). Human activities include many aspects, among which land use/cover change is the primary part. Therefore, most researchers have mainly investigated hydrologic response to land use/cover change and climate change (Legesse *et al.* 2003; Mohamad & Glenn 2008; Lan *et al.* 2009; Li *et al.* 2009; Vimal *et al.* 2010), which are the two important factors influencing hydrological conditions (Li *et al.* 2009). For example, dams/reservoirs and land use change can result in a change of flood frequency (Brath *et al.* 2006), base flow (Wang *et al.* 2006), and annual mean discharge (Costa *et al.* 2003), while climate change/variability can change the flow routing time, peakflows and volume (Prowse *et al.* 2006). In addition, some studies have stressed the effects of vegetation change and urbanization with climate change/variability (Zhao *et al.* 2010; Chung *et al.* 2011; Jung & Chang 2011).

To assess the hydrological effects of environmental change, several methods were developed, which mainly fall into three categories: paired catchments approach; time series analysis (statistical method); and hydrological

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modeling (Li *et al.* 2009). Another classification involves qualitative explanation and quantitative analysis to study the hydrologic response to climate change and human activities. The qualitative explanation mainly focuses on the relationship of the climate change trend and hydrological process change, and the influence of human activities on river basin features and underlying surface characteristics (Kezer & Matsuyama 2006). The quantitative evaluation of the effects of climate variations and human activities on streamflow is significant, but currently makes little progress (Wang *et al.* 2009). Most of the studies reported in the literature use either the statistical analysis method or the hydrological modeling method to quantify the impacts of human activities on streamflow (Xu & Vandewiele 1995; Yates 1996; Jothityangkoon *et al.* 2001; Chen *et al.* 2007b; Li *et al.* 2009). The statistical analysis methods lack physical mechanisms, and are usually based on mean annual timescale and so provide generalized relationships without considering species differences within forest and grasslands, partial land use change and heterogeneity within river basins (Li *et al.* 2009). The hydrological modeling approach is more complex due to all these differences. Hydrologic models are usually used to quantitatively analyze the impact of climate and human factors on the water cycle (Jothityangkoon *et al.* 2001; Chen *et al.* 2007b; Li *et al.* 2009). In this study, a conceptual lumped model was used to simulate the streamflow change and quantitatively investigate the impact and relative importance of climate change and human activities on runoff.

The objective of this study is to quantify the impact of human activities and climate variability on streamflow using the SIMHYD rainfall–runoff model, which was successfully applied in northern China (Wang *et al.* 2008). The data, from 1986 to 1998, are split into two periods, 1986–1990 and 1991–1998, by the Fu formula (Fu 1981); the period 1986–1990 is defined as the pre-treatment period, and the period of 1991–1998 is defined as the testing period. First, we briefly describe the study area, the structure of the SIMHYD model, and the Budyko formula. Second, the SIMHYD model is calibrated using the data from 1986 to 1988, and validated using the data from 1989 to 1990. The calibrated model is then used to simulate streamflow during the testing period. Finally, we compare streamflow changes between pre-treatment and testing periods to quantify the impacts of climate variability and human activities on streamflow.

STUDY AREA AND DATA

Study area

The Bai River basin (115°25′–117°E, 40°25′–41°30′N) with an area of 9,227.5 km^2, which is a sub-basin of the Hai River basin, is within northern China (Figure 1). Currently in the river basin, forest, grassland, and farmland account for more than 95% of the total area. The Bai River converges with the Miyun Reservoir, and accounts for 60% of the upstream watershed area of the Miyun Reservoir, which is the main source of water supply for Beijing City (Pang *et al.* 2010; Zhan *et al.* 2011). The river basin is located in the continental monsoon climate zone with transition from temperate and semi-arid climate to warm and semi-humid climate. Most runoff is generated in the period June to September. The majority of soil texture in the basin is brown and cinnamon soil. The yearly average precipitation within the basin is roughly 440 mm; however, the precipitation shows obvious seasonal variation, and mainly occurs between June and August, accounting for 65–75% of the whole year due to the effect of the continental monsoon climate in the temperate zone (Zhan *et al.* 2009). In the study, Zhangjiafen station is the control guaging station of the Bai River basin, and the observed data from Zhangjiafen station were used to calibrate and validate the constructed SIMHYD model.

Data

Meteorological and hydrological data required in this study are shown in Table 1. The meteorological data mainly include rainfall, daily mean temperature, and total radiation quantity of short wave, and the hydrological data mainly include precipitation and streamflow. The streamflow data are sourced from the Zhangjiafen hydrometric station, the precipitation data from the rain-gauge stations, and the meteorological data from the State Meteorological Administration. Daily potential evapotranspiration (PET) is calculated by the Hargreaves method (Hargreaves & Samani 1982), which is suitable for the arid–semi-arid region in northern China (Liu *et al.* 2006). The Hargreaves

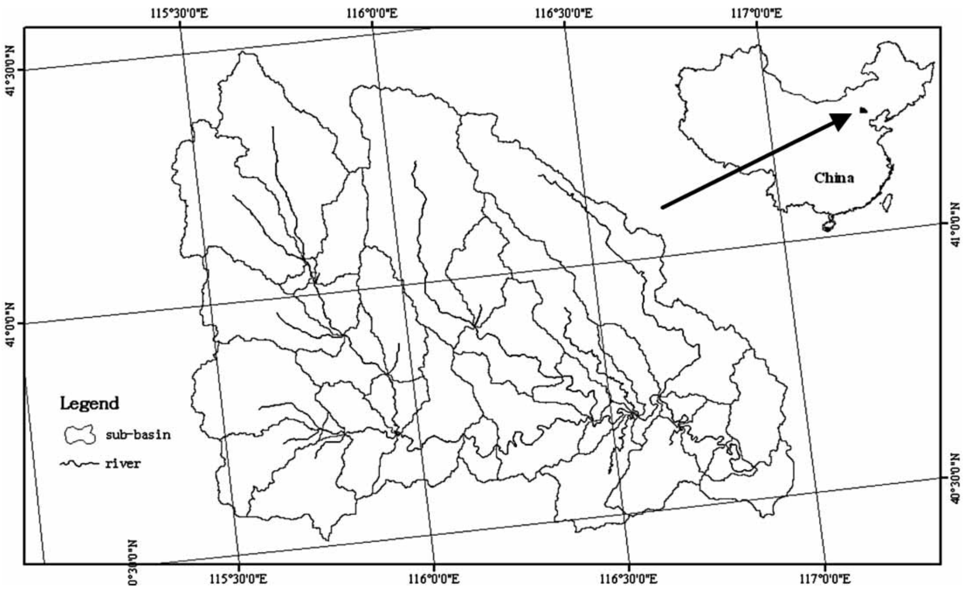

Figure 1 | The location of the Bai River basin.

Table 1 | Meteorological and hydrological data

Data	Data item	Format	Station and location	
Meteorological data	Precipitation, T, R_s	DbaseIII	Huailai	40°24′N,115°30′E
			Zhangjiakou	40°48′N,114°54′E
			Miyun	40°23′N,116°52′E
Hydrological data	Precipitation	Text	64 stations	–
Hydrological data	Streamflow	Text	Zhangjiafen	40°37′–116°47′

model is an empirical equation and takes the form with some modifications (Liu *et al.* 2006) as:

$$PET = 0.0135(T + 17.8)\frac{R_s}{\lambda} \quad (1)$$

where R_s is the daily total short-wave radiation, MJ/(m^2 d), T air temperature, °C, and λ the latent heat of vaporization, $\lambda = 2.45$ MJ/kg.

MODELING METHODOLOGY

Budyko hypothesis and Fu's theoretical formula

In the study, Fu's analytical solutions to the Budyko hypothesis were used to predict the hydrologic response to climate change (Fu 1981). Evapotranspiration links with both water and energy balances and plays a key role in the climate–soil–vegetation interactions. The primary controls on the long-term mean annual evapotranspiration are precipitation and PET. Budyko (1974) proposed a semi-empirical expression for the coupled water–energy balances, here defined as the Budyko hypothesis, which is a partition of annual water balance as a function of the relative magnitude of water and energy supply (Yang *et al.* 2007; Cong *et al.* 2010; Han *et al.* 2011).

On the basis of the Budyko hypothesis, Fu (1981) gave the differential forms of the Budyko hypothesis; he postulated that over a mean annual timescale for a given PET rate (E_0), the rate of the change in basin evapotranspiration with respect to precipitation ($\partial E/\partial P$) increases with residual PET (E_0–E) but decreases with precipitation (P). Similarly, for a given precipitation, the rate of the change in evapotranspiration with respect to PET ($\partial E/\partial E_0$) increases with residual precipitation (P–E), and decreases with PET (E_0).

Through dimensional analysis and mathematical reasoning (Fu 1981; Zhang *et al.* 2004), the analytical solution of Fu's equation is expressed as:

$$\frac{E}{P} = 1 + \frac{E_0}{P} - \left[1 + \left(\frac{E_0}{P}\right)^{\omega}\right]^{1/\omega} \tag{2}$$

where ω is a non-dimensional model parameter, and it indicates the degree of the runoff response to the change of characteristics due to human activities for the whole catchment. It should be noted that the estimation of evapotranspiration using Equation (2) requires mean annual values of precipitation, PET, and estimates of the model parameter ω. These relationships are shown in Figure 2 (Zhang *et al*. 2004).

SIMHYD model

SIMHYD is a daily lumped conceptual rainfall–runoff model (Chiew *et al*. 2002; Zhang & Chiew 2009). The inputs into the SIMHYD model are daily precipitation and daily PET, and the model estimates daily runoff. SIMHYD is one of the most commonly used rainfall–runoff models in Australia and China (Chiew *et al.* 2002, 2009; Wang *et al.* 2008; Zhang & Chiew 2009), and has been tested using data from China (Wang *et al.* 2008). It is one of the rainfall–runoff models in the RRL (Rainfall–Runoff Library), a software product in the Catchment Modelling Toolkit

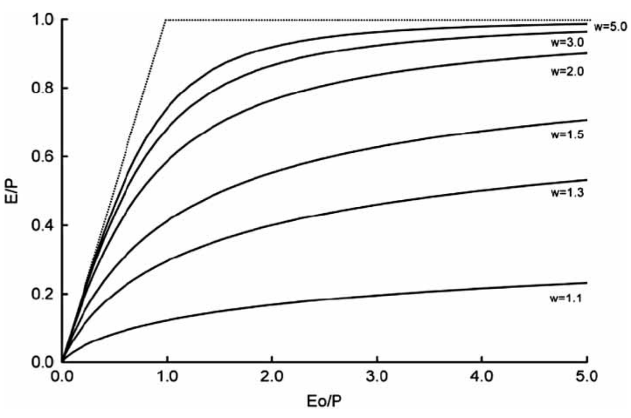

Figure 2 | Ratio of mean annual evapotranspiration to precipitation (E/P) as a function of the index of dryness (E_0/P) for different values of parameter ω.

(www.toolkit.net.au/rrl). The model estimates runoff generation from three sources: infiltration excess runoff, interflow (and saturation excess runoff), and base flow. The detailed description on the structure and the algorithms of the model can be seen in the work of Chiew *et al.* (2002).

Model calibration and validation

In order to validate the simulation results, some criteria must be used, and then some statistical goodness-of-fit approaches are employed to evaluate the model (Song *et al.* 2011b). The generalized pattern search algorithm with particle swarm optimization in MATLAB (The Math Works, Inc.) is used to optimize the parameters of the SIMHYD model. The model is calibrated by maximizing the Nash–Sutcliffe Efficiency (NSE) (Nash & Sutcliffe 1970) of monthly streamflow. NSE is defined as:

$$\mathrm{NSE} = 1 - \frac{\sum_{i=1}^{n}\left(Q_{\mathrm{obs},i} - Q_{\mathrm{sim},i}\right)^2}{\sum_{i=1}^{n}\left(Q_{\mathrm{obs},i} - \overline{Q_{\mathrm{obs}}}\right)^2} \tag{3}$$

Meanwhile, a water balance error (WBE) in percentage is considered as the linear inequality constraint compelling the total simulated streamflow to be within 5% of the total recorded streamflow. WBE is calculated as:

$$\mathrm{WBE} = 100\left(\frac{\sum_{i=1}^{n} Q_{\mathrm{obs},i} - \sum_{i=1}^{n} Q_{\mathrm{sim},i}}{\sum_{i=1}^{n} Q_{\mathrm{obs},i}}\right) \tag{4}$$

The performance of the conceptual rainfall–runoff model is evaluated in this study using the two criteria, NSE and WBE. The model calibration and validation periods are determined from within the pre-treatment period to make sure that both the calibration and validation periods have a relatively similar vegetation cover. A 3-year warm-up period is used for both calibration and simulation.

Separating the effects of human activities and climate variability

For a given basin that is mainly affected by human activities and climate variability, the total change in mean annual streamflow between two independent periods with different human activities and climate characteristics can be estimated as:

$$\Delta Q_{tot} = \overline{Q_{obs}^{test}} - \overline{Q_{obs}^{pre}} \quad (5)$$

where ΔQ_{tot} indicates the total change in mean annual streamflow, $\overline{Q_{obs}^{pre}}$ and $\overline{Q_{obs}^{test}}$ are the mean annual measured streamflow during the pre-treatment period and the testing period, respectively.

The total change ΔQ_{tot} in mean annual streamflow between the two independent periods is a combination of change in streamflow caused by the climatic differences and change in streamflow due to the human activity difference between the two periods. Thus, the total change in mean annual streamflow can be described as:

$$\Delta Q_{tot} = \Delta Q_{clim} + \Delta Q_{hum} \quad (6)$$

$$\Delta Q_{hum} = \overline{Q_{obs}^{test}} - \overline{Q_{sim}^{test}} \quad (7)$$

where ΔQ_{clim} is the change in mean annual streamflow because of climate change/variability between the two periods, ΔQ_{hum} indicates the change in mean annual streamflow as the result of human activities, $\overline{Q_{sim}^{test}}$ and $\overline{Q_{obs}^{test}}$ are the average simulated and observed annual streamflow for the testing period, respectively.

To separate streamflow impacts caused by climate change and human activities, only ΔQ_{hum} or ΔQ_{clim} needs to be quantified since ΔQ_{tot} is available. A widely used approach to quantify ΔQ_{clim} is the hydrological modeling approach. There are numerous studies reported in the literature which use fully distributed and semi-distributed hydrological models to simulate impacts of human activities (e.g. land use changes) on catchment water balance (Bultot *et al.* 1990; Nandakumar & Mein 1997; Niehoff *et al.* 2002; Siriwardena *et al.* 2006; Elfert & Bormann 2010). In this approach, a hydrological model is first calibrated for one period, and then is applied to another independent period to quantify ΔQ_{clim}.

RESULTS AND DISCUSSION

Abrupt point analysis

The parameter ω is a non-dimensional model parameter, and it is closely related to the degree of the runoff response to the basin characteristics' change due to human activities. The abrupt point of ω change is used to define the time point when the basin characteristics change significantly due to human activities. The moving average of the parameter ω in the Fu formula and the observed monthly streamflow for every 5 years are shown in Figure 3. The results provide

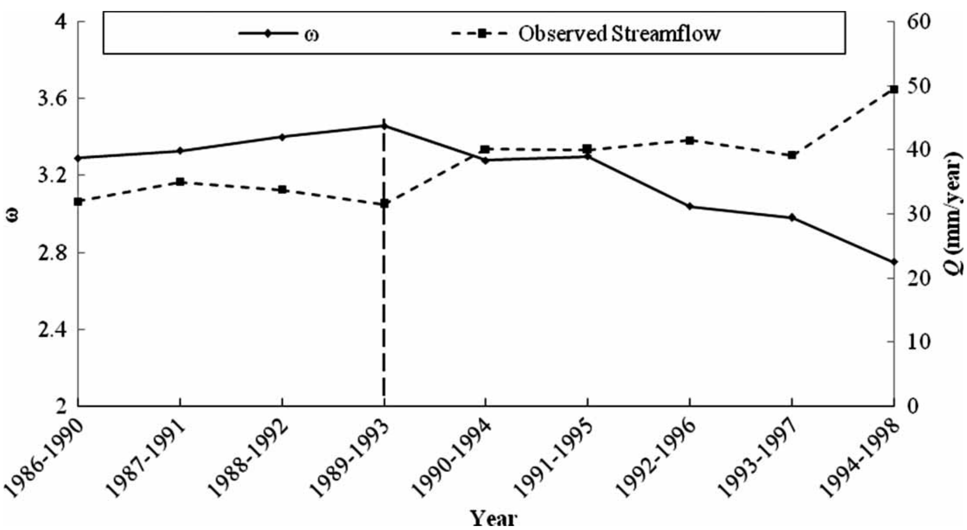

Figure 3 | The moving average of ω and observed streamflow for every 5 years.

the basic judgement criterion for dividing the whole period into the pre-treatment and testing periods. The main curve break point for two moving mean curves for every 5 years is about 1989–1993, thus the abrupt point for streamflow change is regarded as the early 1990s, which also is the abrupt point of synthetic characteristics' change of the underlying surface. The increasing trend of ω appears in the moving average change for every 5 years from 1986 to 1993. The moving average of ω for every 5 years reduces in the period 1989–1998. Based on the change trend of ω, the study period is separated into two parts by 1990, i.e. the pre-treatment period (1986–1990) and the testing period (1991–1998).

The parameter ω can reflect the characteristics of the underlying surface and the capability of runoff yield from the whole basin. It is also possible to make some generalization as to how the parameter ω will vary with the river basin characteristics. The result suggests that runoff change is closely related to the characteristics of the underlying surface from 1986 to 1998. The land use/cover change caused by human activities, such as building water conservation projects, is a main factor influencing the characteristics of the underlying surface. As shown in Figure 3, ω increases gently during 1986–1990, which means that actual evapotranspiration had increased according to the Fu formula. In other words, according to the water balance theory, the runoff decreased in that period. The planning for soil and water conservation was only carried out in some areas, with large-scale remediation yet to be conducted, while little change took place in the way people used the land. With good water permeability of the underlying surface and relatively weak influence by human activities, the runoff was small. After the abrupt point of 1990, the period 1991–1998 was characterized by the decreasing value of ω. We could assume that the actual evapotranspiration was decreasing, with the runoff increasing. After 1990, the integrated remediation, reforestation, embankment consolidation, water conservation projects, and urbanization changed the underlying situation in the Bai River basin. Land utilization statistics showed that, comparing the pretreatment period and the testing period, the area of farmland and grassland decreased by 7.21 and 12.25% respectively, while the forest area increased by 20.02% (Zhan *et al.* 2011). With the forest still being in the growing stage and its canopy interception capacity being weak, most of the rain fell on the ground. It could not permeate easily because of the weakened permeability caused by the hardened and expanded road development in the urbanization process. Thus, the capacity for the runoff yield of the catchment was strengthened. Meanwhile, with the consolidation of the embankment and construction of water conservation projects, the evaporation from the catchment becomes less, and much more runoff yield is routed into streamflow. Such comprehensive effects due to human activities have resulted in the increase of the runoff yield in this period.

The actual evapotranspiration in the Bai River basin in northern China is mainly decided by the rainfall and temperature in the area. The ω value mainly ranges between 2.5 and 3.5, which means the actual evapotranspiration somewhat approaches the rainfall according to Figure 2. Meanwhile the change of ω values showed that, after integrated remediation in this small river basin, the evaporation from the catchment has decreased with the evapotranspiration taking a smaller proportion of the rainfall, thus the runoff increases.

Time series trend analysis

The time series trend analysis was used in the study. The annual time series for streamflow (Q_{obs}), precipitation (P), and PET, along with linear trendlines fitted to the observed values are shown in Figure 4. The linear trendlines showed much sharper decreasing trends in precipitation and PET and an increasing trend in streamflow as a whole.

In addition, the rank-based, non-parametric Mann–Kendall statistical test is commonly used for trend detection due to its robustness for abnormally distributed and censored data, which are frequently encountered in meteorological and hydrological time series (Chen *et al.* 2007a; Burn 2008; Zhang *et al.* 2010). In this work, the Mann–Kendall trend test was also used to analyze the trends in annual Q_{obs}, P, and PET (see Table 2 below). Table 2 obviously shows that only annual streamflow Q_{obs} had a rising rate of 1.518 mm/yr, with a decrease of P and PET. The results of PET reduced significantly ($\alpha = 0.05$) for the Bai River basin, with a decreasing rate of 5.601 mm/yr. However, more significant decreasing trends ($\alpha = 0.1$) are found for P, with a decreasing rate of 6.403 mm/yr. The trend analysis results here suggest that the increasing trend in the observed streamflow in the Bai River basin cannot

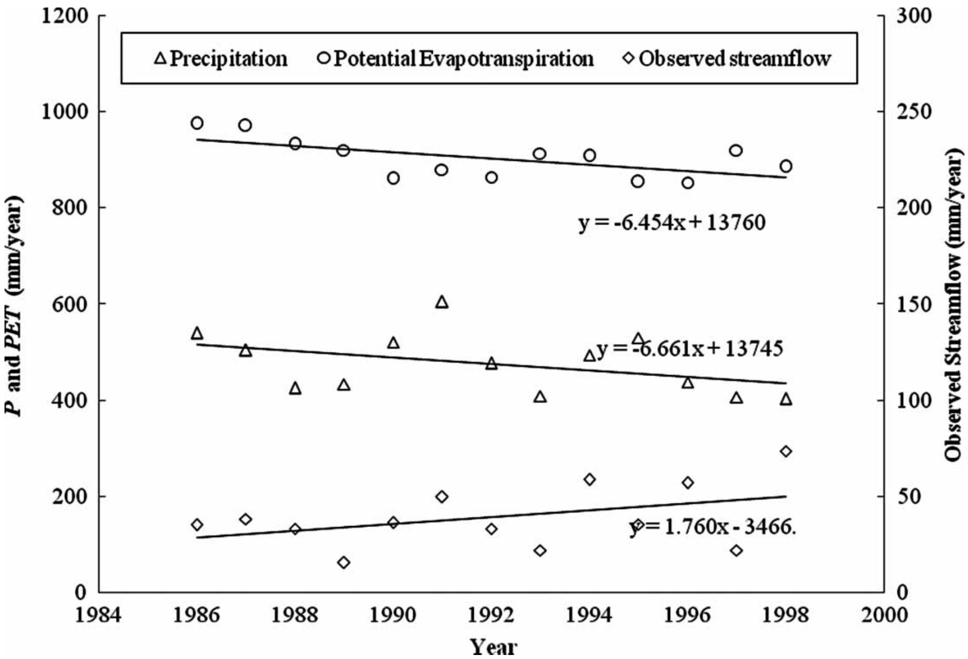

Figure 4 | Changes in annual precipitation, potential evapotranspiration, and streamflow in the Bai river basin during 1986–1998.

Table 2 | Summary of Mann–Kendall trend analysis for observed data

Time series	First year	Last year	Z	Significance level	β_s (mm/yr)
Q_{obs}	1986	1998	0.92	–	1.518
P	1986	1998	−1.65	0.1	−6.403
PET	1986	1998	−2.26	0.05	−5.601

Note: Z and β_s are the Mann–Kendall test statistic and Kendall slope.

be explained by the reduction in P and PET alone, and the introduction of human activities may be an important contribution to this increase.

Calibration and validation of SIMHYD

In this study, the NSE and WBE were used to evaluate the performance of the SIMHYD model. From the calibration and validation results, we can see that the model performed extremely well, with the NSE = 0.886 in calibration and NSE = 0.821 in the validation period. At the same time, the absolute WBE is 0.51% in calibration and 1.15% in validation. Otherwise, the results indicated that there was no evidence of systematic errors in simulated monthly streamflow in the model calibration or validation. The results suggested that the SIMHYD model and the calibration method used in this study were robust enough for the calibrated model to be used adequately over an independent simulation period. The nine parameters of the SIMHYD model, which are displayed in Table 3, were calibrated

Table 3 | Nine calibrated parameters of the SIMHYD model applied in the Bai River basin

Parameters	Description	Range Min	Range Max	Value
COEFF	Maximum infiltration loss (mm)	50	400	86.5
SQ	Infiltration loss exponent	0	6	3.12
K	Baseflow linear recession parameter	0.003	0.3	0.08
INSC	Interception store capacity (mm)	0.5	5	5.00
SUB	Constant of proportionality in interflow equation	0	1	0.04
SMSC	Soil moisture store capacity (mm)	50	500	201.5
CRAK	Constant of proportionality in groundwater equation	0	1	1.00
XE	Muskingum routing model parameter	0	0.5	0.37
KE	Muskingum routing model parameter	0.5	10	0.50

using the pre-treatment data and employed to simulate the streamflow in the testing period in the Bai River basin.

Hydrological effect of human activities and climate variability

In this study, the SIMHYD model with the calibrated parameter values and land cover information from the period 1986–1990, is used to quantify the effects of human activities on streamflow during the testing period. The simulated results compared with the observed monthly streamflow for the Bai River basin are shown in Figure 5. Figure 5 shows that there is large difference between the simulated and observed monthly streamflow during the testing period 1991–1998 for the Bai River basin, which indicates human activities have played an important role in this difference. The observed monthly runoff values are almost higher than the simulated runoff in the testing period (1991–1998). The effects of human activities between the pre-treatment and the testing period have been eliminated through simulation for the testing period by using observed climate data from 1991 to 1998 which drive the calibrated SIMHYD. The difference between observed and simulated streamflow during the testing period only reflects the influence of human activities, and the human activities had caused an increment in streamflow during the testing period.

To separate and quantify the impacts of climate variability and human activities on streamflow during the testing period, the simulated streamflows were compared with the observed streamflows in the pre-treatment and testing periods. The differences between observed and simulated streamflow values were caused by the differences in climatic conditions and human activities during the pre-treatment and testing period. Table 4 summarizes the annual statistics for observed streamflow Q_{obs}, precipitation P, and potential evapotranspiration PET for the pre-treatment and testing periods. The results show that the total increment in flow for the testing period (when compared to the pre-treatment period) due to climate variability and human activities was 12 mm, which represented a 37.5% increment in streamflow. On the whole, the increment in streamflow during the testing period due to human activities was 7.5 mm (23.4% of the pre-treatment flow) and the increment due to climate variability was 4.5 mm (14.1% of the pre-treatment flow).

CONCLUSIONS

A monthly water balance model was used to evaluate the impact of climate variability and human activities on the changes of streamflow in the Bai River basin in northern

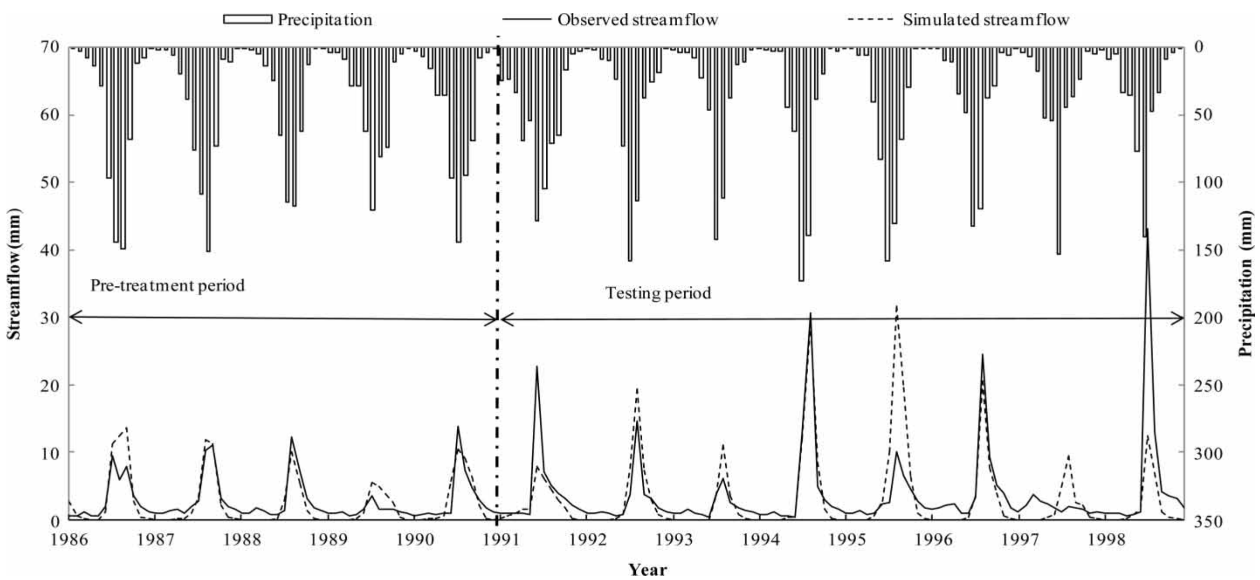

Figure 5 | Time series of monthly precipitation, observed and simulated streamflow.

Table 4 | Annual statistics for observed precipitation, potential evaporation, streamflow, and simulated streamflow

Period	*P* (mm)	PET (mm)	Q_{obs} (mm)	Q_{sim} (mm)
Pre-treatment	485	931	32	–
Testing	471	884	44	36.5

China. The Fu model based on the Budyko hypothesis was applied to explore the integrated underlying surface characteristics of the overall basin. The moving average value of ω for every 5 years indicated that the year 1990 was the abrupt point for the runoff change due to human activities. The SIMHYD model was calibrated using meteorological and hydrological data from the pre-treatment period, and was used to simulate streamflow in the testing period to estimate the impact of climate variability and human activities on streamflow.

The differences of observed streamflow between the pre-treatment period and the testing period reflect the combined influence of climate variability and human activities in the basin. The increment between the simulated and measured streamflow during the testing period, which is 7.5 mm, reflects the contribution rate of human activities to the streamflow change in the basin is 62.5%, at the same the contribution rate of climate variability is 37.5%. Thus, it can be concluded that the impact of human activities exerts a dominant influence upon the runoff change in the Bai River basin compared to climate variability.

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