

Evaluation of changes in streamflow and the underlying causes: a perspective of an upstream catchment in Haihe River basin, China

Sicheng Wan, Jianyun Zhang, Guoqing Wang, Lu Zhang, Lei Cheng, Amgad Elmahdi and Yanli Liu

ABSTRACT

Investigating long-term streamflow changes pattern and its response to climate and human factors is of crucial significance to understand the hydrological cycle under a changing environment. Caijiazhuang catchment located within Haihe River basin, north China was selected as the study area. To detect the trend and changes in streamflow, Mann–Kendall test was used. Elasticity and hydrological simulation methods were applied to assess the relative contribution of climate change and human activities on streamflow variability under three periods (baseline (1958–1977), impact I (1978–1997), and impact II (1998–2012)). The long-term hydro-climatic variables experienced substantial changes during the whole study period, and 1977 was the breaking year of streamflow change. Attribution analysis using the two methods showed consistent results: for impact I, climate change impacts explained 65% and 68% of streamflow reduction; however for impact II, it only represented 49% and 56% of streamflow reduction. This result indicated that human activities were intensifying over time. Various types of human activities presented significant effects on streamflow regimes including volumes and hydrographs. The findings of this paper could provide better insights of hydrological evolution and would thus assist water managers in sustainably managing and providing water use strategies under a changing environment.

Key words | attribution analysis, Caijiazhuang catchment, climate change, human activities, streamflow

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INTRODUCTION

The hydrologic cycle serves as the most critical natural process of the planet (Brutsaert 2005). It conveys mass and energy, influencing physical, biological, and chemical processes, thus supporting the ecological system functioning, which is vital to human well-being and social development. As it is closely interacted with atmosphere, land and humans, the hydrologic cycle is sensitive to environmental change, which gives rise to many problems as well as research issues (Montanari *et al.* 2013; Chiew *et al.* 2014).

Climate functions are a key input into the hydrologic cycle dynamic processes, and any change or fluctuation of any component of the climate system (precipitation, temperature, and solar radiation) would affect hydrologic cycling to various degrees. It is well established that Earth has been experiencing unprecedented warming (Pachauri & Meyer 2014), and hydrological responses to warming climate have been extensively investigated by research communities in the last decade (Arnell 1999; Fu *et al.*

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2007). In general, such responses occur in the form of reduced water yield (Chiew *et al.* 2014), advanced snow melt (Lutz *et al.* 2014) and more intensified and frequent extreme hydrological events like heavy storms, floods, and prolonged droughts (Hirabayashi *et al.* 2013; Trenberth *et al.* 2014; Yang *et al.* 2015). For instance, a 2% increase in temperature could decrease streamflow by 6% (Wang *et al.* 2016a); and peak runoff would occur one month earlier due to warming temperature in Naryn River basin (Gan *et al.* 2015). It is obvious that these changes might be unfavorable for human well-being and the development of society.

In the context of rapid population growth and social development, various forms of human activities affect hydrological processes directly and indirectly. Human intervention comes in different forms, affecting the hydrological regime explicitly and implicitly. For instance, in Caijiazhuang (CJZ) catchment, as will be discussed later, human activities generally include water abstraction, water infrastructure, and land cover change. Increasing daily agricultural, industrial, and domestic water demands have resulted in increasing water abstraction and regulation to the system through water infrastructure measures that, without doubt, result in direct alteration of hydrologic processes (Sivapalan *et al.* 2012; Destouni *et al.* 2013). For example, Räsänen *et al.* (2017) claimed that hydropower operations in Mekong River basin could increase the spring streamflow by more than 100% and decrease the summer streamflow by more than 30%. On the other hand, dramatic land cover change due to soil water conservation and ecological restoration also significantly affects the water cycle (Zhang *et al.* 2012; Gao *et al.* 2016; Marhaento *et al.* 2016). In the research of Gao *et al.* (2016), 70% of streamflow reduction could be attributed to soil conservation measures in Loess Plateau, China.

Therefore, it is essential to quantify the relative impact of climate change and human activities on streamflow in order to develop better adaptive water resources management strategies and manage the water resources more sustainably for future generations. Numerous studies have investigated this topic using different methods. For example, Zhang *et al.* (2014) applied a multivariate statistical approach to study the streamflow change in a small catchment of Loess Plateau, China and found that 74% of the change was attributed to soil conservation measures and

the remaining 26% was induced by climate change. Wang *et al.* (2016b) investigated Luanhe River basin using sensitivity method and claimed that climate variability and human activities were responsible for 40.9 and 59.1% reduction in streamflow, respectively. Using hydrological simulation method, Bao *et al.* (2012b) found that relative impacts of climate variability and human activities varied greatly between catchments in Haihe River basin (HRB). Renner *et al.* (2014) applied a geometric approach and found that human disturbance resulted in vegetation degradation that led to considerable reduction in evapotranspiration and increase in streamflow.

Each method has its own merit and limitations, therefore, a comparative analysis of two or more approaches could produce more reasonable and reliable results and subsequently provide a comprehensive understanding. As relative studies have not been extensively reported, such an analysis still requires more attention. In this study, two methods (hydrological simulation method and elasticity method) are applied and combined to provide better attribution analysis. The results of this analysis will identify the breaking/changing point which will be used to separate the investigation period into before (baseline) and after (impact period) for streamflow analysis.

In this paper, the impact period is further divided into two sub-periods to see whether there is any significant variation or primary rule switch for the two factors (climate change and human activities) for the CJZ catchment which is located in the upstream of HRB. Compared to some catchments in HRB, which have been well studied in the literature, such as Luan River basin (Xu *et al.* 2013; Zeng *et al.* 2015; Wang *et al.* 2016b) and Miyun reservoir basin (Ma *et al.* 2010; Bao *et al.* 2012a; Zheng *et al.* 2015), this catchment has rarely received attention and focus.

Investigations into detecting streamflow change characteristics and exploring the driving factors are essential to support future water resources management decisions for the local area and enrich the understanding of hydrologic regime evolution. This study is aiming to achieve this through: (1) analyzing the hydro-climatic variables' changing pattern and detect streamflow abrupt change point; (2) separate the effects into climate change and human activities; (3) further discuss the mechanism of contribution from those two factors on hydrologic regime.

DATA AND METHODS

Study area

The CJZ catchment, shown in Figure 1, is located in the upper reach of Zhang River catchment, which is a tributary of HRB. The catchment covers a drainage area of about 446 km², with its elevation ranging from 1,256 m to 1,756 m.

The catchment is dominated by a temperate monsoon climate with annual precipitation of 520 mm and mean annual temperature of 6–7 °C. In the winter, the precipitation occurs in the form of snowfall. The monsoon climate gives the area a flood season from late July to early September and more than 60% of total annual precipitation occurs in this period. Short but intensified rainfall storms usually are likely to produce rapid and severe flash floods, whereas in other seasons, the stream channel conveys considerably lower flows.

Data

The CJZ catchment boundary was delineated using DEM data downloaded from SRTM (Shuttle Radar Topography Mission, <http://srtm.csi.cgiar.org>) with spatial resolution of 90 m, and the HRB boundary map was obtained from

Data Center for Resources and Environmental Sciences (<http://www.resdc.cn>). Daily records of precipitation from four rain gauges within the catchment were used for temporally up-scaled analysis and model inputs, while daily streamflow observation data at outlet stream-gauge were used for long-term streamflow variation study and model calibration (Figure 1). Precipitation and streamflow data for the period 1958–2012 and their geographical locations were obtained from China's Hydrologic Year Book, released by the Hydrological Bureau of the Ministry of Water Resources of China. Areal precipitation was calculated using arithmetic average method. Potential evapotranspiration (E_0) data used in the analysis were calculated using the Hargreaves equation (Hargreaves & Samani 1985), by using maximum, minimum, and mean daily air temperature data from Climate Data Center of China Meteorological Administration (<http://data.cma.cn>).

Trend and abrupt change analysis

It is important to detect trends in hydro-climatic series to suggest whether any change occurs. After doing this, the breaking point will be determined to separate the whole study period into baseline period and impact period.

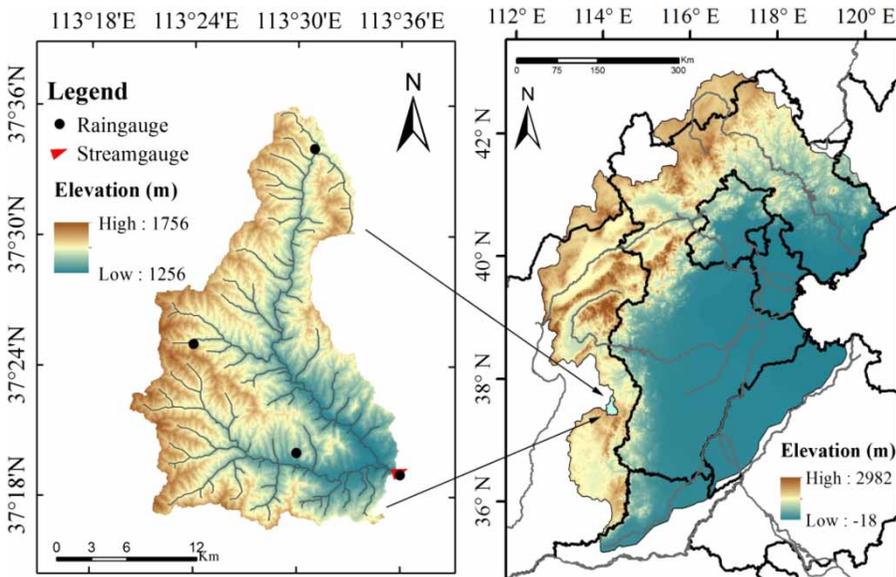


Figure 1 | Location of CJZ catchment (left) in HRB (right).

According to common practice in this field, baseline period is assumed to have minimal human disturbance, meaning that hydrological processes are in a natural state. In this study, the nonparametric Mann–Kendall test (Mann 1945; Kendall 1975) was selected and applied to detect the trend and changing points of streamflow in CJZ catchment. The method is extensively used due to its advantage of not assuming any distributional form of the data (Fu et al. 2004; Jhajharia et al. 2009; Myronidis et al. 2012). The Mann–Kendall’s statistic UF used for null hypothesis test is calculated by the following steps:

$$r_i = \begin{cases} 1, & x_i > x_j \\ 0, & x_i \leq x_j \end{cases} \quad (j = 1, 2, \dots, i - 1) \quad (1)$$

$$S_k = \sum_{i=1}^k r_i \quad (k = 2, 3, \dots, n) \quad (2)$$

$$E(S_i) = \frac{i(i - 1)}{4} \quad (i = 1, 2, \dots, n) \quad (3)$$

$$\text{Var}(S_i) = \frac{i(i - 1)(2i + 5)}{72} \quad (i = 1, 2, \dots, n) \quad (4)$$

where x_i denotes the hydro-climatic variable at a given year i , i is the number of year, j is the number of the year prior to year i , n denotes the length of the data series (here total number of years), S is the intermediate variable with $E(S)$ and $\text{Var}(S)$ being its expected value and variance, respectively.

With all the results above prepared, the Mann–Kendall’s statistic UF is estimated using the following equation:

$$UF_i = \frac{S_i - E(S_i)}{\sqrt{\text{Var}(S_i)}} \quad (i = 1, 2, \dots, n) \quad (5)$$

When the null hypothesis test is rejected, an increasing trend ($UF > 0$) or decreasing trend ($UF < 0$) would be detected. For the case of $|UF| > U_{\alpha/2}$, a statistically significant trend is indicated, where threshold value $U_{\alpha/2}$ is the standard normal deviation at significance level α . In practice, significance level is usually set at 0.05, with its UF being 1.96.

For trend detection, UF_n for the whole series is used to test if it exceeds the threshold value. For changing point analysis, inverse series of $x_j(j = n, n - 1, \dots, 1)$ is

introduced to calculate UF_j , then by defining that the backward sequence $UB_j = -UF_j$, the curves of UF_i and UB_j can be illustrated. The point at which two curves intersect indicates that the series begins to change, and if the absolute value of the point exceeds the threshold, then significant change occurs.

Streamflow elasticity of climate

Streamflow elasticity of climate was proposed by Schaake (1990) to assess the climate impact on streamflow. It is defined as the ratio of proportional change of streamflow to proportional change of a certain climatic factor (such as precipitation or potential evapotranspiration) as follows:

$$\epsilon_X = \frac{\partial Q/Q}{\partial X/X} \quad (6)$$

where ϵ_X is streamflow elasticity of climate, Q is mean annual streamflow, X is climate factor, ∂Q and ∂X are change in streamflow and climate factor. With ϵ_X obtained, one can estimate climate change effect on streamflow (see Attribution analysis). To estimate streamflow elasticity of climate, the Budyko framework-based method is used in this study. According to the Budyko framework, long-term mean annual evapotranspiration showed an empirical relationship with mean annual potential evapotranspiration to mean annual precipitation which act as the demand and supply limit. Following the framework, the elasticity equation can be derived as:

$$\epsilon_P = 1 + \frac{(E_0/P)f'(E_0/P)}{1 - f(E_0/P)}, \quad \text{and } \epsilon_{E_0} = 1 - \epsilon_P \quad (7)$$

where ϵ_P and ϵ_{E_0} denote streamflow elasticity to precipitation P and potential evapotranspiration E_0 , respectively. Several analytical formulations can adequately represent the Budyko framework, among which, Fu’s equation has been widely used (Zhang et al. 2004) and was adopted in this study:

$$\frac{ET}{P} = 1 + \frac{E_0}{P} - \left[1 + \left(\frac{E_0}{P} \right)^w \right]^{1/w} \quad (8)$$

where ET is mean annual evapotranspiration and w is shape parameter. The parameter w indicates the impact of other factors, such as landscape characteristics and climate seasonality (Li et al. 2013). Based on Fu's equation, ε_P is calculated using the following equation:

$$\varepsilon_P = \frac{(1 + (E_0/P)^w) \frac{1-w}{w}}{1 + (E_0/P)^w - E_0/P} \quad (9)$$

In this study, w is fitted at the value of 2.3 so that observed streamflow series of baseline period can be simulated well against Budyko-derived streamflow series. With E_0 , P and w known, ε_P is calculated with the value of 2.1, meaning that 10% change of precipitation leads to 21% change of streamflow, which is similar to those in HRB where the majority of ε_P from various sub-basins ranges from 1.9 to 2.5 (Xu et al. 2014).

Dynamic water balance model

In attribution analysis, it is a key step to use a hydrological model to simulate streamflow during the baseline period because streamflow processes are in natural response to precipitation input, as demonstrated above. With the parameters obtained from the simulation, the hydrological model is executed to reconstruct the 'naturalized' streamflow during the impact period, and subsequently, it will be compared to observed streamflow to find the difference induced by climate variability. In this study, the dynamic water balance model (DWBM) model developed by Zhang et al. (2008) was used to simulate hydrological processes and quantify the relative contribution of climate variability. Due to its parsimony and good conceptualization of water balance, the DWBM model has been extensively applied and shown encouraging performance (Tekleab et al. 2011; Wang et al. 2011a; Li et al. 2012; Zuo et al. 2014). This lumped conceptual model is based on the 'supply and demand' framework which extends the concept of P (supply) and E_0 (demand) in the Budyko equation and generalizes it on a shorter timescale by appropriately defining and describing variables during water balance processes, enabling the consideration of precipitation and potential evapotranspiration seasonality and catchment storage variability. The

model is conceptualized by two types of storage: root-zone storage in the shallow sub-surface area and groundwater storage in the deep aquifer. In different hydrologic cycle stages from ground surface to two storages, the model partitions various water balance components and describes a range of demand and supply relationships, therefore calculating each component by applying generalized Budyko equations.

Initially, rain falls on the ground at a certain time t and is separated by two components: surface runoff $Q_d(t)$ and rainfall retention $X(t)$ which can be considered to constitute the change in soil moisture storage $S(t) - S(t-1)$, evapotranspiration $E(t)$, and recharge $R(t)$. In this stage, the supply limit is the amount of precipitation $P(t)$, whereas the demand limit is the available storage capacity $S_{\max} - S(t-1)$ and potential evapotranspiration $E_0(t)$, termed as $X_0(t)$. Following the similar relationship of the Budyko framework, the $X(t)$ is present as the following equation:

$$\begin{aligned} X(t) &= P(t)f\left(\frac{X_0(t)}{P(t)}, \alpha_1\right) \\ &= P(t)f\left(\frac{E_0(t) + S_{\max} - S(t-1)}{P(t)}, \alpha_1\right) \end{aligned} \quad (10)$$

where $f(\)$ denotes Fu's equation (a variety of Budyko equation), α_1 is the retention efficiency, controlling the partition of direct runoff and retention with lesser α_1 bringing more direct runoff. When water infiltrates downward in the root-zone storage, rainfall retention $X(t)$ and former soil moisture $S(t-1)$ comprise the water availability $W(t)$, which was demanded by evapotranspiration $E(t)$, soil moisture $S(t)$, and recharge $R(t)$. The maximum demand is potential evapotranspiration $E_0(t)$ and soil moisture capacity S_{\max} . Therefore, one can derive each demand component using the equation above:

$$\begin{aligned} E(t) + S(t) &= W(t)f\left(\frac{E_0(t) + S_{\max}}{W(t)}, \alpha_2\right) \\ \text{i.e. } E(t) + S(t) &= (X(t) + S(t-1))f\left(\frac{E_0(t) + S_{\max}}{X(t) + S(t-1)}, \alpha_2\right) \end{aligned} \quad (11)$$

$$\begin{aligned} E(t) &= W(t)f\left(\frac{E_0(t)}{W(t)}, \alpha_2\right) \\ &= (X(t) + S(t-1))f\left(\frac{E_0(t)}{X(t) + S(t-1)}, \alpha_2\right) \end{aligned} \quad (12)$$

where $f()$ denotes Fu's equation, α_2 is the evapotranspiration efficiency, higher α_2 implies more available water transferring to evapotranspiration. Therefore, soil moisture $S(t)$ can be calculated:

$$S(t) = W(t)f\left(\frac{E_0(t) + S_{\max}}{W(t)}, \alpha_2\right) - W(t)f\left(\frac{E_0(t)}{W(t)}, \alpha_2\right) \quad (13)$$

With all terms above ready, recharge $R(t)$ is given as:

$$R(t) = S(t-1) + X(t) - E(t) - S(t) \quad (14)$$

In the next stage, when water comes into deeper groundwater storage which was conceptualized as a linear reservoir, the base-flow $Q_b(t)$ can be considered as a portion of groundwater storage $G(t-1)$ by multiplying a constant d which determines the discharge rate of the 'tank':

$$Q_b(t) = dG(t-1) \quad (15)$$

Then, the water balance of this stage is presented as:

$$G(t) = G(t-1) + R(t) - Q_b(t) = (1-d)G(t-1) + R(t) \quad (16)$$

The total streamflow $Q(t)$ comprises surface runoff $Q_d(t)$ and baseflow $Q_b(t)$, i.e.:

$$Q(t) = Q_d(t) + Q_b(t) \quad (17)$$

With initial variable $S(t-1)$ and $G(t-1)$ set and four parameters, that is, α_1 , α_2 , S_{\max} , and d calibrated, the catchment water balance can be estimated and modeled streamflow can be calculated.

Attribution analysis

A change in mean annual streamflow over two periods can be represented as follows:

$$\Delta Q^{tot} = \bar{Q}_2^{obs} - \bar{Q}_1^{obs} \quad (18)$$

where ΔQ^{tot} denotes the total change of runoff, and \bar{Q}_1^{obs} and \bar{Q}_2^{obs} represent the mean annual streamflow during baseline and impact period, respectively. In any catchment, both

climate variation and human perturbation constitute the source for streamflow change. Given the assumption that anthropogenic factors are independent of climate factors, the total change of streamflow can also be expressed as the forms (Bao et al. 2012b; Wang et al. 2013; Ahn & Merwade 2014):

$$\Delta Q^{tot} = \Delta Q_c + \Delta Q_h \quad (19)$$

where ΔQ_c and ΔQ_h represent streamflow changes due to climate variation and human activities, respectively.

As ΔQ^{tot} can be obtained from observed streamflow records, one needs to either quantify ΔQ_c or ΔQ_h in order to attribute climatic or anthropogenic effect on streamflow. In this study, the streamflow change induced by climate variation ΔQ_c is estimated using both hydrological simulation results from DWBM and calculated streamflow elasticity of climate:

- For the first approach, ΔQ_c is denoted as the difference between simulated mean annual streamflow of the impact period and baseline period, i.e.:

$$\Delta Q_c = \bar{Q}_2^{sim} - \bar{Q}_1^{sim} \quad (20)$$

where \bar{Q}_2^{sim} and \bar{Q}_1^{sim} indicate the mean annual simulated streamflow during impact period and baseline period, respectively.

- For the second approach, ΔQ_c is represented as the change induced by precipitation ΔQ_p and potential evapotranspiration ΔQ_{E_0} according to their corresponding elasticity:

$$\Delta Q_c = \varepsilon_P \frac{Q}{P} \Delta P + \varepsilon_{E_0} \frac{Q}{E_0} \Delta E_0 \quad (21)$$

RESULTS

Long-term hydro-climatic regime variation analysis

Figure 2 illustrates annual precipitation and streamflow variation in CJZ catchment from 1958 to 2012. The precipitation series fluctuated between years with mean,

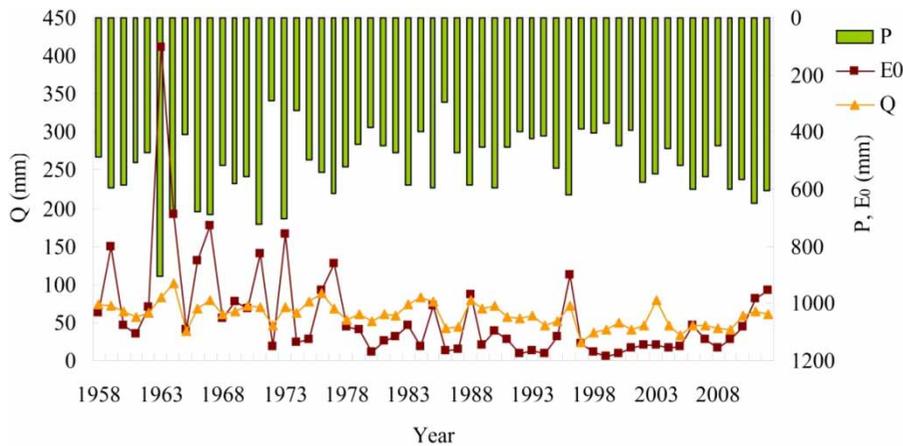


Figure 2 | Long-term hydro-climatic series evolution in CJZ catchment, P, E_0 and Q represent precipitation, potential evapotranspiration, and streamflow, respectively.

maximum, and minimum value being 517 mm, 902 mm (1963) and 294 mm (1986), respectively. It is clear that mean annual precipitation tended to be lower in the 1980s and 1990s; however, an increasing trend occurred after 1998 with an average rate of 15.3 mm/a. The potential evapotranspiration exhibited a steady increasing trend with a rate of 12.9 mm per decade; however, compared to its mean annual value of 1,040 mm, the change in magnitude was not that obvious. The streamflow decreased over time with a rate of -18.9 mm per decade and Z value from Mann–Kendall trend analysis was -3.55 , indicating a significant decreasing trend. The streamflow showed a sharp reduction visually around 1978; a similar changing point was also detected using the Mann–Kendall abrupt change

analysis (see Figure 3). Thus, the whole study period was separated into baseline period (1958–1977) and impact period (1978–2012). The mean annual streamflow after 1978 was 32.6 mm, about 31% of that before the abrupt change (105.5 mm). Therefore, it is both precipitation and streamflow that exhibited substantial change, with the streamflow reduction being more dramatic.

Considering the changing point of streamflow around 1978 and the increasing phase of rainfall after 1998, the entire period was divided into three sub-periods:

- baseline period (1958–1977)
- impact period I (1978–1997)
- impact period II (1998–2012).

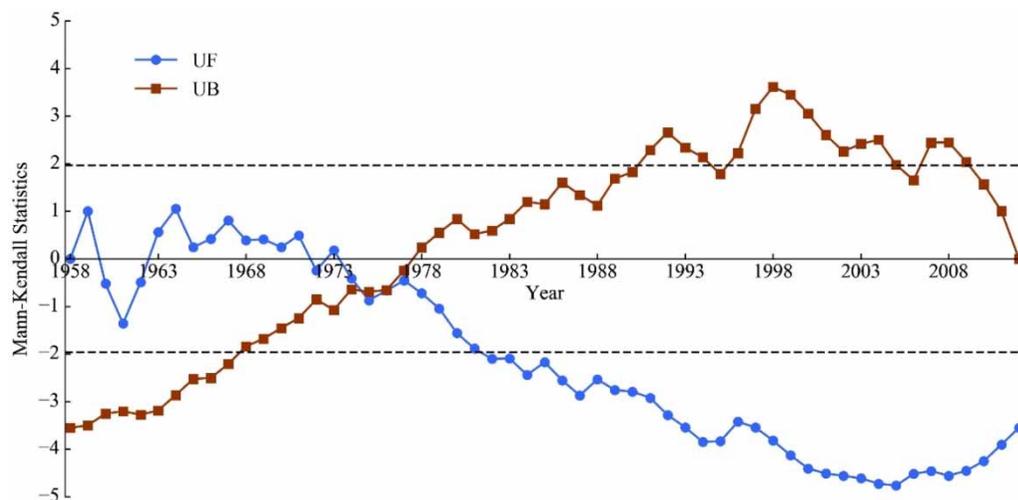


Figure 3 | Streamflow abrupt change detection using Mann–Kendall method.

Table 1 | Summary of potential evapotranspiration, streamflow, and runoff ratio in mm

	Baseline period (1958–1977)	Impact period I (1978–1997)	Impact period II (1998–2012)
Potential ET	1,016	1,041	1,070
Streamflow	105.5	34.4	30.3
Runoff ratio	0.183	0.073	0.06

The mean annual precipitation over the three periods was 577 mm, 469 mm, and 501 mm, respectively. Table 1 summarizes the values of the potential evapotranspiration, streamflow, and runoff ratio under the three periods. The runoff ratio for the three periods is decreasing over the periods following the same trend as streamflow.

To further investigate the inter-relationships between precipitation and streamflow, the precipitation–streamflow double cumulative curve was depicted and it was found that the direction of the curves began to change around 1978 (see Figure 4), implying that the rainfall–runoff relationship had altered. The rainfall–runoff relationships for the three periods are shown in Figure 5. From the figure, it is clear that the points for the two impact periods were lower than those for the baseline period, indicating that with the same amount of precipitation, less runoff was released during the impact periods compared to the baseline period. Furthermore, it is worth noting that the relationship between precipitation and runoff tended to be weaker during the impact periods (lower values of coefficient of

determination), which suggests that the runoff appeared to be influenced by a set of environmental factors apart from precipitation.

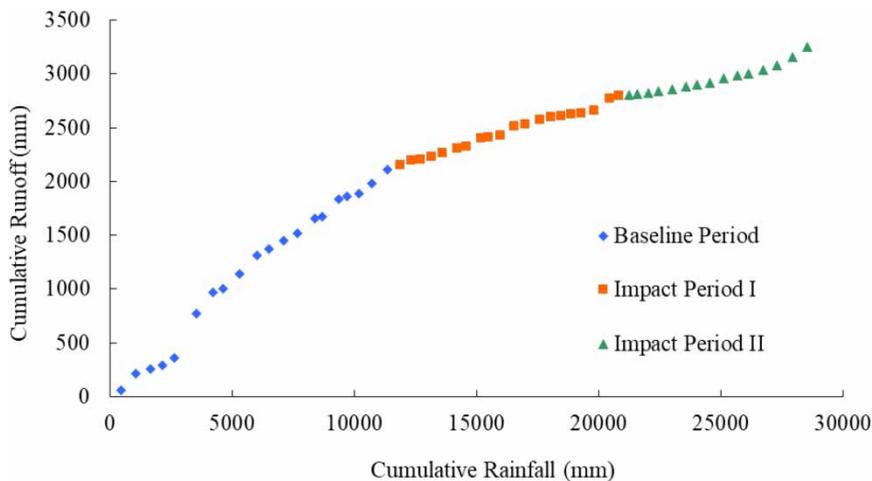
Hydrological simulation

As indicated by attribution analysis method, streamflow of the baseline period (1958–1977) was used for simulation with the DWBM model as the human disturbance could be neglected, which was also supported by the Hydrologic Year Book. Monthly streamflow during the period of 1958–1967 was selected for the calibration with the first two years being spinning up period, while the period of 1968–1977 was selected for the validation. The Rosenbrock method was adopted to obtain the optimized parameters. The observed and the simulated hydrograph are illustrated in Figure 6.

The model performance was assessed by Nash–Sutcliffe efficiency (NSE):

$$NSE = 1 - \frac{\sum_{i=1}^n (Q^{sim}(i) - Q^{obs}(i))^2}{\sum_{i=1}^n (Q^{obs}(i) - \bar{Q}^{obs})^2} \quad (22)$$

where $Q^{sim}(i)$ and $Q^{obs}(i)$ are simulated and observed streamflow on a given month i , n is the number of months, and \bar{Q}^{obs} is the mean value of observed streamflow over the whole period.

**Figure 4** | Double mass curve for precipitation and runoff from 1958 to 2012.

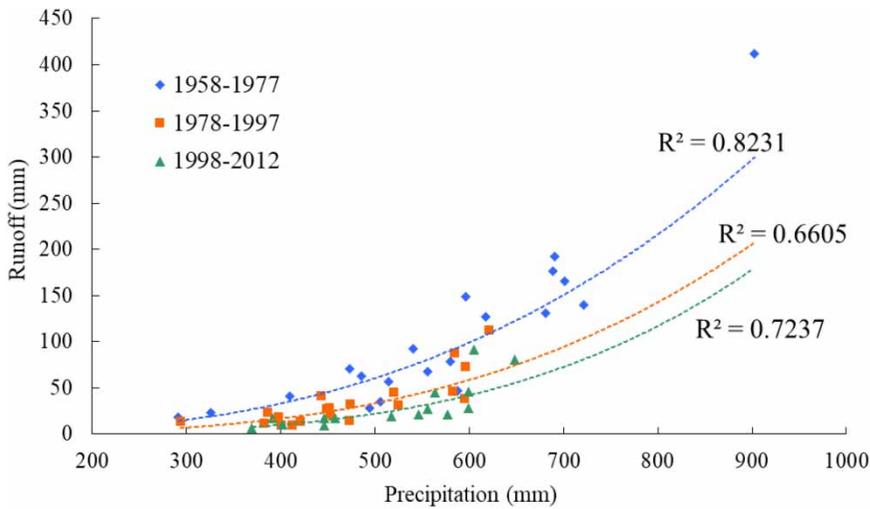


Figure 5 | Rainfall–runoff relationship under three periods (R^2 value is the value of coefficient of determination).

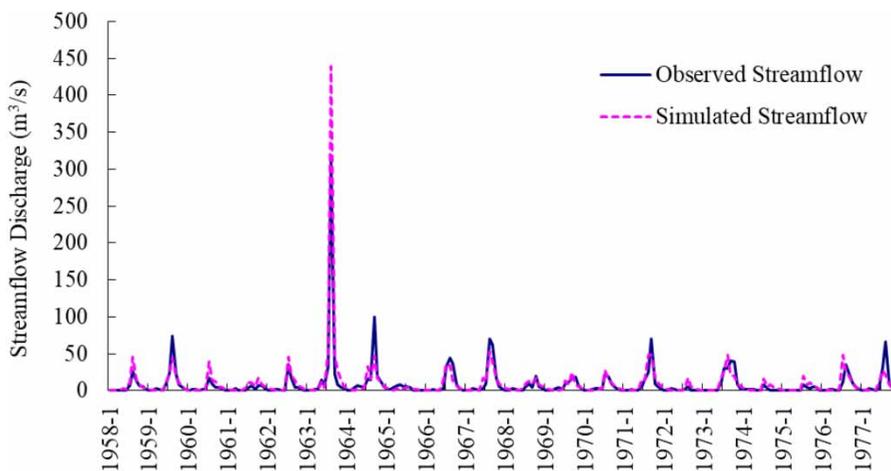


Figure 6 | Observed and simulated monthly streamflow over baseline period.

The model was well calibrated with NSE of 0.796, while NSE in the validation period was 0.715. Both the NSE value of calibration and validation can be accepted as they exceed the value of 0.6, which is defined as the criteria of goodness of fit in common practice. The simulation results indicated that the model can adequately represent the rainfall–runoff processes in the case study. Using the calibrated DWBM model parameters, the streamflow series of the two impact periods were reconstructed. From the comparison of observed and reconstructed streamflow of impact periods (Figure 7), it is clear that the reconstructed streamflow is significantly higher than the observed streamflow. For the two

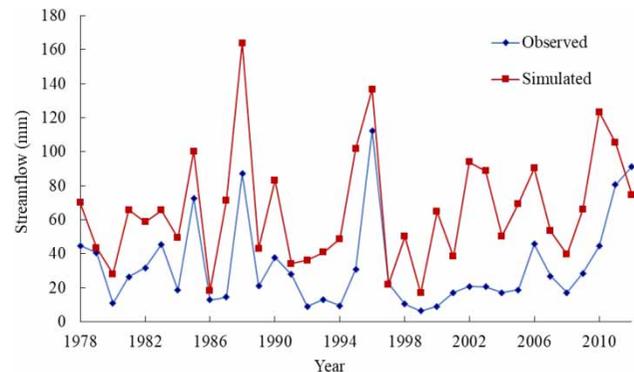


Figure 7 | Observed and simulated annual streamflow over impact periods.

impact periods, I and II, the reconstructed streamflow recorded 57.5 mm and 63.3 mm, respectively, about 67% and one times larger than observed streamflow of the same period.

Quantifying effects of climate variation and human activities on streamflow

Elasticity method and hydrological simulation method were employed to account for the relative contribution of climate variation and human activities on streamflow change. As can be seen in Table 2, from the first method, the streamflow under the two impact periods I and II was lower than the baseline by 46.3 mm and 37.0 mm, respectively. According to the latter approach, climate induced streamflow changes for the two impact periods I and II by 48.0 mm and 42.2 mm. Thus, streamflow change due to human activities over the two impact periods was 24.8 mm (23.1 mm) and 38.2 mm (33.0 mm) using the elasticity method (hydrological simulation method).

Figure 8 presents the comparison of the relative contribution of the two factors (climate variation and human activities) for the two periods to baseline under the different methods (hydrological simulation and elasticity). It is very clear that under the hydrological simulation method, climate variation contributes up to 65.1% and 49.2% of streamflow reduction for impact period I and II, respectively, while under the elasticity method it was 67.5% and 56.1%, respectively. Both methods arrive at a similar conclusion, that the climate change played a dominant role for streamflow reduction under impact period I, while under impact period II, the contribution from human activities increased significantly and tended to be responsible more for streamflow reduction or change, that accounted from 40% to 51%.

Note: S0, S1, and S2 denote baseline period, impact period I, and impact period II, respectively. ΔQ_{c1} and ΔQ_{c2}

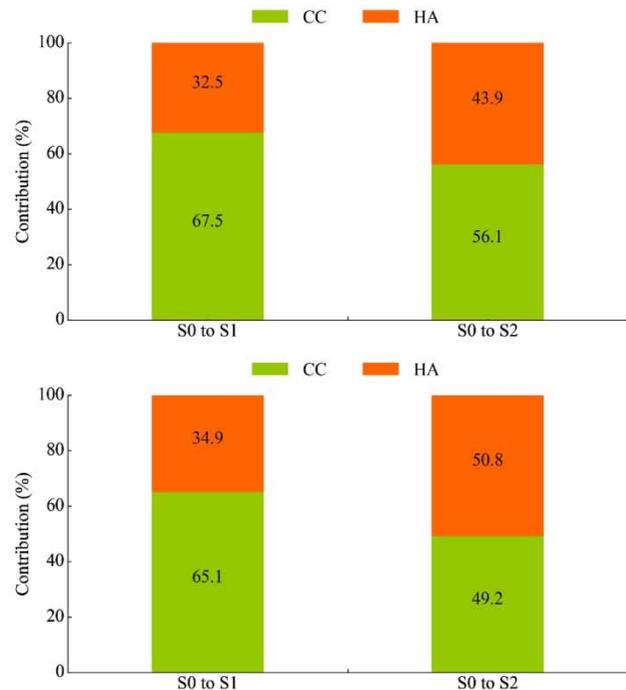


Figure 8 | Relative contribution of climate variation (CC) and human activities (HA) on streamflow for impact period I (S1) and impact period II (S2) compared to baseline period (S0) using hydrological simulation method (top) and elasticity method (bottom).

denote climate-induced streamflow change based on elasticity method and hydrological simulation method. ΔQ_p denotes precipitation-induced streamflow change and ΔQ_{E0} denotes E_0 -induced streamflow change.

DISCUSSION

Climate variation and its hydrological response

The long-term precipitation change has a direct relationship with the large-scale atmospheric circulation variation. HRB is dominated by monsoon climate; its precipitation is closely related to the East Asian summer monsoon (Li & Pan 2006; Ding et al. 2008) with stronger monsoon resulting in less

Table 2 | Climate and streamflow change over three periods

Period	P	E_0	Q	ΔP	ΔE_0	ΔQ	$\Delta Q_{c1}(\Delta Q_p \text{ vs } \Delta Q_{E0})$	ΔQ_{c2}
1958–1977	576.5	1,015.8	105.5					
1978–1997	469.4	1,041	34.4	–107.2	25.3	–71.1	–46.3 (–43.1 vs –3.1)	–48.0
1998–2012	501.4	1,070.1	30.3	–75.1	54.3	–75.2	–37.02 (–30.26 vs –6.76)	–42.2

precipitation, and vice versa. Luo *et al.* (2014) reported that precipitation in the HRB was negatively correlated with NINO3.4 (a variation of El Niño–South Oscillation (ENSO) indicators to characterize monsoon); however, it was significantly increasing during summer in the early 1980s. This could explain the decline in precipitation during the same period.

The CJZ catchment is located within the HRB, thus the precipitation variability of the catchment shows a good agreement with the general pattern of the basin or region (Wang *et al.* 2018b). The streamflow is very sensitive to the variability of the precipitation as reported by numerous studies worldwide, particularly in the drier catchments (Chiew 2006). This can be explained by Equation (21), where the variation of streamflow induced by precipitation change is determined by precipitation elasticity of streamflow, and relative variation of precipitation. Streamflow elasticity of precipitation is about two times that of potential evapotranspiration. More importantly, precipitation is more sensitive to either short-term dry/wet switch of climate variation or long-term climate change than that of potential evapotranspiration and other climatic factors. Thus, streamflow variability is primarily dominated by precipitation in most cases, which explains the majority of the total streamflow change induced by climate variation as shown in Table 2. The changing range detected in this study is in good agreement with published studies (Zheng *et al.* 2009; Xu *et al.* 2014).

From the seasonality perspective, the precipitation exhibited a dramatic decline during the flood season (July and August) when the precipitation of the two impact periods had decreased by more than 30% compared to that of the baseline period (Figure 9). This pattern of variability was also noted by Chu *et al.* (2010); precipitation in

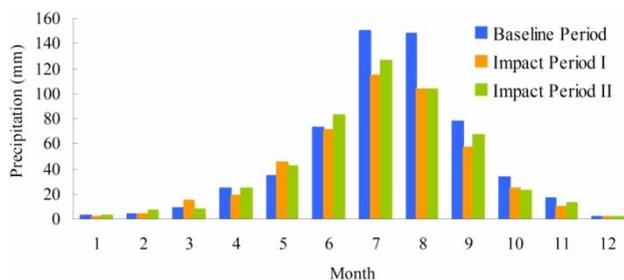


Figure 9 | Seasonal distribution of precipitation under different periods.

HRB showed significant reduction during summer and the declining trend was even strong after the 1980s. As a result of summer precipitation decrease, the streamflow also showed tremendous change during summer months (July and August). Streamflow during the impact periods was only about 20% of that during the baseline period (Figure 10). In addition, streamflow during September and October was also affected by insufficient antecedent precipitation; it was less than one-third of that during the baseline for these months.

However, it should be highlighted that streamflow of January exhibited an increasing trend, although the magnitude is limited. The possible reason for streamflow increasing during the coldest month could be attributed to the warmer winter climate. The rising winter temperature intensifies the soil thawing processes, resulting in streamflow recharged by more frequent infiltrating water from soil thawing. Therefore, rising hydrograph processes occurred earlier and more frequently during the winter and zero flow days tended to disappear. The soil thawing effect on hydrology has been reported as an important issue in boreal and alpine areas across the world (Cherkauer & Lettenmaier 1999; Niu & Yang 2006). It has not been recorded in HRB, north China, although this effect may not be neglected in catchments with higher altitude within the region.

GCM outputs for HRB (Bao *et al.* 2012a) indicated a relatively high degree of confidence that precipitation would be expected to increase during the 21st century. As shown in Figure 2, this projection was somewhat justified by the increasing trend of precipitation from 1998 to 2012, which alleviated the severe streamflow reduction in the last few years. However, how precipitation will change in the

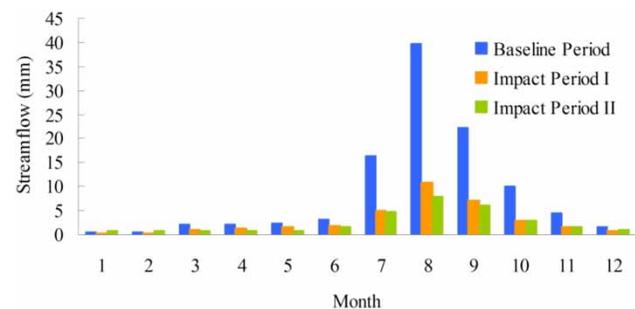


Figure 10 | Seasonal distribution of streamflow under different periods.

future, and what hydrological response will occur, are still not clearly known at present, hence more observations need to be collected and accumulated to explore these issues in the future.

Human activities form and their hydrological responses

As discussed above, human intervention comes in different forms, affecting the hydrological regime explicitly and implicitly. Human activities in CJZ catchment are generally water abstraction, water infrastructure, and land cover change. Water abstraction and water infrastructure regulations are directly altering the streamflow amount and hydrographs. Population growth and social development could be the main attributions for increasing agriculture, industry, and domestic water use, thereby reducing total streamflow. Furthermore, intensive water use has changed the streamflow processes, leaving them more complicated. For example, water returned from irrigation and industrial use significantly disturbs the natural daily streamflow hydrograph. The area is also restrained by the county's mountainous topography. The industrial plants and inhabited areas are deployed along the flatter zones of the county's town center where the mainstream of the CJZ catchment flows, therefore, the population and industry development and distribution pattern are imposing enormous pressure on the water supply. The CJZ hydrometric station is located downstream of the county's town center, so water use will be easily reflected by streamflow data records.

With these water use types understood, how to quantify their possible influences on streamflow reduction will provide further valuable and detailed information on future water resource strategies. Due to the lack of detailed long-term data of human activities, we just took the year 2010 as an example to illustrate the individual influence of different water use types on stream flow reduction. Based on a previous publication (Gao *et al.* 2017), water consumption for irrigation, industry, and domestic demand in the year 2010 is equivalent to 8.5 mm, 3.2 mm, and 2.3 mm of water depth for the study area, respectively. Among them, irrigation accounts for the largest proportion of water use. Although there is only one year of data and water use might be at a lower level, it still reflects water use status in this area to some degree.

Water infrastructure regulation acts as another primary factor of direct human disturbance on hydrology. Although this type of disturbance might not affect mean annual or annual water balance, its impact on streamflow at shorter timescales could be remarkable. Streamflow hydrograph alterations occur in terms of timing, high/low flow magnitude, duration, and frequency (Dang *et al.* 2016) which raise issues in local water management.

In CJZ catchment, the regulation effect tended to be more intensive over time, leading to the fact that consecutive constant flow values occurred more frequently and lasted longer (see Figure 11 – with two samples of daily flow for the two impact periods (1987.6.1 to 1987.8.31 and 2009.6.1 to 2009.8.31), respectively).

From 1987.6.1 to 1987.8.31, the daily streamflow discharge in CJZ catchment responded naturally to daily precipitation events, with rising and recession processes occurring by turns. However, during the same period in 2009, the daily streamflow displayed a totally different pattern. The hydrograph was smooth and stable with a constant value of $0.2 \text{ m}^3/\text{s}$ during most of the time, and only a few flood peaks occurred following storm events; however, the value soon dropped back to $0.2 \text{ m}^3/\text{s}$ within 1 day without any recession processes, which did not reflect the normal response of rainfall. Thus, it is evident that streamflow had been regulated moderately without extremely high or low flows so that floods and droughts could be effectively controlled and channel water could be reserved for recreational and emergency use.

Apart from direct effects, indirect human activities, which mainly occur in the form of land use change, could also induce hydrological regime alteration (Zhang *et al.* 2001; Brown *et al.* 2005). As the region has long implemented the strategic program of afforestation and soil and water conservation, large-scale plantations have been established in this area. Galdos *et al.* (2012) and Donohue *et al.* (2006) indicated that vegetation cover has direct effects on catchment hydrology processes (interception and evapotranspiration) and strongly alter the hydrologic cycle.

Leaf area index (LAI) is a good indicator of vegetation cover and has a significant implication for hydrological processes (Cheng *et al.* 2014). Figure 12 shows the LAI variation for CJZ catchment. It is very clear that LAI has increased significantly with a mean value of 1.36 and 1.47 for the

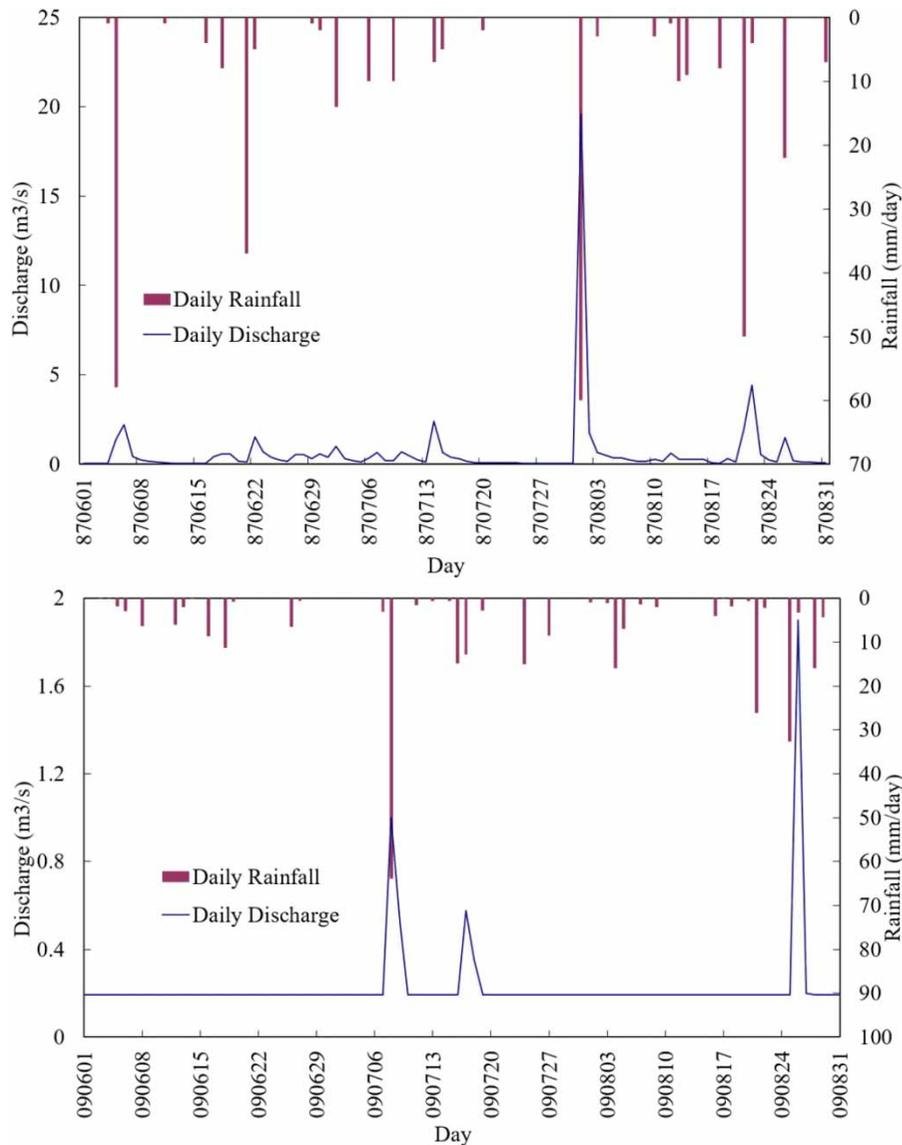


Figure 11 | Typical examples for daily streamflow processes during impact period I (top) and impact period II (down).

two impact periods, respectively. It should be noted that LAI has experienced a fast growth rate of 0.03/a, with Mann-Kendall statistics value being 3.22 which shows a significant trend for impact period II. Larger LAI indicates increased water consumption by vegetation, which results in more interception and evapotranspiration with the subsequent effect of reduced water yield. Thus, this explains that under wetter conditions (impact period II), the streamflow was even less than that of comparatively arid conditions (impact period I).

Previous research carried out for the Zhang River basin where CJZ catchment is located suggested that human activities were contributing about 66.6% and 73.9% of streamflow change for Kuangmenkou and Guantai catchments, respectively (Bao *et al.* 2012b; Xu *et al.* 2014). This is very high in comparison to CJZ catchment in the upstream part. This indicates the trend of increasing human activities' contribution to streamflow change by moving downstream with increasing population, developments, and various water uses. Also, there are a number of water diversion

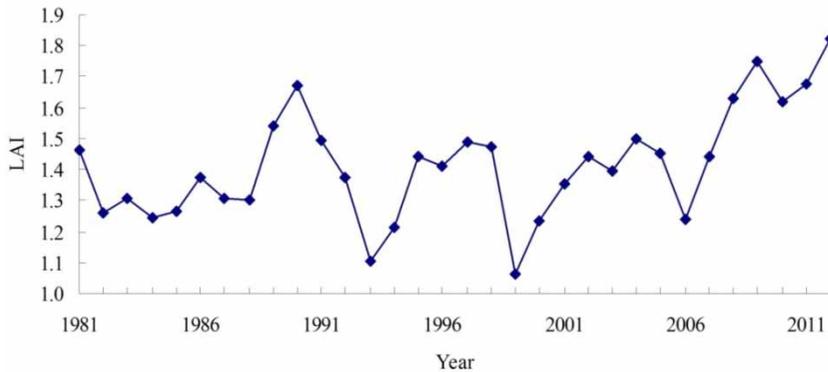


Figure 12 | LAI of CJZ catchment during 1981–2012.

infrastructures on the mainstream of the Zhang River that supply water to other basins, which also plays an important role in intensifying the human intervention.

Uncertainties

It is very important to consider uncertainty in such type of analysis. The uncertainty in this study derived from various sources including input data, model assumption, and model parameters. The available input data could not adequately represent the spatial heterogeneity of the region and this can be a dominant source of uncertainty. As in this study, mountainous topography produces the orographic effects of precipitation, which might increase the bias in computing areal precipitation.

It has been reported in several studies that changing rainfall–runoff relationship induced by climate variation exerts an influence on model parameters (Merz *et al.* 2011; Saft *et al.* 2015), hence the simulation performance. Generally, a hydrological model calibrated during wetter periods tends to overestimate streamflow compared to the drier periods, and vice versa. However, in this study, the model's parameters are treated as time-invariant due to limited data and information; therefore, capturing the hydrological response is still a challenge despite the satisfactory performance from the calibrated parameters.

In the Budyko hypothesis, precipitation and potential evapotranspiration are conceptualized as the only two climatic controls of the mean annual water balance. In the real world, other factors may also impose influences on the water balance processes to various degrees, among

them rainfall seasonality influence (Potter & Zhang 2009). Also, it is generally an implicit assumption that the w in Fu's equation is a steady value given that no land use change occurs. In fact, w is likely to vary with rainfall seasonality and other changing climatic features such as temperature and rainfall variabilities.

The uncertainty in the model outputs resulted from the level of uncertainty in the model preparation and implementation that can induce bias in the calculated streamflow changes influenced by climate variability compared to the observed streamflow changes, hence affecting the partition of climate variation and human intervention impacts on streamflow.

In this study, we categorized two types of drivers for runoff reduction, i.e., human activities and climate change, and quantitatively identified the contribution of each driver to change in runoff. Due to the lack of data of detailed human activities for water uses, we took just 2010 as an example to illustrate the influence of individual human activities on runoff reduction. However, this is not sufficient to represent multiple year average status. Detailed monitoring for water use is essential to reduce the uncertainty in attribution analysis.

CONCLUSIONS

Water resources in North China are very limited and stressed. Streamflow variability and changes are induced by two key factors, climate variation and human activities. China's economic development is progressing very fast with many planned projects in the north that might induce

many challenges and exacerbate streamflow changes. Understanding and quantifying streamflow changes are very significant for water managers and policy-makers in order to sustainably manage the precious water. In this study, long-term hydrological characteristics including mean annual variation and trend, rainfall–runoff relationships, and seasonal distribution of the CJZ catchment were first investigated, then the hydrological simulation methods and Budyko framework based on elasticity were adopted to quantify the contributions of climate variation and human activities on streamflow changes. The paper concludes as follows.

First, the hydro-climatic variables in the CJZ catchment underwent remarkable changes over the entire period of 1958–2012, whereas streamflow change tended to be more dramatic with the abrupt change point occurring around 1978. Three sub-periods were separated (baseline period (1958–1977), impact period I (1978–1997), and impact period II (1998–2012)).

Second, seasonal distribution change showed that precipitation as well as streamflow decreased significantly during the summer season. However, there was an increase in streamflow during the winter season, which might indicate the advanced and increased soil thawing processes under warmer winters.

Third, the relative contribution of streamflow changes due to climate variation using two methods (elasticity and hydrological simulations); ranges decrease from 65.1% (67.5%) for impact period I to 49.2% (56.1%) for impact period II, indicating more extensive and intensified human activities over the periods and, in particular, under period II. Human activities come in various forms, including water withdrawal, water infrastructure regulation, and land cover change, and all of these have profound influences on streamflow regimes.

Quantifying the contribution of climate and human impacts on streamflow provides better insights on how to adjust and manage the water resources utilization strategies under changing climate conditions in the future to sustain social and economic developments. This study investigated the relative contribution of climate variability and human activities on streamflow change, and qualitatively state how different forms of human activities alter streamflow. However, to what extent these forms of disturbance

influence the streamflow, and how they interact with future climate change still requires further quantitative studies based on detailed long-term data, and these works will be explored in further research.

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REFERENCES

- Ahn, K.-H. & Merwade, V. 2014 [Quantifying the relative impact of climate and human activities on streamflow](#). *Journal of Hydrology* **515**, 257–266.
- Arnell, N. W. 1999 [The effect of climate change on hydrological regimes in Europe: a continental perspective](#). *Global Environmental Change* **9** (1), 5–23.
- Bao, Z., Fu, G., Wang, G., Jin, J., He, R., Yan, X. & Liu, C. 2012a [Hydrological projection for the Miyun Reservoir basin with the impact of climate change and human activity](#). *Quaternary International* **282**, 96–103.
- Bao, Z., Zhang, J., Wang, G., Fu, G., He, R., Yan, X., Jin, J., Liu, Y. & Zhang, A. 2012b [Attribution for decreasing streamflow of the Haihe River basin, northern China: climate variability or human activities?](#) *Journal of Hydrology* **460**, 117–129.
- Brown, A. E., Zhang, L., McMahon, T. A., Western, A. W. & Vertessy, R. A. 2005 [A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation](#). *Journal of Hydrology* **310** (1), 28–61.
- Brutsaert, W. 2005 *Hydrology: An Introduction*. Cambridge University Press, New York.
- Cheng, L., Zhang, L., Wang, Y.-P., Yu, Q., Eamus, D. & O'Grady, A. 2014 [Impacts of elevated CO₂, climate change and their interactions on water budgets in four different catchments in Australia](#). *Journal of Hydrology* **519**, 1350–1361.
- Cherkauer, K. A. & Lettenmaier, D. P. 1999 [Hydrologic effects of frozen soils in the upper Mississippi River basin](#). *Journal of*

- Geophysical Research: Atmospheres* **104** (D16), 19599–19610.
- Chiew, F. H. 2006 Estimation of rainfall elasticity of streamflow in Australia. *Hydrological Sciences Journal* **51** (4), 613–625.
- Chiew, F. H. S., Potter, N. J., Vaze, J., Petheram, C., Zhang, L., Teng, J. & Post, D. A. 2014 Observed hydrologic non-stationarity in far south-eastern Australia: implications for modelling and prediction. *Stochastic Environmental Research and Risk Assessment* **28** (1), 3–15.
- Chu, J., Xia, J., Xu, C., Li, L. & Wang, Z. 2010 Spatial and temporal variability of daily precipitation in Haihe River basin, 1958–2007. *Journal of Geographical Sciences* **20** (2), 248–260.
- Dang, T. D., Cochran, T. A., Arias, M. E., Van, P. D. T. & Vries, T. T. 2016 Hydrological alterations from water infrastructure development in the Mekong floodplains. *Hydrological Processes* **30** (21), 3824–3838.
- Destouni, G., Jaramillo, F. & Prieto, C. 2013 Hydroclimatic shifts driven by human water use for food and energy production. *Nature Climate Change* **3** (3), 213–217.
- Ding, Y., Wang, Z. & Sun, Y. 2008 Inter-decadal variation of the summer precipitation in East China and its association with decreasing Asian summer monsoon. Part I: observed evidences. *International Journal of Climatology* **28** (9), 1139–1161.
- Donohue, R., Roderick, M. & McVicar, T. R. 2006 On the importance of including vegetation dynamics in Budyko's hydrological model. *Hydrology and Earth System Sciences Discussions* **3** (4), 1517–1551.
- Fu, G., Chen, S., Liu, C. & Shepard, D. 2004 Hydro-climatic trends of the Yellow River basin for the last 50 years. *Climatic Change* **65** (1–2), 149–178.
- Fu, G., Barber, M. E. & Chen, S. 2007 Impacts of climate change on regional hydrological regimes in the Spokane River Watershed. *Journal of Hydrologic Engineering* **12** (5), 452–461.
- Galdos, F. V., Álvarez, C., García, A. & Revilla, J. A. 2012 Estimated distributed rainfall interception using a simple conceptual model and Moderate Resolution Imaging Spectroradiometer (MODIS). *Journal of Hydrology* **468**, 213–228.
- Gan, R., Luo, Y., Zuo, Q. & Sun, L. 2015 Effects of projected climate change on the glacier and runoff generation in the Naryn River Basin, Central Asia. *Journal of Hydrology* **523**, 240–251.
- Gao, Z., Zhang, L., Zhang, X., Cheng, L., Potter, N., Cowan, T. & Cai, W. 2016 Long-term streamflow trends in the middle reaches of the Yellow River Basin: detecting drivers of change. *Hydrological Processes* **30** (9), 1315–1329.
- Gao, Y., Hu, H. & Wang, G. 2017 *Rainfall and Runoff Evolution Principles and Water Resources Optimized Allocation in Zhang River Watershed*. China Water & Power Press, Beijing, China (in Chinese).
- Hargreaves, G. H. & Samani, Z. A. 1985 Reference crop evapotranspiration from temperature. *Applied Engineering in Agriculture* **1** (2), 96–99.
- Hirabayashi, Y., Mahendran, R., Koirala, S., Konoshima, L., Yamazaki, D., Watanabe, S., Kim, H. & Kanae, S. 2013 Global flood risk under climate change. *Nature Climate Change* **3** (9), 816–821.
- Jhajharia, D., Shrivastava, S. K., Sarkar, D. & Sarkar, S. 2009 Temporal characteristics of pan evaporation trends under the humid conditions of northeast India. *Agricultural & Forest Meteorology* **149** (5), 763–770.
- Kendall, M. 1975 *Rank Correlation Measures*. Griffith, London, UK.
- Li, C. & Pan, J. 2006 Atmospheric circulation characteristics associated with the onset of Asian summer monsoon. *Advances in Atmospheric Sciences* **23** (6), 925–939.
- Li, C., Zhang, L., Wang, H., Zhang, Y., Yu, F. & Yan, D. 2012 The transferability of hydrological models under nonstationary climatic conditions. *Hydrology and Earth System Sciences* **16** (4), 1239–1254.
- Li, D., Pan, M., Cong, Z., Zhang, L. & Wood, E. 2013 Vegetation control on water and energy balance within the Budyko framework. *Water Resources Research* **49** (2), 969–976.
- Luo, Y., Wang, Z., Liu, X. & Zhang, M. 2014 Spatial and temporal variability of precipitation in Haihe River Basin, China: characterization and management implications. *Advances in Meteorology* **2014** (14), 701–718.
- Lutz, A., Immerzeel, W., Shrestha, A. & Bierkens, M. 2014 Consistent increase in High Asia's runoff due to increasing glacier melt and precipitation. *Nature Climate Change* **4** (7), 587–592.
- Ma, H., Yang, D., Tan, S. K., Bing, G. & Hu, Q. 2010 Impact of climate variability and human activity on streamflow decrease in the Miyun Reservoir catchment. *Journal of Hydrology* **389** (3–4), 317–324.
- Mann, H. B. 1945 Nonparametric tests against trend. *Econometrica: Journal of the Econometric Society* **13**, 245–259.
- Marhaento, H., Booij, M. J. & Hoekstra, A. Y. 2016 Attribution of changes in stream flow to land use change and climate change in a mesoscale tropical catchment in Java, Indonesia. *Hydrology Research* **48** (4), 1143–1155.
- Merz, R., Parajka, J. & Blöschl, G. 2011 Time stability of catchment model parameters: implications for climate impact analyses. *Water Resources Research* **47** (2), 2144–2150.
- Montanari, A., Young, G., Savenije, H. H. G., Hughes, D., Wagener, T., Ren, L. L., Koutsoyiannis, D., Cudennec, C., Toth, E. & Grimaldi, S. 2013 Panta Rhei-everything flows: change in hydrology and society – The IAHS Scientific Decade 2013–2022. *Hydrological Sciences Journal/Journal Des Sciences Hydrologiques* **58** (6), 1256–1275.
- Myronidis, D., Stathis, D., Ioannou, K. & Fotakis, D. 2012 An integration of statistics temporal methods to track the effect of drought in a shallow Mediterranean lake. *Water Resources Management* **26** (15), 4587–4605.
- Niu, G.-Y. & Yang, Z.-L. 2006 Effects of frozen soil on snowmelt runoff and soil water storage at a continental scale. *Journal of Hydrometeorology* **7** (5), 937–952.

- Pachauri, R. K. & Meyer, L. A. 2014 IPCC, 2014: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva.
- Potter, N. J. & Zhang, L. 2009 Interannual variability of catchment water balance in Australia. *Journal of Hydrology* **369** (1–2), 120–129.
- Räsänen, T. A., Someth, P., Lauri, H., Koponen, J., Sarkkula, J. & Kumm, M. 2017 Observed river discharge changes due to hydropower operations in the Upper Mekong Basin. *Journal of Hydrology* **545**, 28–41.
- Renner, M., Brust, K., Schwärzel, K., Volk, M. & Bernhofer, C. 2014 Separating the effects of changes in land cover and climate: a hydro-meteorological analysis of the past 60 yr in Saxony, Germany. *Hydrology and Earth System Sciences* **18**, 389–405.
- Saft, M., Western, A. W., Zhang, L., Peel, M. C. & Potter, N. J. 2015 The influence of multiyear drought on the annual rainfall-runoff relationship: an Australian perspective. *Water Resources Research* **51** (4), 2444–2463.
- Schaake, J. C. 1990 From climate to flow. In: *Climate Change and US Water Resources* (P. E. Waggoner, ed.). John Wiley and Sons Inc., New York, USA, pp. 177–206.
- Sivapalan, M., Savenije, H. H. & Blöschl, G. 2012 Socio-hydrology: A new science of people and water. *Hydrological Processes* **26** (8), 1270–1276.
- Tekleab, S., Uhlenbrook, S., Mohamed, Y., Savenije, H., Temesgen, M. & Wenninger, J. 2011 Water balance modeling of Upper Blue Nile catchments using a top-down approach. *Hydrology and Earth System Sciences* **15** (7), 2179–2193.
- Trenberth, K. E., Dai, A., van der Schrier, G., Jones, P. D., Barichivich, J., Briffa, K. R. & Sheffield, J. 2014 Global warming and changes in drought. *Nature Climate Change* **4** (1), 17–22.
- Wang, E., Zhang, Y., Luo, J., Chiew, F. H. & Wang, Q. 2011a Monthly and seasonal streamflow forecasts using rainfall-runoff modeling and historical weather data. *Water Resources Research* **47** (5), W05516.
- Wang, Z., Luo, Y., Liu, C., Xia, J. & Zhang, M. 2011b Spatial and temporal variations of precipitation in Haihe River Basin, China: six decades of measurements. *Hydrological Processes* **25** (18), 2916–2923.
- Wang, W., Shao, Q., Yang, T., Peng, S., Xing, W., Sun, F. & Luo, Y. 2013 Quantitative assessment of the impact of climate variability and human activities on runoff changes: a case study in four catchments of the Haihe River basin, China. *Hydrological Processes* **27** (8), 1158–1174.
- Wang, G., Zhang, J., Pagano, T. C., Xu, Y., Bao, Z., Liu, Y., Jin, J., Liu, C., Song, X. & Wan, S. 2016a Simulating the hydrological responses to climate change of the Xiang River basin, China. *Theoretical and Applied Climatology* **124** (3–4), 769–779.
- Wang, H., Chen, L. & Yu, X. 2016b Distinguishing human and climate influences on streamflow changes in Luan River basin in China. *Catena* **136**, 182–188.
- Xu, X., Yang, H., Yang, D. & Ma, H. 2013 Assessing the impacts of climate variability and human activities on annual runoff in the Luan River basin, China. *Hydrology Research* **44** (5), 940.
- Xu, X., Yang, D., Yang, H. & Lei, H. 2014 Attribution analysis based on the Budyko hypothesis for detecting the dominant cause of runoff decline in Haihe basin. *Journal of Hydrology* **510**, 530–540.
- Yang, L., Scheffran, J., Qin, H. & You, Q. 2015 Climate-related flood risks and urban responses in the Pearl River Delta, China. *Regional Environmental Change* **15** (2), 379–391.
- Zeng, S., Zhan, C., Sun, F., Du, H. & Wang, F. 2015 Effects of climate change and human activities on surface runoff in the Luan River Basin. *Advances in Meteorology* **2015** (6), 1–12.
- Zhang, L., Dawes, W. & Walker, G. 2001 Response of mean annual evapotranspiration to vegetation changes at catchment scale. *Water Resources Research* **37** (3), 701–708.
- Zhang, L., Hickel, K., Dawes, W. R., Chiew, F. H. S., Western, A. W. & Briggs, P. R. 2004 A rational function approach for estimating mean annual evapotranspiration. *Water Resources Research* **40** (2), W02502.
- Zhang, L., Podlasly, C., Ren, Y., Feger, K. H., Wang, Y. & Kai, S. 2014 Separating the effects of changes in land management and climatic conditions on long-term streamflow trends analyzed for a small catchment in the Loess Plateau region, NW China. *Hydrological Processes* **28** (3), 1284–1293.
- Zhang, L., Potter, N., Hickel, K., Zhang, Y. & Shao, Q. 2008 Water balance modeling over variable time scales based on the Budyko framework – Model development and testing. *Journal of Hydrology* **360** (1–4), 117–131.
- Zhang, L., Zhao, F. & Brown, A. 2012 Predicting effects of plantation expansion on streamflow regime for catchments in Australia. *Hydrology and Earth System Sciences* **16** (7), 2109–2121.
- Zheng, H., Zhang, L., Zhu, R., Liu, C., Sato, Y. & Fukushima, Y. 2009 Responses of streamflow to climate and land surface change in the headwaters of the Yellow River Basin. *Water Resources Research* **45** (7), W00A19.
- Zheng, J., Sun, G., Li, W., Yu, X., Zhang, C., Gong, Y. & Tu, L. 2015 Impacts of land use change and climate variations on annual inflow into the Miyun Reservoir, Beijing, China. *Hydrology & Earth System Sciences Discussions* **12** (8), 7785–7819.
- Zuo, D., Xu, Z., Wu, W., Zhao, J. & Zhao, F. 2014 Identification of streamflow response to climate change and human activities in the Wei River Basin, China. *Water Resources Management* **28** (3), 833–851.

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