

## Trend and change points of streamflow in the Yellow River and their attributions

Dunyu Zhong, Zengchuan Dong, Guobin Fu, Jiaqi Bian, Feihe Kong, Wenzhuo Wang and Yan Zhao

### ABSTRACT

The impacts of climate change and human activity, combined with streamflow reduction in the Yellow River Basin, have presented significant challenges to water resource management strategies. Here, the trends and change points of streamflow were determined for the period 1956–2017 via five statistical methods. A runoff-sensitive coefficients method (the Budyko hypothesis) and a conceptual rainfall–runoff model (the TUW model) were applied to assess the streamflow variation. The following conclusions were ascertained: (1) 1989, 1986, and 1990 were the change points for streamflow in the upstream Tang-Nai-Hai and Lan-Zhou stations and the downstream Hua-Yuan-Kou hydrological station; (2) the streamflow showed statistically significant decreasing trends with spatiotemporal variations in the Yellow River Basin; (3) the relationship between runoff and precipitation showed a downward trend over time; (4) comparisons of the Budyko and TUW models show that human activity is responsible for more than 65% of streamflow reduction, while climate change contributes to less than 35% of the reduction. Therefore, human activity is the main reason for streamflow reduction in the Yellow River Basin. This finding is of critical importance for water resources management under changing environment.

**Key words** | climate change, human activities, streamflow variation, Yellow River

### INTRODUCTION

The temporal and spatial distribution of runoff is affected by both climate change and human activities (Ma *et al.* 2010; Tan & Gan 2015). Accordingly, streamflow changes under a changing environment, as well as the contributions of climate change and human activities to streamflow changes, must be thoroughly understood for effective water resource management. Climate change mainly affects streamflow through precipitation and temperature. With an increase in both global temperature and rainstorm frequency, the streamflow in river basins shows either an increasing or a decreasing

trend (Fu *et al.* 2007b; Silberstein *et al.* 2012; Hattermann *et al.* 2018; Sönmez & Kale 2020). Human activities affect the mechanism of streamflow generation and confluence by changing the underlying surface of the river basin. For example, irrigation, reservoir construction, land use, and land cover change all exacerbate changes in streamflow (Ahn & Merwade 2014; Felfelani *et al.* 2017; Liu *et al.* 2020). Therefore, quantifying the contribution of climate change versus the contribution of human activities to runoff change is a current challenge in the field of environmental change impact research. Furthermore, the analysis of river responses to climate change and human activities is the basis for understanding hydrology and land use management in river basins.

In response to the recent increase in water resource shortages resulting from environmental changes, many

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methods have been proposed to assess the impacts of climate change and human activities on runoff (Sankarasubramanian *et al.* 2001; Zhang *et al.* 2009; Li & Singh 2014; Brikowski 2015; Slezziak *et al.* 2016); these mainly include catchment experiments, empirical statistical methods, hydrological models, and elasticity-based methods. The catchment experiment helps us understand the effects of the hydrologic cycle and land use on hydrologic cycle; however, catchment experiments are generally applicable to small watersheds (Chang *et al.* 2015). The empirical statistical methods use long time series data to establish the correlation between climate factors and runoff to analyze the effects of climate change. This method requires time series data to be long enough and lacks physical meanings (Gao *et al.* 2016). The hydrological model method allows the study of the hydrological cycle of a river; this is based on the physical significance of simulating a river basin's hydrological cycle process to analyze the impacts of climate change and human activities on runoff (Chang *et al.* 2015; Zhang *et al.* 2017a). However, the structure and parameters of the model are uncertain, input data requirements are high, and the varying accuracy of data sources may lead to high errors in simulation results. In contrast, elasticity-based methods use observed meteorological and hydrological data directly to assess runoff responses to climate change. There have been many studies to quantify the effects of precipitation changes and temperature on runoff using the streamflow elasticity model (Fu *et al.* 2007a; Zhang *et al.* 2017b). The Budyko hypothesis (Budyko *et al.* 1974) is not only easy to implement, but also includes climate factors and underlying surface characteristic parameters in a watershed context. Recently, the Budyko hypothesis was widely applied to assess the impact of climate change and human activity on streamflow (Zheng *et al.* 2009; Roderick & Farquhar 2011; Yang *et al.* 2014; Liu *et al.* 2017). At present, it is considered that hydrothermal coupling control parameters are controlled mainly by climate factors and underlying surface characteristics. However, the adaptability of different Budyko equations to underlying surfaces varies, and some formulas cannot reflect the influence of different underlying surfaces well. Wu *et al.* (2017) analyzed the applicability of the Budyko framework in different timescales and found that it performs well at long-term mean annual scale and its performance in arid regions is

better than in humid regions. Ning *et al.* (2018) used four methods (total differential, complementary, extrapolation, and decomposition) to analyze the actual evapotranspiration of 13 watersheds in the Loess Plateau in China. The results show that the contribution of total difference method, complementary method, and decomposition method to climate change and human activities has been estimated similarly. Based on this, this study uses the Budyko framework to quantify the impacts on runoff from both climate change and human activities, and uses the hydrological model to confirm the robustness of the Budyko model and the reliability of the research results.

The Yellow River is China's mother river; it supports 12% of the national population and feeds 15% of the irrigation area. Influenced by global climate change and human activities, the streamflow of the Yellow River has changed significantly. Since 1970, zero-flow events have occurred in the lower Yellow River Basin (Zhang *et al.* 2008). These changes pose serious challenges to the management of water resources in the Yellow River. Therefore, it is necessary to assess the contribution of human activities and climate change to changes in Yellow River runoff. Numerous investigations have been conducted to identify the characteristics of climate change and human activity across the Yellow River Basin (Fu *et al.* 2007b; Huang *et al.* 2009; Li *et al.* 2017a; Jin *et al.* 2020). Huang *et al.* (2009) analyzed the total days of rainstorm and the average precipitation of the rainstorm days in a year in the Yellow River, finding that the total days of rainstorm show an increasing trend from 1957 to 2006. Fu *et al.* (2013) analyzed the time series of the number of extreme rainfall events for various rainfall durations (1, 5, 10, and 30 days) based on the extreme precipitation index; the results indicated that the Yellow River basin had experienced a decreasing trend of extreme rainfall events during the last 50 years. Tang *et al.* (2013) found that the Yellow River runoff showed a pick-up phenomenon in the period of 2003–2011 compared with that in the current period (1991–2002), although it remains less than the base period (1960–1990). Zhao *et al.* (2014) quantified the impact of variability and human activities on streamflow in the middle reaches of the Yellow River basin and reported that water and soil conservation, reservoir operation, and water consumption were the main reasons for the significant decline in the annual

streamflow. *Li et al. (2017a)* investigated the contribution of human activity to streamflow reduction in the Yellow River Basin, finding a mean fractional contribution of 73.4% from 1980 to 2000 and 82.5% from 2001 to 2014. *Li et al. (2017b)* discussed the cropland and climatic change impacts on streamflow change in the Yellow River using the Budyko framework; results indicated streamflow decreased significantly from the mid-1980s until the mid-1990s. *Jin et al. (2020)* found that recorded temperature presented a significant increasing trend. Daily minimum temperature presented a higher increasing trend than daily maximum temperature during the period 1951–2014 in the Yellow River source region.

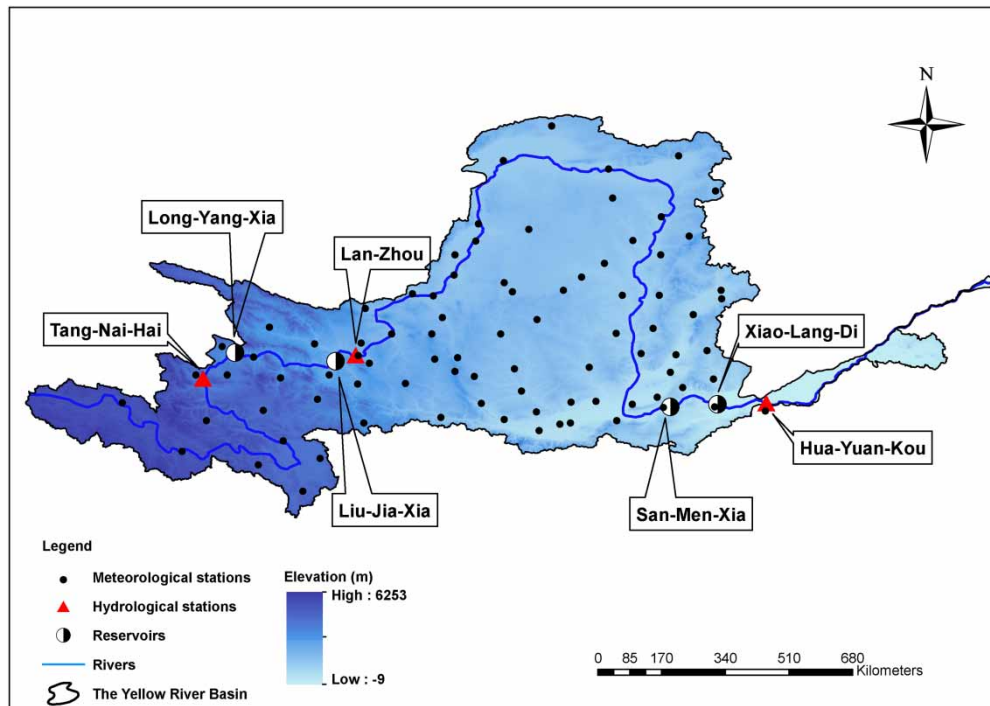
Despite the insights into streamflow reduction garnered from these works, streamflow investigations have yet to thoroughly consider hydrologic variation. Under the dual influence of climate change and human activities, a hydrologic situation undergoes dramatic changes, such that the overall distribution before and after hydrologic variation significantly varies. Accordingly, analysis of hydrologic variation can further inform the causes of hydrological variation and reveal the extent to which various factors influence river runoff.

This work aims to examine the hydrological regimes of streamflow in the Yellow River Basin by: (1) analyzing the trend and change points of streamflow during different periods; (2) assessing the spatial and temporal variation of streamflow; (3) exploring the relationships between streamflow and precipitation; and (4) quantifying the contributions of climate change and human activities to streamflow variations.

## MATERIAL AND METHODS

### Study area

The Yellow River, which is the second largest river in China, is located between  $95^{\circ}53'$ – $119^{\circ}05'$  E,  $32^{\circ}10'$ – $41^{\circ}50'$  N (*Figure 1*). The Yellow River originates from the Bayan Kala Mountain on the Qinghai-Tibet Plateau, flowing through nine provinces from west to east. It is injected into the Bohai Sea, Shandong Province, with a total length of 5,464 km and a basin area of 752,443 km<sup>2</sup> (*Wang et al. 2018*). Unlike other rivers, the upper and middle reaches



**Figure 1** | Locations of hydrological stations and meteorological stations in the Yellow River Basin, China.

of the Yellow River Basin account for 97% of the total area. The basin above the Tang-Nai-Hai station is the headwater region of the Yellow River, with a drainage area of 121,972 km<sup>2</sup>. The watershed above the Lan-Zhou station, with an area of 222,551 km<sup>2</sup>, is the main source of runoff of the Yellow River and produces approximately 55.6% of the total annual average runoff (Fu et al. 2007b). Hua-Yuan-Kou station is the boundary point between the middle and lower reaches of the Yellow River, with a catchment area of 730,036 km<sup>2</sup>, and is the most important station in terms of hydrologic station.

## Data

The monthly observed and naturalized streamflow data time series for three major hydrologic stations (Tang-Nai-Hai, Lan-Zhou, Hua-Yuan-Kou) from 1956 to 2017 were obtained from the Hydrological Bureau of Yellow River Conservancy Commission of Ministry of Water Resource. Daily streamflow data were only collected at the Tang-Nai-Hai station from 1970 to 2017 and were used for calibration and simulation of the hydrological model.

Climate data from 1956 to 2016 were obtained from 86 meteorological stations and consisted of daily precipitation, temperature, sunshine time, wind speed, and relative humidity. The meteorological data were obtained from the Climatic Data Centre, National Meteorological Information Centre of the China Meteorological Administration (<http://data.cma.cn>).

## Detection of change points

Under the dual influence of climate change and human activities, the statistical rules of hydrological sequences have significant variation before and after a certain time point (Duhan & Pandey 2013). Here, this is referred to as the change point. The change point of the hydrological sequence is analyzed to understand and diagnose the change rules of the hydrological sequence. With different assumptions and application conditions inherent to various test methods, results of change point analysis often vary in practical application. To avoid this potential lack of robustness from the utilization of a single method, this study uses a combination of multiple methods to analyze change points;

the following methods were used to explore the abrupt changes of streamflow series in the Yellow River: the Rank sum test (Shi et al. 2017), the Mann–Kendall test (Yi et al. 2013; Langat et al. 2017), the Moving t-test (Zhang et al. 2017a), the Ordered cluster analysis (Lei et al. 2007), and the Pettitt test (Wei et al. 2016).

## Detection of trend

The Mann–Kendall test is a non-parametric test method proposed by Mann and Kendall (Kendall 1975; Hirsch et al. 1982) and recommended by the World Meteorological Organization (Chaudhuri & Dutta 2014). The Mann–Kendall test method does not require a certain distribution and will be not influenced by abnormal values. Therefore, this method has been widely utilized by many researchers in meteorology and hydrology to analyze the time series change trends of runoff, temperature, precipitation, and water quality, which are usually non-normally distributed (Fu et al. 2004; Petrone et al. 2010; Shi et al. 2017; Chang et al. 2018). The Mann–Kendall test statistic is calculated by:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^n \text{sgn}(x_j - x_i) \quad (1)$$

and

$$\text{sgn}(x) = \begin{cases} 1 & \text{if } x > 0 \\ 0 & \text{if } x = 0 \\ -1 & \text{if } x < 0 \end{cases} \quad (2)$$

where  $n$  is the length of a sequence. When  $n > 8$ , it is assumed that the measured data are independent and identically distributed, the statistic  $S$  obeys normal distribution, and its mean and variance satisfy the following formula:

$$E(S) = 0 \quad (3)$$

$$\text{Var}(S) = \frac{\{n(n-1)(2n+5) - \sum_t t(t-1)(2t+5)\}}{18} \quad (4)$$

where  $t$  is the extent of any given tie. The statistic  $S$  is approximately normally distributed, provided that the

following Z-transformation is employed (Hirsch et al. 1982):

$$Z = \begin{cases} \frac{S - 1}{\sqrt{\text{Var}(S)}} & \text{if } S > 0 \\ 0 & \text{if } S = 0 \\ \frac{S + 1}{\sqrt{\text{Var}(S)}} & \text{if } S < 0 \end{cases} \quad (5)$$

The null hypothesis refers to  $Z$ , when  $Z$  is not statistically significant with the significant level  $\alpha$ . If  $|Z| < Z_{1-\alpha/2}$ , the hypothesis will be accepted (Gan 1998), signifying that the trend was not significant; vice versa,  $\alpha = 0.05(0.01)$  was used in this study.

### The Budyko framework

The water balance equation of the basin can be expressed as follows:

$$Q = P - E - \Delta S \quad (6)$$

where  $Q$  is the total streamflow,  $P$  is the total precipitation,  $E$  is the total evapotranspiration,  $\Delta S$  is the variation of water storage in a river basin; at a long timescale,  $\Delta S$  is considered to be zero. Budyko found that evapotranspiration is controlled by both the precipitation and evaporation capacity in the process of global water and energy balance. Accordingly, Budyko proposed the idea of establishing the coupled equation of water and energy in the basin. Based on the Budyko hypothesis, the functional forms  $E/P$  and  $E_o/P$  have been investigated by many researchers (Pike 1964; Fu 1981; Choudhury 1999; Zhang et al. 2001; Yang et al. 2008). Of these, Fu's equations have become widely used. Numerous studies show that Fu's equations apply well in the Yellow River Basin (Sun et al. 2007; Zhao et al. 2014; Gao et al. 2016; Ning et al. 2018). Therefore, Fu's function is chosen for this study as below:

$$\frac{E}{P} = F(\varnothing) = 1 + \varnothing - (1 + \varnothing^m)^{1/m} \quad (7)$$

where  $\varnothing$  is the aridity index ( $\varnothing = E_o/p$ ),  $E_o$  is the potential evapotranspiration, and  $m$  is a parameter estimated based on the vegetation type. Precipitation and potential

evapotranspiration are the primary climate variables determining the annual water balance (Zhao et al. 2014). Variations in these variables could lead to changes in the annual streamflow. The relationship between these variables can be estimated as:

$$\Delta Q_c = \varepsilon_p \frac{Q}{P} \Delta P + \varepsilon_{E_o} \frac{Q}{E_o} \Delta E_o \quad (8)$$

where  $\varepsilon_p$  is the elasticity of precipitation and  $\varepsilon_{E_o}$  is the elasticity of potential evapotranspiration.  $\Delta Q_c$ ,  $\Delta P$ , and  $\Delta E_o$  are the changes in climate, precipitation, and potential evapotranspiration, respectively.

The precipitation elasticity of streamflow is then expressed as (Zheng et al. 2009):

$$\varepsilon_p = 1 + \frac{F'(\varnothing)}{1 - F(\varnothing)}; \quad \varepsilon_{E_o} = -\frac{F'(\varnothing)}{1 - F(\varnothing)} \quad (9)$$

### Rainfall–runoff model (TUW)

The TUW model is a lumped conceptual rainfall–runoff model following the structure of the HBV model (Lindström 1997). The model runs on a daily or shorter time step and consists of a snow routine, a soil moisture routine, and a flow routing routine. Further details regarding the concept of this model can be found in Parajka et al. (2007). The model was run for all 320 gauged catchments in Austria and exhibited satisfactory results. The TUW model is only applied to the upstream of the Yellow River in this study, i.e., the Tang-Nai-Hai. This is because the large spatial span of the Yellow River Basin with different climate and underlying surface conditions, makes it very hard to turn into a lumped rainfall–runoff model.

The model requires inputs, including precipitation, air temperature, and potential evapotranspiration, which are allowed to vary with elevation within a catchment. The input of evapotranspiration was calculated by the FAO Penman–Monteith method, as follows:

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma((900)/(T + 273))U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \quad (10)$$



Here,  $ET_o$  is the reference evapotranspiration [ $\text{mm day}^{-1}$ ];  $R_n$  is the net radiation at the crop surface [ $\text{MJ m}^{-2} \text{day}^{-1}$ ];  $G$  is the soil heat flux density [ $\text{MJ m}^{-2} \text{day}^{-1}$ ];  $T$  is the mean daily air temperature at 2 m height [ $^{\circ}\text{C}$ ];  $U_2$  is the wind speed at 2 m height [ $\text{m s}^{-1}$ ];  $e_s$  is the saturation vapor pressure [ $\text{kPa}$ ];  $e_a$  is the actual vapor pressure [ $\text{kPa}$ ];  $e_s - e_a$  is the saturation vapor pressure deficit [ $\text{kPa}$ ];  $\Delta$  is the slope vapor pressure curve [ $\text{kPa } ^{\circ}\text{C}^{-1}$ ];  $\gamma$  is the psychrometric constant [ $\text{kPa } ^{\circ}\text{C}^{-1}$ ].

Moreover, the differential evolution algorithm with Nash–Sutcliffe efficiency (NSE) and the relative error (RE) were used to optimize the model parameters. These equations are given by:

$$NSE = 1 - \frac{\sum_{i=1}^n (Q_{obs,i} - Q_{sim,i})^2}{\sum_{i=1}^n (Q_{obs,i} - \overline{Q_{obs}})^2} \quad (11)$$

$$RE = \frac{\sum_{i=1}^n (Q_{sim,i} - Q_{obs,i})}{\sum_{i=1}^n Q_{obs,i}} \quad (12)$$

where  $Q_{obs,i}$  is the observed runoff on day  $i$ ,  $Q_{sim,i}$  is the simulated runoff on day  $i$ ,  $\overline{Q_{obs}}$  is the average of the observed runoff over the calibration period of  $n$  days.

### Quantitative assessment for climate change and human activity impacts on streamflow

Streamflow change is a comprehensive result of changing environments. It is assumed that the aspects of a changing environment that induce streamflow changes can only be divided into climate change and human activities. To evaluate the varying impacts of climate change and human activities on streamflow changes, quantitative assessments based on change-point detection and the hydrologic model were proposed. The change point serves as the break point between the baseline period and the impacted period. The baseline period is the period before the change point, without significant human activities. The impacted period is the period after the change point, where there is a statistically significant climate change as well as impacts from human activity. The formulae to calculate different impacts of human activities and climate change on

streamflow are as follows:

$$\Delta Q = Q_i - Q_b = \Delta Q_C + \Delta Q_H \quad (13)$$

$$\Delta Q_C = Q_{is} - Q_{bs} \quad (14)$$

$$\eta_c = \frac{\Delta Q_C}{\Delta Q} \times 100\% \quad (15)$$

$$\eta_H = \frac{\Delta Q_H}{\Delta Q} \times 100\% \quad (16)$$

Here,  $\Delta Q$  is the change in observed streamflow attributed to the combined impacts of human activities and climate change;  $Q_i$  is the observed mean annual streamflow in the ‘impacted period’;  $Q_b$  is the observed mean annual streamflow in the ‘baseline period’;  $\Delta Q_C$  is the streamflow change caused by climate variability;  $\Delta Q_H$  is the streamflow change caused by the human activities;  $Q_{is}$  and  $Q_{bs}$  are the reconstructed mean annual streamflow in the ‘impacted period’ and the ‘baseline period’, respectively;  $\eta_c$  and  $\eta_H$  are percentages of climate change and human activities’ impacts on streamflow variation, respectively.

## RESULTS

### Change points of streamflow series

The change points of the streamflow of Tang-Nai-Hai, Lan-Zhou, and Hua-Yuan-Kou stations from 1956 to 2017 were detected via the five methods shown in Table 1. According to the results, 1989, 1986, and 1990 were the change points, respectively, for the Tang-Nai-Hai, Lan-Zhou, and Hua-Yuan-Kou streamflow series. Consequently,

**Table 1** | Abrupt change points at each of the three hydrological stations in the Yellow River Basin

Method	Tang-Nai-Hai	Lan-Zhou	Hua-Yuan-Kou
Mann–Whitney U test	1989	1986	1990
Moving t-test	1989	1990	1990
Mann–Kendall test	1989	1986	1985
Ordered cluster analysis	1989	1985	1985
Pettitt test	1989	1986	1990

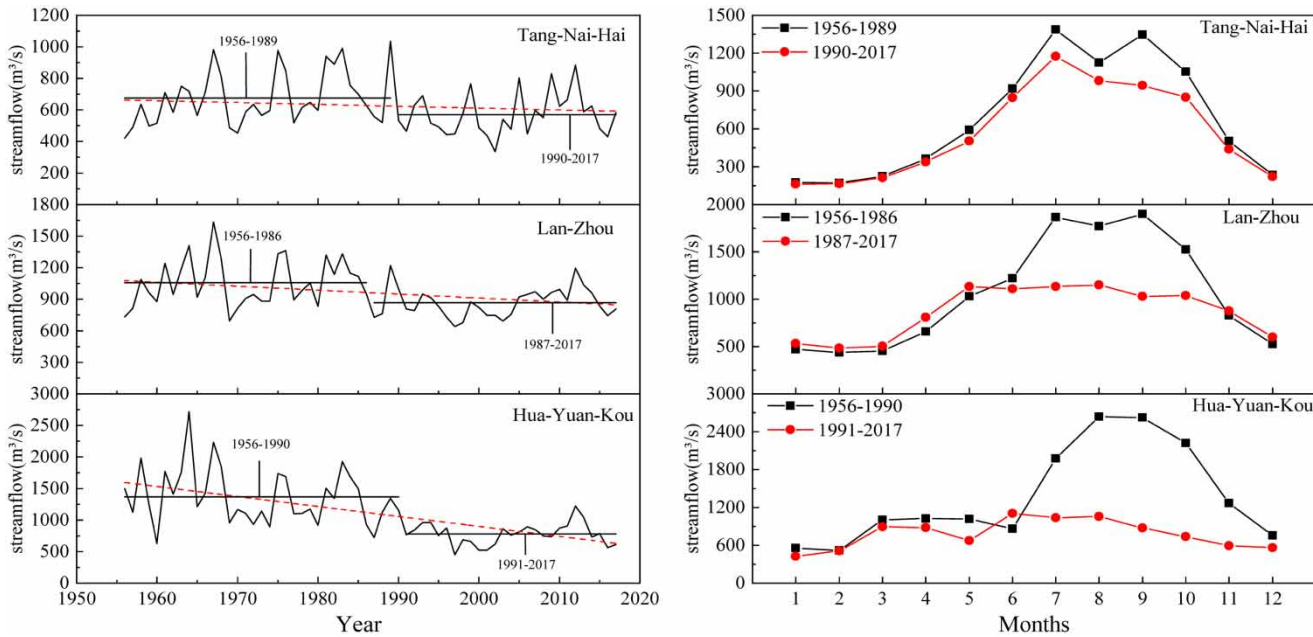


Figure 2 | Annual and monthly streamflow during the two evaluated periods at each of the three hydrological stations.

the entire streamflow series were subdivided into two sub-periods: the baseline period and the impacted period.

Compared to the baseline period, the impacted period’s annual streamflow for Tang-Nai-Hai, Lan-Zhou, and Hua-Yuan-Kou was reduced by 16%, 18%, and 43%, respectively (Figure 2). The streamflow at each of the three hydrological stations in the impacted period is significantly lower than that in the baseline period and is mainly concentrated in the flood season (July–October). Compared to the baseline period, the streamflow was reduced by 15%–30% from the flood season in the impacted period at the Tang-Nai-Hai station. The streamflow at the Lan-Zhou and Hua-Yuan-Kou stations decreased by 32%–46% and 47%–67%, respectively.

**Trend for streamflow**

As shown in Figure 2, the annual observed streamflow of all the three stations exhibit different trends in the baseline period and the impacted period. The streamflow observed at all stations has a significant trend of decline. The downstream flow changed more significantly than the upstream flow, and the streamflow shows a decreasing trend, both spatially and temporally, in the Yellow River Basin. Results

of the Mann–Kendall trend test (Table 2) agreed with the results of direct observation of Figure 2. The streamflow at Tang-Nai-Hai station exhibited a non-significant trend of streamflow in the 1956–2017 period, and increasing trends in the baseline period ( $Z = 2.19, P < 0.03$ ). In the 1956–2017 period, the streamflow at Lan-Zhou exhibited statistically significant positive trends ( $Z = -2.32, P < 0.05$ ), whereas at Hua-Yuan-Kou, a strong downward trend ( $Z = -5.48, P < 0.0013$ ). However, the trends were quite different from month to month. The monthly streamflow trend of Tang-Nai-Hai station is not statistically significant (Table 3).

Table 2 | Mann–Kendall testing results for annual streamflow

Station	Time	Z	P-value
Tang-Nai-Hai	1956–2017	-1.07	0.30
	1956–1989	2.19*	0.03
	1990–2017	0.855	0.37
Lan-Zhou	1956–2017	-2.32*	0.05
	1956–1986	1.33	0.18
	1987–2017	0.55	0.21
Hua-Yuan-Kou	1956–2017	-5.48**	0.001
	1956–1990	-1.48	0.14
	1991–2017	0.08	0.93

\*Expressed through the level of significance  $\alpha = 0.05$ .

\*\*Expressed through the level of significance  $\alpha = 0.01$ .

Table 3 | Mann-Kendall trend analysis of monthly streamflow in the three hydrologic stations of the Yellow River Basin

Station	Time	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Tang-Nai-Hai	1956–2017	-0.32	-0.14	-0.04	-0.64	-1.39	0.65	-0.65	-1.25	-1.36	-0.58	-0.57	0.53
	1956–1989	0.4	0.93	1.41	1.39	1.13	2.521*	1.62	0.5	1.13	1.13	0.74	1.54
	1990–2017	1.56	1.09	1.25	-0.71	-1.32	0.57	1.03	-0.34	0.52	1.76	1.5	2.352*
Lan-Zhou	1956–2017	3.01**	2.63**	2.93**	4.42**	3.07**	-0.51	-3.84**	-4.11**	-3.55**	-1.71	2.26*	2.61**
	1956–1986	4.8**	4.51**	4.01**	3.19**	1.92*	0.49	-0.29	-0.7	-0.05	0.15	1	3.145**
	1987–2017	-0.56	-1.41	0.31	1.19	0.32	2.466*	1.11	-0.43	1.09	3.03**	1.9	-1.28
Hua-Yuan-Kou	1956–2017	-1.77	0.3	-1	-1.66	-2.49**	1.77	-3.80**	-5.39**	-5.59**	-4.67**	-4.85**	-2.36**
	1956–1990	1.8	1.09	0.13	-0.7	0	0.16	-1.52	-1.65	-0.36	-0.82	-2.03	0.55
	1991–2017	0.06	-0.67	-0.21	0.21	2.09*	3.00**	1.79	-2.00*	-2.29*	0.21	0.5	-0.71

\*Expressed through the level of significance  $\alpha = 0.05$ .

\*\*Expressed through the level of significance  $\alpha = 0.01$ .

However, significant changes have taken place in the Lan-Zhou and Hua-Yuan-Kou stations. Over the period from 1956 to 2017 at Lan-Zhou hydrological station, the months of November to May in the next year showed a statistically significant increasing trend of streamflow and July to September showed a statistically significant reduction trend. As most of the runoff in the Yellow River Basin occurs during the rainy season (June to October), the net effect was a decrease in annual runoff. Over the 1956 to 2017 period, records at Hua-Yuan-Kou hydrological station, a total of seven months, showed a decreasing trend and all of them fell within the rainy season; the result was an annual decreasing trend. From upstream to downstream, the number of months with reduced runoff increases and the downward trend became more significant, which explained why the river dry-up phenomenon has increased in frequency in the lower Yellow River Basin.

### Runoff–precipitation relationship

Runoff in the Yellow River Basin strongly depends upon precipitation (Fu et al. 2007b). Thus, analysis of the relationship between runoff and precipitation is necessary to understand the evolution of hydrological runoff. The relationship between precipitation and runoff before and after the change point of each of the three hydrological stations is shown in Figure 3; the correlation coefficient  $R^2$ , between the precipitation and runoff at each of the three stations, Tang-Nai-Hai, Lan-Zhou, and Hua-Yuan-Kou, before and after the change point, is reduced by 0.125, 0.361, and 0.5, respectively. Because there was no large reservoir construction in the upper reaches of Tang-Nai-Hai station, the impact of human activities is relatively less, and the relationship between precipitation and runoff remains relatively strong, with a  $R^2$  of 0.73 and 0.61, before and after the change point, respectively. Thus, at Tang-Nai-Hai station, precipitation has a direct impact on runoff in the headwater Yellow River Basin. Lan-Zhou and Hua-Yuan-Kou stations were strongly influenced by human activities; the  $R^2$  after the change point is only 0.259 and 0.048, signifying that precipitation does not directly affect runoff in the control area. At Lan-Zhou and Hua-Yuan-Kou stations, runoff changes are affected by many factors (Zhao et al. 2014).



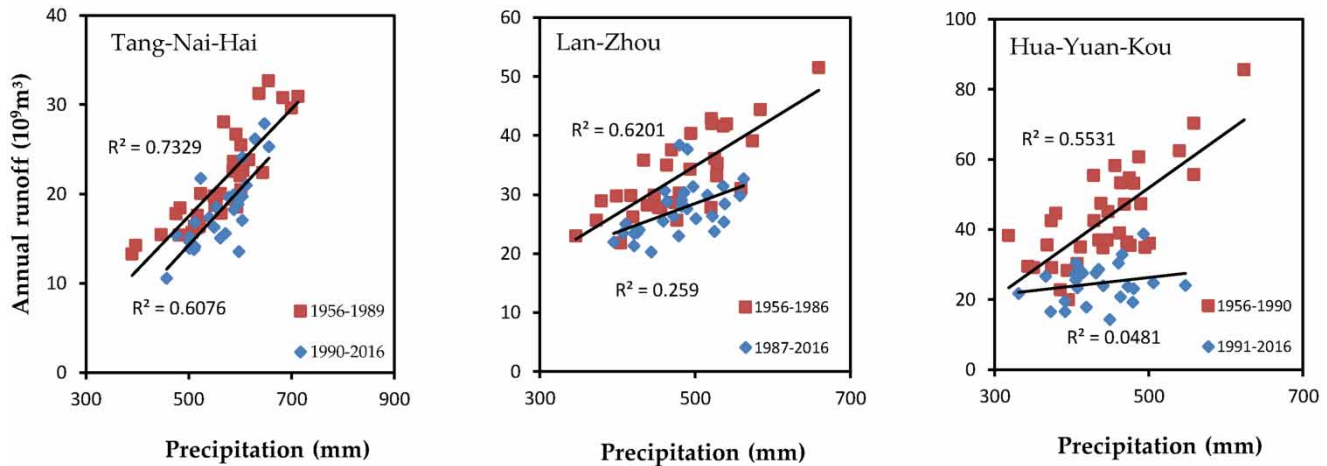


Figure 3 | Correlation between precipitation and streamflow.

### Effects of climate change and human activities

#### Evaluation of streamflow variation using the Budyko framework

According to the results of streamflow change points, the observed annual streamflow series can be divided into two periods. Based on Equations (7) and (9), the elasticity coefficients of precipitation at Tang-Nai-Hai, Lan-Zhou, and Hua-Yuan-Kou hydrological stations are 1.57, 1.64, and 1.59, respectively; the potential evapotranspiration elasticity coefficients are 0.57, 0.64, and 0.59, respectively. As shown in Table 4, the contribution rates of precipitation change to streamflow reduction are 23.3%, 13.4%, and 7.2%, while the contribution rates of potential evapotranspiration increase to streamflow reduction are 10.3%, 5%, and 3.5% at Tang-Nai-Hai, Lan-Zhou, and Hua-Yuan-Kou hydrological stations, respectively. Thus, among the higher impact

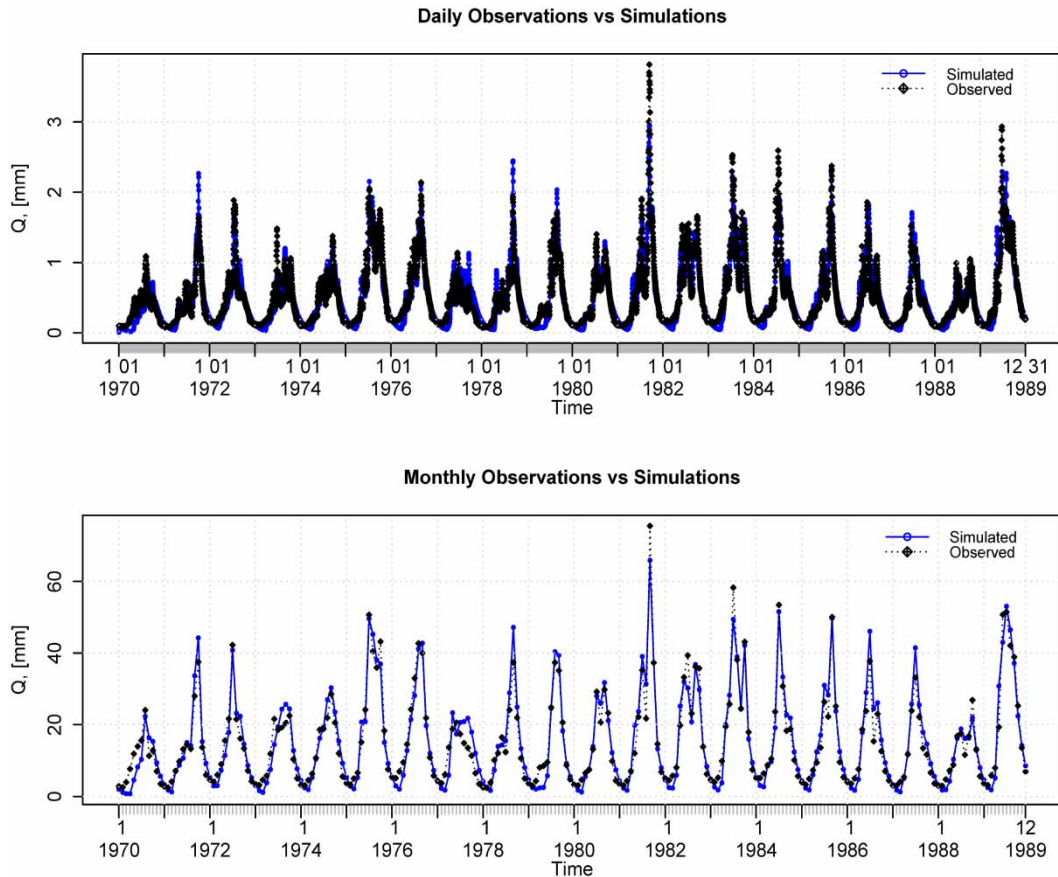
climate change factors, changes in precipitation have a dominant role. Furthermore, compared to climate change, human activities played a dominant role in the reduction of streamflow for most catchments, especially those downstream. The main reason is that China has implemented the Reform and Open policy since 1980; to support this, the construction of hydraulic engineering facilities and water reservoirs has been pursued vigorously, leading to changes in the underlying surface of the river basin.

#### Evaluation of streamflow variation using the TUW model

To assess the model skill, the baseline period is divided into two parts: the calibration period (1970–1984) and validation period (1985–1989). Daily streamflow and hydrometeorological data were used. The simulation and observation runoff in the calibration and validation periods are shown in Figure 4. The observed runoff is consistent with the

Table 4 | Effects of climate variability and human activities on streamflow in the Yellow River

Stations	Period	Q (mm/yr)	P (mm/yr)	E <sub>o</sub> (mm/yr)	$\Delta Q_P$		$\Delta Q_{E_o}$		$\Delta Q_C$		$\Delta Q_H$	
					(mm)	(%)	(mm)	(%)	(mm)	(%)	(mm)	(%)
Tang-Nai-Hai	1960–1989	180.7	576.2	793.9								
	1990–2017	148.86	559.7	822.4	-7.6	23.3%	-3.3	10.3%	-10.9	34.3%	-20.9	65.7%
Lan-Zhou	1960–1986	153.7	490.0	869.0								
	1987–2017	123.1	480.9	884.8	-4.1	13.4%	-1.5	5.0%	-5.6	18.4%	-25.0	81.6%
Hua-Yuan-Kou	1960–1990	59.0	443.2	1,027.8								
	1991–2017	33.7	432.7	1,061.2	-1.8	7.2%	-0.9	3.5%	-2.7	10.7%	-22.6	89.3%



**Figure 4** | The observed and simulated daily and monthly runoff depths during calibration and validation periods.

simulated runoff, and the NSE in the calibration and validation periods was 89% and 86%, respectively, while the RE in the calibration and validation periods was  $-0.3\%$  and  $0.5\%$ , respectively. This indicates that this application of the TUM model in calculating the natural runoff influenced human activities to have a higher degree of credibility.

The calibrated TUW mode parameters were applied to simulate the runoff in different periods (Zhang et al. 2017a). Based on Equations (13)–(16), the impacts on

streamflow from climate change and human activities were evaluated for the impacted period (1990–2017) (Table 5). As shown in Table 5, the runoff at Tang-Nai-Hai station decreased 33.4 mm during the impacted period (1990–2017) compared to the baseline period (1970–1989), including a decrease of 9.92 mm from climate change and a decrease of 23.48 mm from human activities. Climate variability results in a decrease of 30% in runoff, while human activities contribute to a decrease of 70% in runoff.

**Table 5** | Effects of climate and human activities on runoff at the Tang-Nai-Hai station via the TUW model

Time	$Q_{obs}^a$ (mm)	$Q_{sim}^a$ (mm)	$\Delta Q^a$ (mm)	$Q_c$		$Q_H$	
				(mm)	%	(mm)	%
1970–1989	182.26	182.04	–	–	–	–	–
1990–2017	148.86	172.12	–33.4	–9.92	30%	–23.48	70%

<sup>a</sup> $Q_{obs}$  is the mean annual observed runoff,  $Q_{sim}$  is the mean annual simulated runoff, and  $\Delta Q$  is the variation of annual runoff in the 1990–2017 period compared to the 1970–1989 period.

## DISCUSSION

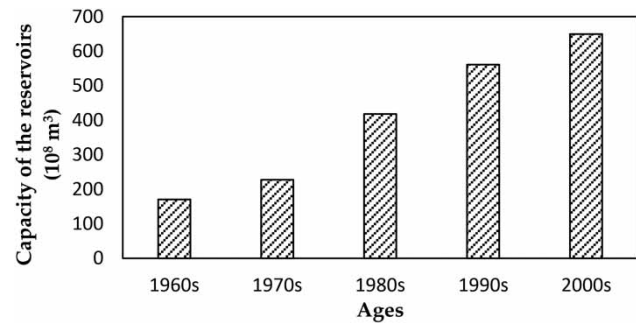
### Comparative analysis of Budyko and TUW models for evaluating streamflow

Here, two different methods were used to distinguish the effects of climate variability and human activities on streamflow. The Budyko framework is a statistical method that should only be implemented on an annual timescale. The TUW model is a physical model method that can simulate hydrological processes using daily data. The effect of climate variability at Tang-Nai-Hai station was 10.9 mm for the 1990–2017 period, according to the Budyko framework, and 9.92 mm according to simulations with the TUW model. The fractional contributions of climate change to changes in the streamflow at Tang-Nai-Hai station are 34.3% and 30% according to the Budyko framework and TUW model, respectively. However, the results of these two methods in estimating the impacts of climate change and human activities on streamflow were quite similar.

### Impact of reservoir operation on runoff

Reservoir regulation is a human activity that directly affects runoff changes (Zhao et al. 2014). The main scheduling rules for the reservoir, to maintain the ecology of the river and regulate agricultural irrigation, were water storage in the rainy season and water release in the dry season.

The upper reaches of the Yellow River are one of the primary hydropower bases in China. By 2015, 20 hydropower stations had been built in this region, with an annual power generation of 50.06 terawatt-hours (TWh) and a total storage capacity of  $35.096 \times 10^9 \text{ m}^3$  (Figure 5). Among these, Long-Yang-Xia reservoir (operating time: 1986, storage capacity:  $247 \times 10^8 \text{ m}^3$ ) has many years of regulation capability, Liu-Jia-Xia reservoir (operating time in 1968, storage capacity:  $57 \times 10^8 \text{ m}^3$ ) has annual regulation capability (Bai et al. 2015). In the upper reaches of Tang-Nai-Hai station, the relationship between precipitation and streamflow is relatively strong, there was no large reservoir construction, and the reservoir scheduling is not the main factor of occurrence change point of streamflow at Tang-Nai-Hai station. However, for the relationship between



**Figure 5** | Cumulative capacity of the reservoirs in the Yellow River mainstream across decades.

precipitation and streamflow at Lan-Zhou station, correlation coefficient  $R^2$  is only 0.259 after the change point (Figure 3). An analysis of this shows that annual runoff changed abruptly in 1986, which is when the Long-Yang-Xia reservoir began operations. This is the main cause of the abrupt change in annual runoff at Lan-Zhou station. The M-K trend analysis of monthly streamflow shows that over the period from 1956 to 2017 at Lan-Zhou hydrological station, November to May the following year showed a statistically significant increasing trend of streamflow and July to September showed a statistically significant reduction trend. This is because the reservoirs reduced the flood peaks dramatically through water storage in the rainy season (June to October) and water release in the dry season (November to May). Therefore, the main reason for the decrease of runoff at Lan-Zhou station is the operation of the Long-Yang-Xia reservoir. From Lan-Zhou to Hua-Yuan-Kou, the main large reservoirs on the main stream of the Yellow River are Wan-Jia-Zhai (operating time: 2002, storage capacity:  $9 \times 10^8 \text{ m}^3$ ), San-Men-Xia (operating time: 1957, storage capacity:  $162 \times 10^8 \text{ m}^3$ ), and Xiao-Lang-Di reservoirs (operating time: 2001, storage capacity:  $126.5 \times 10^8 \text{ m}^3$ ). In this study, the change point of the Hua-Yuan-Kou station occurred in 1990, before that, only the San-Men-Xia reservoir was operational. Shi et al. (2017) found the change points of the Hua-Yuan-Kou were 1968 and 1985 using the multi-point mutation test. The San-Men-Xia reservoir was remodeled in 1965 and reopened in 1968 due to siltation. The reservoir operation was the main factor of the change point of Hua-Yuan-Kou station in 1968. In 1990, the construction of soil and water conservation measures, such as forest and grass, terraced field, and warping dams

implemented in the middle reaches of the Yellow River are, in addition to the impact of reservoir operation, the main reason for the change point of Hua-Yuan-Kou.

### Impact of land use/land cover change on runoff

Land cover/land use change (LUCC) is a major way by which humans change the natural environment and is a main driving force of land cover change (Fu et al. 2004).

In 1990, the population of the headwater region of the Yellow River was only 490,000, and by 2016 the population of the headwater region had reached 710,000, an increase of 45% over 1990. Overgrazing destruction of grasslands and the increase in cultivated land, forest area, and sandy land are the reasons for low runoff in the upper reaches of the Tang-Nai-Hai. The current area of cultivated land, forest area, and sandy land, compared to that in 1990, increased by 125.53%, 157.4%, and 133.74%, respectively. However, grassland areas have decreased by 15.01%, compared to those in 1990 (Table 6). Therefore, LUCC leading to underlying surface change is the main reason for the low runoff in the upper reaches of Tang-Nai-Hai.

The main causes of LUCC in the middle reaches of the Yellow River Basin are the soil and water conservation measures (Gao et al. 2016). The soil and water conservation measures are mainly to protect the reduction of water and sediment, including engineering structures such as terraces and dams and biological measures such as afforestation and planting grass. There is extreme soil erosion in the middle reaches of the Yellow River flowing through the Loess Plateau. After 1980, the government strengthened

water and soil conservation measures in the middle reaches of the Yellow River. The annual amount of sediment reduction was  $4.6 \times 10^8$  t from 1980 to 1989,  $5.3 \times 10^8$  t from 1990 to 1996, and  $5.6 \times 10^8$  t from 1997 to 2006 (Shi et al. 2017). By 2006, 37.2% of the vegetation of the middle reaches had been restored as a result (Zhao et al. 2014). The increase of forests, grasses, terraces, and silt dams has led to the change of underlying surface conditions and the decrease of runoff yield. Through field investigation and scientific analysis of the Yellow River Basin, Liu (2016) found that between Lan-Zhou and Hua-Yuan-Kou, forest and grass vegetation reduced runoff by  $2.45 \times 10^8$  m<sup>3</sup> and terraces by  $1.35 \times 10^8$  m<sup>3</sup> in 2007–2014 compared with before the mid 1970s. The water and soil conservation measures are one of the main causes of runoff change in Hua-Yuan-Kou. There is no doubt that the reservoir construction and underlying surface conditions' change have also significantly impacted the reduction of runoff at Hua-Yuan-Kou station. In addition to the reasons analyzed above, other factors like population increase, agricultural irrigation, groundwater pumping, and water transfer probably contributed to the runoff reduction as well.

### Uncertainties

There are several aspects to the uncertainties in the analysis of attribution for streamflow decrease depending on the detection of the change point of streamflow and the climate change and human activities' effects on streamflow. As shown in Table 1, the abrupt change points of the streamflow time series are different with different test methods at the Lan-Zhou and Hua-Yuan-Kou stations. The mutation occurred from 1985 to 1990. Some studies have found that the change point of streamflow at Hua-Yuan-Kou station occurred in 1985 (Zhao et al. 2014; Li et al. 2017a), which is the same as the result obtained by using the Mann-Kendall test and Ordered cluster analysis methods in this paper. However, the change point of Hua-Yuan-Kou in 1990 was found by combining various methods. The impact of climate change and human activities on runoff at Lan-Zhou station were 18.4% and 81.6%, respectively (Table 4) with 1986 as the change point (result of three methods in Table 1). If we shift the point to 1990 (a different method, Table 1), the corresponding values are 18% and

**Table 6** | Land use before and after 1990 at the Upper Tang-Nai-Hai station of the Yellow River Basin

Land use	Area (km <sup>2</sup> )		
	Before 1990	After 1990	Change rate (%)
Cultivated	474	1,069	125.53
Forest	3,143	8,090	157.40
Grassland	109,094	92,723	-15.01
Water bodies	1,797	2,588	44.02
Residential	0	56	-
Sandy land	7,464	17,446	133.74

Statistics data were collected from Zheng et al. (2009).

82%, respectively. There is almost no effect in this case. The impacts of climate change and human activities on runoff at Hua-Yuan-Kou station were 10.7% and 89.3%, respectively (Table 4) with 1990 as the change point (result of three methods in Table 1). If we shift the change point to 1985 (result of two methods in Table 1), then the corresponding values are 12.6% and 87.4%, respectively. The differences are less than 2%. These results indicate that the influence of the change point on the final runoff attribution are limited for our study. Here, the variation analysis of hydrological sequences has been conducted via five different types of change-point detection methods, which improves the reliability of the results. However, there are many factors affecting the variation of hydrological sequencing. The methods used herein still contain several limitations: (1) the combination of multiple variations causes the uncertainty of the overall variability to weaken or enhance each other, leading to fluctuations in the efficiency test; (2) the method itself does not recognize certain variabilities, resulting in reduced efficiency; and (3) the method sets the degree of conditional satisfaction and can affect the efficiency of the test.

The Budyko and hydrological model methods used to estimate the effects of climate change, land use, and land cover changes on water flow patterns are relatively limited. There are differences in the calculation results of different Budyko equations. *Zheng et al. (2009)* used different Budyko models to analyze the effects of climate change and land use on the headwaters of the Yellow River Basin, and found that the contribution of climate change to the runoff change in the source area of the Yellow River was from 26.1% to 39.5%, and the contribution of land use change to the runoff of the source area of the Yellow River was from 60.5% to 73.9%. *Ning et al. (2018)* found that although the attribution equation requires the variables to be independent, major factors such as potential evapotranspiration, precipitation, and controlling parameters can interact with each other, increasing uncertainties. In the analysis of runoff attribution at the inter-annual scale, Budyko control parameters are not only controlled by vegetation, but also by seasonal climate. There is uncertainty when the hydrological model simulates runoff. The hydrological model parameters are determined according to the historical data and the correlation complementarity

between the parameters affects the simulation results of the model. Different model parameter estimation methods also affect the model's simulation results (*Parajka et al. 2007*).

The assumption of the framework also has an uncertain effect on the result in this study. It should be noted that the framework used to analyze the impact of climate change and human activity on runoff is based on the independence of human activity and climate change. Climate variability and human activities were expected to evolve independently of the two methods in this study. In fact, the impacts of climate change and human activities on runoff are not totally independent. For example, the effects of temperature on evapotranspiration and runoff are treated as a result of climate change, but it is highly related to the urban heat island effect. In turn, land use/land cover changes change the characteristics of surface energy balance change, evapotranspiration and surface reflection, which in turn, affects the climate. In future studies, the interaction between climate change and human activities will be further analyzed in order to better distinguish the impacts of climate change and human activities on streamflow.

## CONCLUSIONS

From 1956 to 2017, the hydrologic streamflow time series of the Yellow River Basin has significantly changed as a result of human activities and climate change. This study investigated streamflow variation in the Yellow River Basin and ascertained the following conclusions. (1) The change point of the streamflow sequence was concentrated in 1985–1990, within which, the change point was 1989, 1986, and 1990 at Tang-Nai-Hai, Lan-Zhou, and Hua-Yuan-Kou stations, respectively. Streamflow in the impacted period compared to that in the baseline period decreased by 16%, 18%, and 43% at Tang-Nai-Hai, Lan-Zhou, and Hua-Yuan-Kou stations, respectively. (2) According to the non-parametric test method and linear trend analysis, the annual streamflow of the three stations trended downward, especially at Lan-Zhou and Hua-Yuan-Kou stations. (3) The correlation coefficient between precipitation and runoff decreased with the change of environment. The correlation coefficient of Tang-Na-Hai stayed above 0.6,



while the correlation coefficients between precipitation and runoff in Lan-Zhou and Hua-Yuan-Kou were only 0.25 and 0.04, respectively, during the impacted period. (4) In the Yellow River Basin, human activities have a greater effect on hydrological processes than climate change. Relative to the baseline period, the fractional contribution from human activities to streamflow changes during the impacted period was 65.7%, 81.6%, and 89.3%, at Tang-Na-Hai, Lan-Zhou, and Hua-Yuan-Kou stations, respectively.

The results could be useful for water resource managers to understand the impacts of climate change and human activities on runoff, and provide reference for water resources planning and management in the Yellow River Basin in the future. This study discussed the rule of runoff change, and quantitatively analyzed the impact of climate change and human activities on runoff. For the watershed managers, the research results will help management to further understand the impact of climate change and human activities on runoff. Human activities are the main factors of runoff reduction, but the impact of climate change on runoff cannot be ignored. In order to improve the ecological health of the Yellow River basin and the sustainable utilization of water resources, the following countermeasures are put forward:

1. The impacts of different human activities and climate factors on runoff changes should be further analyzed so as to cope better with the increasingly severe water shortage in the Yellow River Basin.
2. According to the change of runoff in different reaches and the influencing factors, choose the appropriate crop planning structure and irrigation methods.
3. Optimize operating rules of reservoirs under the new situation of environmental change, and utilize maximum efficiency of reservoirs.
4. Strengthen watershed management, increase publicity on water resources protection, and raise public awareness of water saving and enthusiasm for participation.

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