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Attribution for decreasing streamflow of the Haihe River basin, northern China: Climate variability or human activities?

Zhenxin Bao [a,b,c,*], Jianyun Zhang [a,b,c], Guoqing Wang [a,b,c], Guobin Fu [d], Ruimin He [a,b,c], Xiaolin Yan [a,b,c], Junliang Jin [a,b,c], Yanli Liu [a,b,c], Aijing Zhang [e]

[a] *Nanjing Hydraulic Research Institute, Nanjing 210029, China*
[b] *State Key Laboratory of Hydrology–Water Resources and Hydraulic Engineering, Nanjing 210098, China*
[c] *Research Center for Climate Change, Nanjing 210029, China*
[d] *CSIRO, Land and Water, Private Bag 5, Wembley, WA 6913, Australia*
[e] *Faculty of Infrastructure Engineering, Dalian University of Technology, Dalian 116024, China*

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SUMMARY

Climate variability and human activities are regarded as the two driving factors for the hydrological cycle change. In the last several decades, there were statistically significant decreasing trends for streamflow and precipitation, but an increasing trend for mean temperature in the Haihe River Basin (HRB). The attribution of climate variability and human activities for streamflow decrease was quantitatively assessed in three catchments located in different parts of the HRB. They are the Taolinkou catchment in the Luanhe River, Zhangjiafen catchment in the north of Haihe River, and Guantai catchment in the south of Haihe River. Based on the break point of streamflow, the whole period was divided into two periods: "natural period" (before the break point) and "impacted period" (after the break point). Using the Variable Infiltration Capacity (VIC) model calibrated in the "natural period", the "natural streamflow" without the impact of human activities was reconstructed for the whole period. The differences of the "natural streamflow" between the "natural period" and "impacted period" indicated the impact of climate variability on streamflow decrease. The remaining contribution to streamflow decrease was made by human activities. The results indicated that the decrease of streamflow between the two periods could be attributed to 58.5% (41.5%), 40.1% (59.9%), and 26.1% (73.9%) from climate variability (human activities) in the Taolinkou, Zhangjiafen and Guantai catchment, respectively. That was to say, climate variability was the major driving factor for the streamflow decrease in the Taolinkou catchment; on the other hand, human activities was the main driving factor for the streamflow decrease in the Zhangjiafen and Guantai catchment.

1. Introduction

Haihe River Basin (HRB) encompassing Beijing, Tianjin, Shijiazhuang city, and 23 other large and medium cities, is the political, economic, cultural, and transport center of China. In 2005, it had a population of 0.132 billion, 55.92 million ton total grain yield, and 2140 billion RMB yuan GDP (Gross Domestic Product), accounting for 10%, 12%, and 14% of the national total, respectively. Otherwise, water resources shortage and related environmental problems have become major critical challenges for the regional social and economic development. In the HRB, the amount of water resources per capita is only 305 m^3, representing 1/7 of the average in China and 1/27 of the average in the world (Haihe River Commission, 2010). Furthermore, water crisis in the HRB has become more and more severe recently: (1) there has been a statistically significant decreasing trend for streamflow in some catchments in the HRB (Zhang et al., 2007b; Yang and Tian, 2009; Cong et al., 2010), for example, Chaobai River (Yao et al., 2003), Yanghe River (Zhang and Yuan, 2004), Sanggan River (Zhang, 2003), Hutuo River (Cui and Cui, 2007), Yehe River (Fan et al., 2007), etc.; (2) the plain groundwater tables have declined rapidly (Liu et al., 2001; Liu and Xia, 2004); (3) the area of wetland has decreased from 10,000 km^2 in 1950s to 1000 km^2 now (Xia et al., 2007), etc. The two driving factors for these problems are climate variability (mainly the change of temperature and precipitation) and human activities (water withdrawal from river, groundwater exploitation, hydraulic projects, land use/covers change (LUCC), etc.) (Chen and Xia, 1999).

Hydrological cycle and water resources system are extensively influenced by climate variability and human activities (Vorosmarty et al., 2000; Beven, 2001; Kezer and Matsuyama, 2006; IPCC, 2007;

* Corresponding author at: Nanjing Hydraulic Research Institute, Nanjing 210029, China. Tel.: +86 25 85828827; fax: +86 25 85828555.
E-mail address: nhri.bzx@gmail.com (Z. Bao).

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Zhang et al., 2007a). However, which is the major driving factor for streamflow decrease in the HRB? The answer to this question is very important for future water resources planning and management decisions to ensure sustainable water resources utilization. If human activities is the major driving factor, current hydro-climatic data could continue to be used for water use planning, thus policymakers could focus on water resources management and projection. However, if climate variability makes more contribution, it is essential to study the impact of climate variability on future water resources under different climate change scenarios, for planning and management agencies (Fu et al., 2004). Some hydrologists tried to investigate this problem by the trend analysis of historical data. For example, according to long-term observation data, Ren et al. (2002) analyzed the impact of direct human activities on runoff in the northern areas of China and pointed out that besides the climate variability, the increase in the amount of water taken from river course was the direct reason for observed runoff decrease. Yang and Tian (2009) concluded that the high percentage of agricultural land use and related water use was the most probable driving factor for runoff decline in the HRB. However, it was difficult to quantitatively assess the contribution of climate variability and human activities to streamflow change by trend analysis.

Some researches attempted to solve this problem by the water balance equation and the sensitivity analysis of streamflow to precipitation, temperature, and evaporation. By such sensitivity analysis, Liu et al. (2004) concluded a semi-quantitative analysis approach and summarized the attribution for streamflow decrease in the HRB. Zhang et al. (2008) used the sensitivity of streamflow to precipitation and potential evaporation to study the response of streamflow to changes in climate and land use/cover in the Loess Plateau of China and pointed out that LUCC accounted for over 50% of the reduction in mean annual streamflow in 8 out of 11 catchments. By water balance equation based on empirical evapotranspiration formula, Li et al. (2007) demonstrated that soil conservation measures accounted for 87% of the total reduction in mean annual streamflow in the Wuding River basin, a sub-basin of the Yellow River basin. Ma et al. (2008) estimated that climate variability accounted for over 64% of the reduction in mean annual streamflow in the Shiyang River basin located in arid region of Northwest China.

However, there are some shortcomings for this methodology. Firstly, it is difficult to estimate the sensitivity of streamflow to climate change accurately. For example, some different results were concluded in the same basin by different studies (Sankarasubramanian et al., 2001). Furthermore, it could only be applied to analyzing the annual streamflow response to climate change, but could not be used to investigate the inter-annual time step (Fu et al., 2007). Some hydrologists tried to construct other more reasonable methodologies with the hydrological model to avoid this shortage. Using the SIMHYD model, Wang et al. (2006) investigated the impact of climate variability and human activities on runoff separately in Fenhe River of the middle Yellow River. Wang et al. (2010) quantitatively attributed separately the impacts of climate variability and human activities on hydrological response in a sub-basin of Yellow River with the Variable Infiltration Capacity model. By distributed time-variant gain model, Wang et al. (2009) concluded that decrease in runoff between two periods (before and after 1980) could be attributed to 35% (31%) from climate variations and 68% (70%) from human activities in Chao River (Bai River), the two rivers flowing into Miyun Reservoir of the HRB, thus human impact exerted a dominant influence upon streamflow decline in the Chaobai River basin compared to climate variability. Also in Chaobai River catchment, Ma et al. (2010) studied the contribution of climate variability and human activities on runoff decline by geomorphology-based hydrological model and climate elasticity model, but they had different conclusions compared to Wang et al. (2009): climate variability was accountable for about 55–51% of the decrease in Miyun Reservoir inflow, but the indirect impact of human activity (mainly manmade land use and vegetation changes) accounted for 18% of the decrease in Miyun reservoir inflow.

A statistically significant decreasing trend for streamflow was detected in some catchments of the HRB, and some hydrologists tried to assess the contribution from climate variability and human activities to it. However, there are some questions needing to be further investigated. Did the runoff decrease in the whole HRB? Was there any change of the relationship between precipitation and runoff? What was the contribution of climate variability and human activities to streamflow change in different parts of the HRB? Why did Wang et al. (2009) have different conclusions with Ma et al. (2010) in the Chaobai River? These problems would be solved in this study. The remaining sections of this paper are organized as follows: the study area and dataset are summarized in Section 2; the methodologies (attribution assessment, hydrological model, and trend analysis) are introduced in Section 3; Section 4 shows the hydro-meteorological trends, streamflow simulation, and the contribution of climate variability and human activities to streamflow decrease in the HRB; and the conclusions are summarized in Section 5.

2. Study area and datasets

2.1. Study area

Haihe River basin is located in the northern China (112–120°E, 35–43°N). The Mongolian Plateau, Yellow River, and Bohai Sea are the northern, south-western, and eastern boundary, respectively (Fig. 1). Accounting for 3.3% of the national total, the area of the

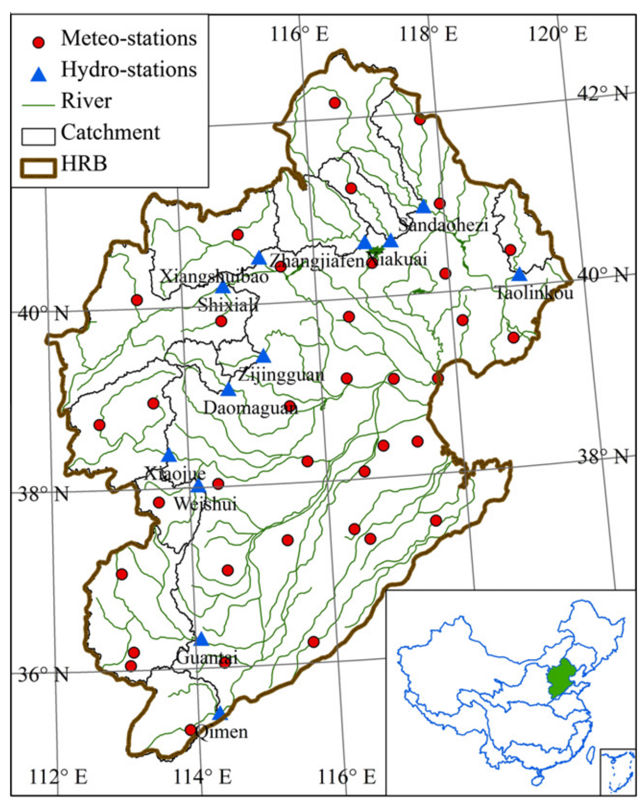


Fig. 1. The 12 selected catchments of the Haihe River basin and the location of which in China.

HRB is 317,800 km^2, 60% and 40% of which are mountain in the western and northern part and plain in the eastern and southern part, respectively. Located in a semi-humid and semi-arid region, HRB belongs to continental monsoon climate zone (Liu and Wei, 1989). The annual mean temperature is 9.6 °C, and annual precipitation is about 530.3 mm (1951–2007), which decreases from south-eastern coastal zone to north-western inland area. Meantime, precipitation varies monthly and annually. The precipitation in flood season (June–September) generally accounts for 70–85% of the annual precipitation and mainly concentrates in several rain processes during July and August. Annual variability of precipitation is also very large, because of the unstable characteristics of the duration, intensity, and impacting region of the subtropical high over the northern pacific in summer. For example, the annual precipitation is more than 800 mm in wet years, but it is only about 270 mm in drought years. That leads to a very high frequency of floods and droughts in the HRB.

There are three river systems in the HRB: Haihe River system, Luanhe River system, and Tuhaimajiahe River system. As the biggest, the Haihe River system contains Jinyun River, Chaobai River, Beiyun River, and Yongding River in the northern part, and Daqing River, Ziya River, and Zhangwei River in the southern part. The Luanhe River system and Tuhaimajiahe River system are in the northern and southern parts of the HRB, respectively.

2.2. Human activities in the HRB

The human activities has become more and more extensive in the HRB during the last several decades and impacts the streamflow by withdrawal of surface water, exploitation of groundwater, LUCC, and the control of runoff by reservoirs.

(1) *Direct human activities.* Due to the increase of population, industry, and farmland area, the amount of surface water withdrawal and groundwater exploitation has been increasing rapidly. According to the census, the total population of HRB was only 63.12 million in 1953, a little increase to 78.19 million in 1964, 102.54 million in 1982, 117.63 million in 1993, 122 million in 1998, and reached 132 million in 2005 (Fig. 2) (Zhu, 2007). The rapid increase in population led to a tremendous increase in water supply. Additional, in the recent 50 years, the GDP of HRB has increased by 33 times and reaches to 1000 billion RMB yuan (Wang, 2002). The area of farmland has increased for the food supply for the increasing population. The industry product (agricultural product) was 1.5 (3.5), 4.3 (5.3), 18.6 (6.3), 79.2 (17.5), 739.7 (115.8), 1177.0 (127.3) billion RMB yuan in 1949, 1952, 1965, 1980, 1994, 1998, respectively (Fig. 2) (Guo and Cao, 2000). On the other hand, the area increase in the land use for city also indicated the increase in the population and industry (Fig. 3a). These factors all led to a significant increase in water supply from surface water and groundwater. As a result, the total withdrawal of water was about 100 km^3 in 1949, 200 km^3 in the end of 1950s, 268 km^3 in 1965 and reached to 396.5 km^3 in 1980 in the HRB (Liu et al., 2010). Meantime, there are about 1900 reservoirs built after 1949, with a total storage capacity being 31.6 billion m^3. The construction of reservoir leads to a increase in evaporation because of the increase in water area and also affects the inter-annual distribution of streamflow.

(2) *Indirect human activities.* As a result of soil and water conservation project, there is an increase in vegetation coverage, a significant LUCC in the HRB since 1980s (Fig. 3) (Wang and Wang, 2009). That would lead to an increase in the canopy interception, soil regulation effect, and soil moisture capacity, and then an increase in the duration of rainfall–runoff process and evapotranspiration. Eventually, there will be a decrease in the direct runoff and peak discharge and an increase in the amount of base flow (Maidment, 1993).

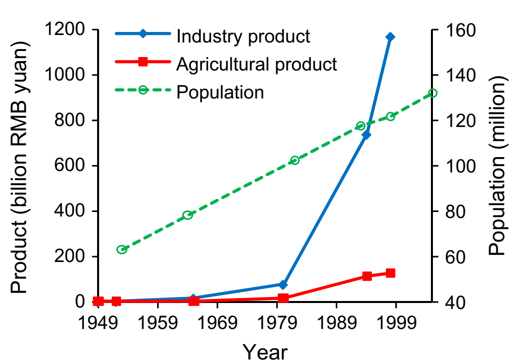


Fig. 2. Increase of industry and agricultural product and population in the Haihe River basin during the last several decades.

2.3. Datasets

There are 37 standard meteorological stations with daily precipitation and mean temperature data in the HRB (Fig. 1). The longest available data period is from 1951 to 2007, and 33 stations have data more than 50 years. These 37 stations, having high-quality data, are maintained according to the standard methodology of the China Meteorological Administration, which applies data quality control before releasing these data.

Twelve hydrological stations in different parts of the HRB are selected to analyze the streamflow trend and the change of the precipitation–runoff-relationship (Fig. 1). The details of the 12 hydrological stations are expressed in Table 1. The daily streamflow data in these hydrological stations are extracted from the "China's Hydrological Year Book", which is published by the Hydrological Bureau of China.

The soil data are extracted from the FAO two-layer 5-min 16-category global soil texture maps. The DEM data are obtained from the SRTM 90 m Digital Elevation Data.

3. Methodology

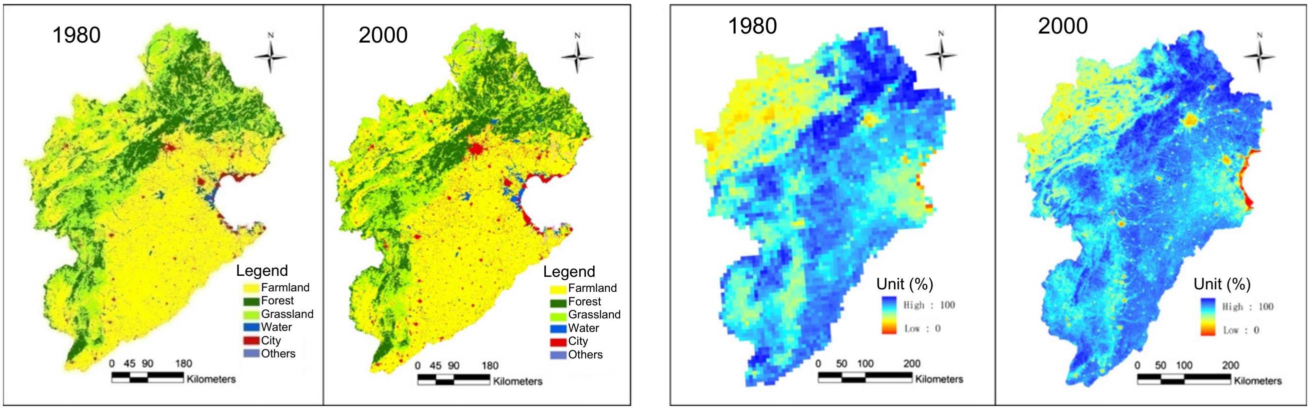
3.1. Mann–Kendall's test

The nonparametric Mann–Kendall's test (Mann, 1945; Kendall, 1975) developed by H.B. Mann and M.G. Kendall is used to detect trends and break points of streamflow, precipitation, and mean temperature in the HRB. This methodology is widely used and has following advantages: (1) it can handle non-normality and censoring data; (2) it has a high asymptotic efficiency (Berryman et al., 1988; Gan, 1998; Fu et al., 2004; Zhang et al., 2007a).

A hypothesis test based on the Mann–Kendall's statistic, UF_i, for a significance level of α, is applied to all variables. The following test is done to prove or to disprove an assumption, that is, was there any statistically significant increasing or decreasing trend for the variables. The test statistic (UF_i) is calculated by the following formula (Zhang et al., 2007a, 2007b):

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

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



(a) Land use (b) Vegetation coverage

Fig. 3. The land use (a) and vegetation coverage (b) of the Haihe River basin in 1980 and 2000.

Table 1
Basic information of the 12 hydrological stations.

Hydrological station	River	Lon. (E°)	Lat. (N°)	A[a] (km^2)	Data period	Prc[a]
Sandaohezi	Luan River	117.70	40.97	17,100	1954–2000	0.08
Taolinkou	Qinlong River	119.05	40.13	5060	1957–2000	0.19
Xiakuai	Chao River	117.17	40.62	5340	1961–2004	0.10
Zhangjiafen	Bai River	116.78	40.62	8506	1954–2004	0.13
Xiangshuibao	Yang River	115.18	40.52	14,507	1951–2004	0.06
Shixiali	Sanggan River	114.62	40.22	23,627	1950–2004	0.05
Zijingguan	Jvma River	115.17	39.43	1760	1950–2000	0.25
Daomaguan	Tang River	114.63	39.08	2770	1957–2000	0.16
Xiaojue	Hutuo River	113.72	38.38	14,000	1956–2000	0.08
Weishui	Ye River	114.13	38.03	5387	1956–2000	0.11
Guantai	Zhang River	114.08	36.33	17,800	1951–2004	0.09
Qimen	Wei River	114.30	35.50	8427	1957–1996	0.24

[a] A, Catchment area; Prc, Runoff ratio.

$$r_i = \begin{cases} +1, & x_i > x_j \\ 0, & x_i \leqslant x_j \end{cases} \quad (j = 1, 2, \ldots, i-1) \tag{3}$$

where x_i is the variable, which is an independent and identically distributed random variable with sample of n. The expected value $E(S_k)$ and variance $Var(S_k)$ could be estimated as follows:

$$E(S_i) = \frac{i(i-1)}{4} \tag{4}$$

$$Var(S_i) = \frac{i(i-1)(2i+5)}{72} \tag{5}$$

The null hypothesis, H_0, meaning that UF_i are not statistically significant, that is, no significant warming/cooling or wetting/drying trend is accepted if $|UF_i| < U_{\alpha/2}$, where $U_{\alpha/2}$ is the standard normal deviates. Alternatively, it is accepted that H_1, that is, UF_i are statistically significant, if $|UF_i| > U_{\alpha/2}$. A positive UF_i value denotes a positive trend, and a negative UF_i value denotes a negative trend.

Then according to the inverse time series: $x_n, x_{n-1}, \ldots, x_1$, UF_i could be calculated again. By the definition of $UB_i = -UF_i$, $i = n$, $n-1, \ldots, 1$, the curve of UF_i and UB_i could be plotted. If there is a match point of the two curves and the trend of the series is statistically significant, the match point would be regarded as the break point of the series.

3.2. A brief review of the VIC model

The Variable Infiltration Capacity (VIC) model is used in this study. It is a semi-distributed macro-scale hydrological based land surface model, which could balance both the water and surface energy budgets within the grid cell (Liang et al., 1994, 1996; Liang and Xie, 2001). The key characters of the VIC model are the representation of multiple land cover types, spatial variability of soil moisture capacity, soil water moving between three soil layers, surface flow considering both infiltration excess and saturation excess, and non-linear base flow. With good performance of the streamflow simulation, the VIC model has been applied in a number of catchments over the world (Abdulla et al., 1996; Lohmann et al., 1998; Su et al., 2005; Zhu and Lettenmaier, 2007; Bao et al., 2011).

In the VIC model, surface runoff generated from the upper two soil layers is accounted based on the variable soil moisture capacity curve, which is described by the Xinanjiang model, in order to represent the sub-grid spatial variability in soil moisture capacity (Zhao et al., 1980; Zhao, 1992). That is expressed as:

$$w = w_m(1 - (1 - A)^{1/b}) \tag{6}$$

where w and w_m are the point and maximum point soil moisture capacity, respectively; A is the fraction of area for which the soil moisture capacity is less than w; and b is the soil moisture capacity shape parameter.

Using the Arno model formulation (Franchini and Pacciani, 1991; Todini, 1996), base flow (subsurface runoff) from the third soil layer is expressed as:

$$Q_b = \begin{cases} \frac{D_S D_m}{W_S \theta_S} \theta_3, 0 \leqslant \theta_3 \leqslant W_S \theta_S \\ \frac{D_S D_m}{W_S \theta_S} \theta_3 + \left(D_m - \frac{D_S D_m}{W_S}\right)\left(\frac{\theta_3 - W_S \theta_S}{\theta_S - W_S \theta_S}\right)^2, \quad \theta_3 > W_S \theta_S \end{cases} \tag{7}$$

where D_m is the maximum subsurface flow; D_s and W_s are the fraction of D_m and maximum soil moisture of third layer (θ_s), respectively; and θ_3 is the current soil moisture of third layer. The base flow recession curve is linear and nonlinear below and above a threshold ($W_s\theta_s$), respectively.

The VIC model is used for streamflow simulation at a 0.25° spatial and daily temporal resolution in three catchments: Taolinkou catchment in the Luanhe River, Zhangjiafen catchment in the north of Haihe River, and Guantai catchment in the south of Haihe River. There are six parameters needing to be calibrated. That includes three baseflow parameters: D_m, W_s, and D_s; the variable soil moisture capacity curve parameter: b; and two parameters, d_2 and d_3, that controls the thickness of the second and third soil layer, respectively. These parameters are calibrated by two objectives:

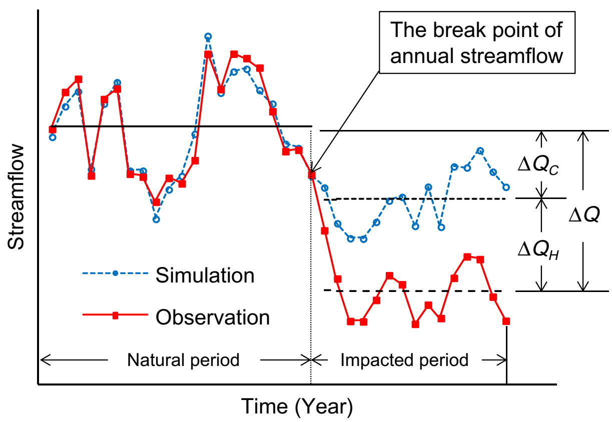


Fig. 4. The framework for quantitative assessment of the contribution of climate variability and human activities for the decreasing streamflow.

Nash–Sutcliffe coefficient (Nsc) and relative error (Re), which are defined as:

$$Nsc = 1 - \frac{\sum(Q_{obs} - Q_{sim})^2}{\sum(Q_{obs} - \overline{Q}_{obs})^2} \quad (8)$$

$$\mathrm{Re} = \frac{R_{sim} - R_{obs}}{R_{obs}} \times 100\% \quad (9)$$

where Q_{obs} and Q_{sim} are the observed and simulated stream discharge, respectively; $\overline{Q}_{obs}$ is the mean value of Q_{obs}; R_{obs} and R_{sim} are the observed and simulated average annual runoff, respectively. The observed precipitation and streamflow data in 1957–1972, 1954–1970 and 1955–1966 are used for calibration, and the data in 1973–1980, 1971–1980, and 1967–1970 are used for verification in the Taolinkou, Zhangjiafen and Guantai catchment, respectively.

3.3. Quantitative assessment of the attribution for streamflow decrease

The driving factors for streamflow change conclude climate variability and human activities. The break point of annual streamflow indicates the abrupt change of annual streamflow. Using the break point, the whole time series could be divided into two periods (Fig. 4). The first one before the break point is called the “natural period”, in which there is not a statistically significant increasing or decreasing trend for streamflow. That means the hydrological cycle and water resources system keep natural status and are not impacted by human activities. Spontaneously, the second one is after the break point, called the “impacted period”, in which there is a statistically significant change of streamflow, compared to it in the “natural period”. That means the hydrological cycle and water

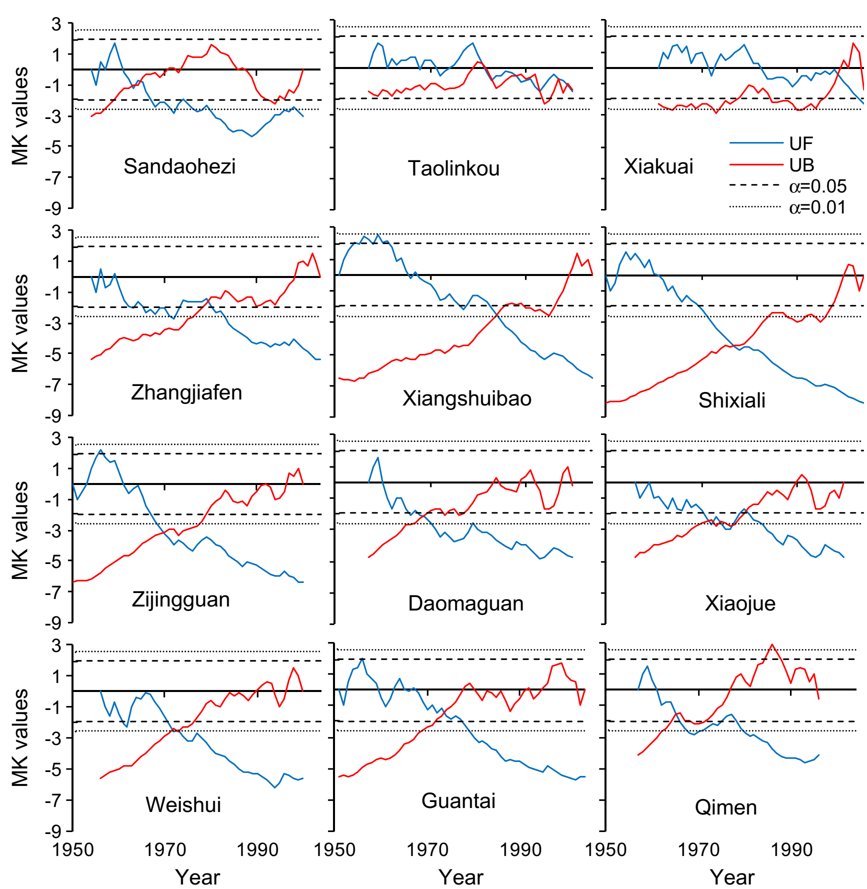


Fig. 5. Mann–Kendall’s testing statistics values for annual streamflow of the 12 hydrological stations (1950–2004).

resources system are extensively influenced by climate variability and/or human activities.

The illustration of the assessment of the attribution for streamflow decrease is shown in Fig. 4. The observed average annual streamflow in the "natural period" and "impacted period" are defined as Q_{on} and Q_{oi}, respectively. The change of annual streamflow (ΔQ) could be calculated by:

$$\Delta Q = Q_{oi} - Q_{on} = \Delta Q_C + \Delta Q_H \quad (10)$$

where ΔQ contains two parts: the streamflow change caused by climate variability (ΔQ_C) and human activities (ΔQ_H). With the estimation of ΔQ_C or ΔQ_H, the contribution of climate variability and human activities to streamflow change, which are defined as η_C and η_H, respectively, could be separated and estimated by:

$$\eta_C = \frac{\Delta Q_C}{\Delta Q} \times 100\%, \quad \eta_H = \frac{\Delta Q_H}{\Delta Q} \times 100\% \quad (11)$$

Using the hydrological data in the "natural period", the parameters of hydrological model could be calibrated and would represent the characteristics of catchment under natural conditions without the impact of human activities (Wang et al., 2008; Zhang et al., 2007a). Then, using the same model parameters and meteorological data in the "impacted period", the "natural streamflow" in the "impacted period" without the impact of human activities could be reconstructed by hydrological model. Therefore, the gap of the reconstructed "natural streamflow" between it in the "natural period" and "impacted period" would indicate the impact of climate variability on streamflow.

$$\Delta Q_C = Q_{si} - Q_{sn} \quad (12)$$

where Q_{sn} and Q_{si} are reconstructed average annual streamflow in the "natural period" and "impacted period", respectively. Finally, the contribution of climate variability and human activities to streamflow decrease could be quantitatively estimated.

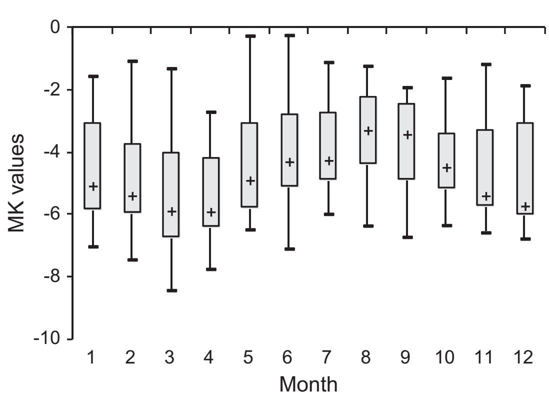


Fig. 6. Mann–Kendall's testing statistics values (*UF*) for monthly streamflow of the 12 hydrological stations throughout the whole period (1950–2004). (The boxes indicated the 25th and 75th percentiles; the whiskers indicated the lowest and highest data value; and + indicated the 50th percentiles value.)

4. Results and discussion

4.1. Hydro-meteorological trends in the HRB

4.1.1. The trend for streamflow

Overall, for the whole available period, the Mann–Kendall's test results showed a decreasing trend for annual streamflow in all the 12 hydrological stations of the HRB, with 11 of them being statistically significant at $\alpha = 0.05$ level, and 10 of them being statistically significant at $\alpha = 0.01$ level (Fig. 5). Only the decreasing trend in Taolinkou station was statistically insignificant at $\alpha = 0.05$ level. Among the 11 hydrological stations with statistically significant decreasing trend, in Xiakuai station, the *UF* value was not lower than -1.96 until in 2003, but the *UF* values in other hydrological stations had been lower than -1.96 since 1983. The earliest one was in 1968 in Zijingguan and Daomaguan station of the Daqing River. The lowest *UF* value was -8.11 in Shixiali station of Yongding River. The detected decreasing trend for streamflow was consistent with the conclusions of Liu et al. (2004), Zhang et al. (2007b), and other researches.

The Mann–Kendall's test results for monthly streamflow throughout the whole period of the 12 hydrological stations were presented in Fig. 6. It could be seen that all the 50th percentiles values of the *UF* values in every month were lower than -2.58 ($\alpha = 0.01$ level). That meant the streamflow of the entire basin had a statistically significant decreasing trend in every month. Sea-

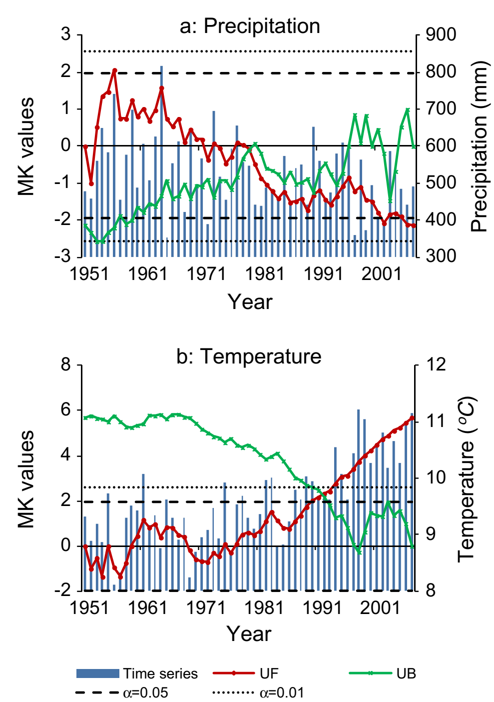


Fig. 7. Time series and Mann–Kendall's testing statistics values of the annual precipitation and mean temperature for the HRB from 1951 to 2007 (a, precipitation; b, temperature).

Table 2
The break point of annual streamflow for the 12 hydrological stations.

Station	Sandaohezi	Taolinkou	Xiakuai	Zhangjiafen	Xiangshuibao	Shixiali
Year	1965	1980	1999	1980	1984	1977
Station	Zijingguan	Daomaguan	Xiaojue	Weishui	Guantai	Qimen
Year	1970	1968	1974	1972	1973	1973

sonally, the highest decreasing trend of streamflow was in spring (March), and the lowest one was in summer (August).

The break points of the annual streamflow were shown in Table 2. Except in Xiakuai station, they were all before 1984, and the earliest one was in 1965 in Sandaohezi station. Most of them happened about in 1980. That was consistent with Yang and Tian (2009).

4.1.2. The trend for precipitation

The time series of HRB areal precipitation, from 1951 to 2007, were shown in Fig. 7a. It could be founded that there was a decreasing trend in HRB during the last 60 years. The annual precipitation in 1964 reached 817 mm, the highest one in the last 60 years. But the annual precipitation in the following year, 1965, was only 354.5 mm, the lowest one in the whole period. The decadal variability of precipitation indicated that 1953–1964 was a wet period. Then, it fluctuated from 1965 to 1975 near the long-term average value. 1976–1979 was another wet period, although of smaller magnitude than 1953–1964. HRB suffered a long dry period from 1980 to 1989. The decadal variation of precipitation from 1990 to 1996 was less. Then, from 1997 to 2007 was another long dry period, in which 1997 and 1999 were the second and third driest year for the last 60 years, with higher extent than 1980–1989. Due to the different data, there was a slight difference compared to Hao et al. (2010) who documented that the highest and lowest precipitation were 799 mm in 1964 and 360 mm in 1965, respectively, with 47 meteorological stations. The same decreasing trend had also been detected by Gong et al. (2004), Chu et al. (2010), and Cong et al. (2010), who founded that the decreasing trend for precipitation in the north of China was mainly due to the weakening monsoon winds over the past 50 years.

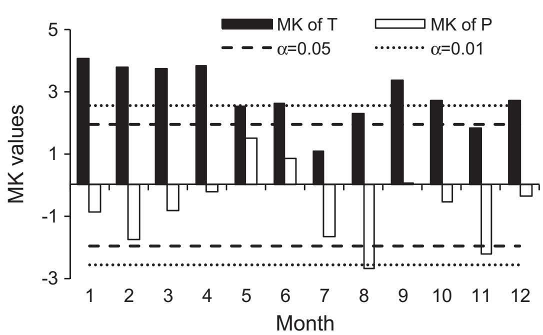


Fig. 8. Mann–Kendall's testing statistics values (*UF*) for monthly precipitation and mean temperature of the HRB (1951–2007).

The result of Mann–Kendall's test showed the same decreasing trend for annual precipitation in HRB from 1951 to 2007 (Fig. 7a). There was not a statistically significant decreasing trend until 2006 at $\alpha = 0.05$ level. The break point of annual precipitation was detected in 1979. The trend of precipitation varied monthly (Fig. 8). Out of the 12 months, May, June, and September showed an increasing trend without statistical significance at $\alpha = 0.05$ level; but other nine months showed a decreasing trend, with statistically significant trend only in two months, August and November at $\alpha = 0.05$ level, and the decreasing trend in August was even statistically significant at $\alpha = 0.01$ level. Therefore, the precipitation decrease in summer was the most important reason for the decrease of annual precipitation.

The spatial distribution of annual precipitation trend was shown in Fig. 9a. There were 35 out of 37 stations, showing a decreasing trend, with five of them located in the north of HRB being statistically significant at $\alpha = 0.05$ level, and two of them located in the northwest of HRB being statistically significant at $\alpha = 0.01$ level. However, only two stations located in the south of HRB showed an increasing trend without statistical significance.

4.1.3. The trend for mean temperature

The time series of HRB mean temperature, from 1951 to 2007, were shown in Fig. 7b. The result showed that the climate of the HRB had become warmer during the last 60 years. There was an oscillation of the annual temperature before 1987. The year of 1956 was the coldest year for the last 60 years. But after 1987,

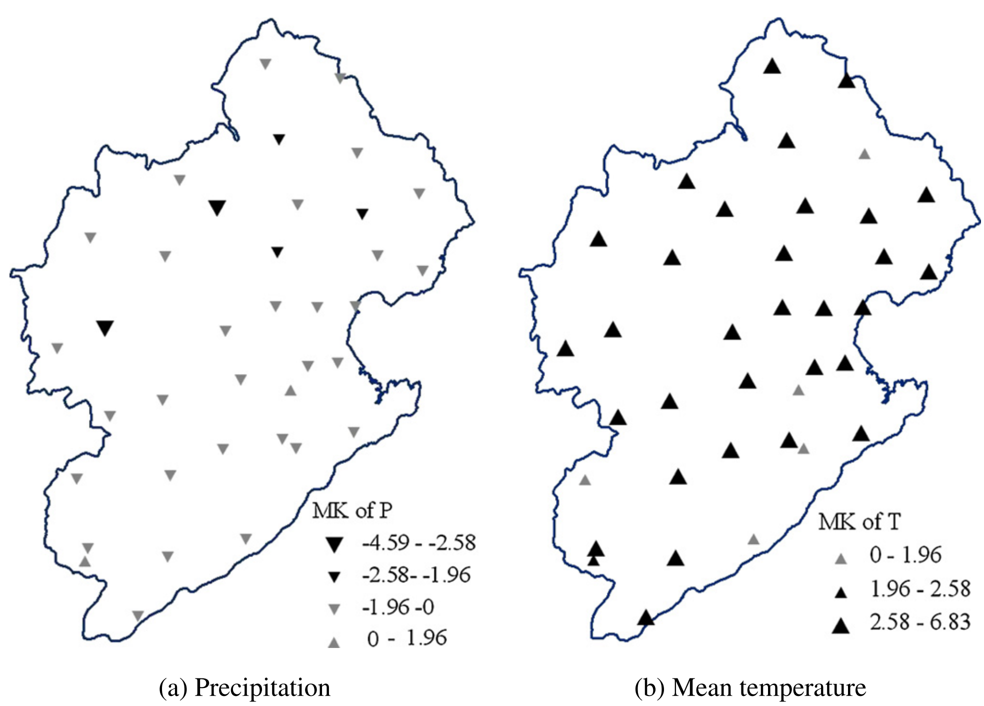


Fig. 9. Mann–Kendall's testing statistics values (*UF*) of annual precipitation (a) and mean temperature (b) for each station in HRB (1951–2007).

the annual temperature was always higher than the long-term mean temperature.

The result of Mann–Kendall's test showed the same obvious increasing trend for annual mean temperature in HRB from 1951 to 2007 (Fig. 7b). There had been a statistically significant increasing trend since 1990 ($\alpha = 0.05$ level); and the MK value had been higher than 2.58 ($\alpha = 0.01$ level) since 1994. Over the whole period, the MK value was 5.7, which meant a high extent of warming trend. The break point of the annual mean temperature was detected in 1991. Monthly, all the 12 months showed an increasing trend for monthly mean temperature, with 10 months having statistical significance at $\alpha = 0.05$ level except July and November, and eight months having statistical significance at $\alpha = 0.01$ level (Fig. 8). The lowest increasing trend was in July, and the highest one was in January, that meant winter months usually had larger increasing trend than summer months. Responsive to global warming, Zhou and Yu (2006) also analyzed the increasing trend of mean temperature in the HRB.

Spatially, all the 37 stations showed an increasing trend for annual mean temperature, only five of them were not statistically significant at $\alpha = 0.05$ level with four stations located in the south of HRB, and 31 out of the 37 stations had a statistically significant trend at $\alpha = 0.01$ level (Fig. 9b).

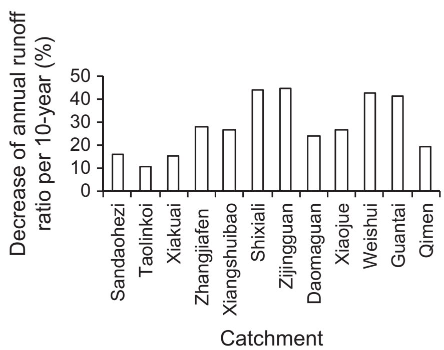


Fig. 10. The decrease of annual runoff ratio in the 12 catchments.

4.2. The change of the precipitation-runoff-relationship

The relationship between precipitation and runoff was a recapitulative description of the hydrological process. It was very complicated especially in semi-humid and semi-arid regions, where a slight change in precipitation might lead to a tremendous change of runoff (Bao et al., 2011). Overall, the average annual runoff ratio (runoff divided by precipitation) of the selected 12 catchments in HRB was 0.13 approximately, with 10 of them being lower than 0.2 (Table 1). The lowest one was in Shixiali station, in which it was only 0.05. Although the annual runoff ratio was low in HRB, it had decreased 0.036 (28%) per 10-year from 1951 to 2004 (Fig. 10). Out of the 12 catchments, there were four catchments: Shixiali, Zijingguan, Weishui, and Guantai catchment, in which the decrease of annual runoff ratio was higher than 40% per 10-year, and that was 44%, 45%, 43%, and 42%, respectively. Generally, the decrease of annual runoff ratio in the northern catchments was lower than that in the southern catchments in the HRB.

The relationship between precipitation and runoff of the 12 catchments in the two periods divided by 1980 was shown in Fig. 11. For each catchment, the points after 1980 were lower than them before 1980. This implied that with the same precipitation, the amount of runoff generation after 1980 was less than that before 1980. Thereby, runoff might be driven by intensive human

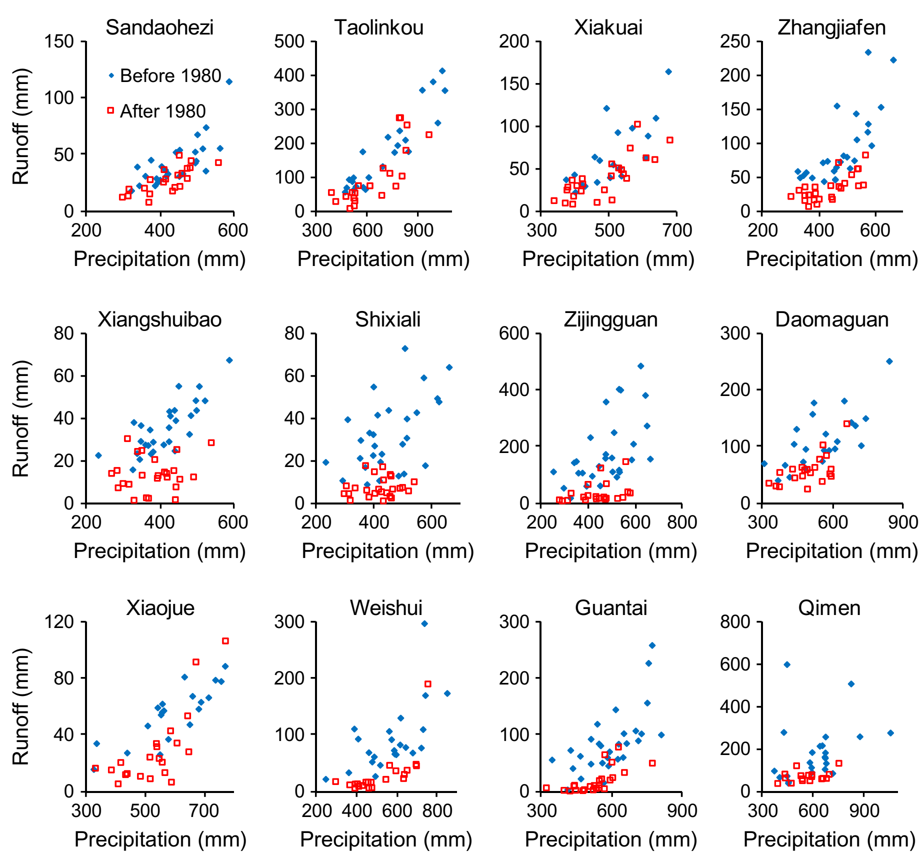


Fig. 11. The relationship of the annual precipitation and runoff during the two periods divided by 1980 for the 12 catchments.

activities in HRB. Some biggest differences of the points in Fig. 11 between the two periods were in Shixiali, Zijingguan, Weishui, and Guantai catchment. That was consistent with the decrease of annual runoff ratio. Therefore, the contribution of human activities on streamflow decrease in these catchments might be higher than other catchments of the HRB.

4.3. Assessment of the attribution for decreasing streamflow

Three catchments: Taolinkou catchment in the Luanhe River, Zhangjiafen catchment in the north of Haihe River, and Guantai catchment in the south of Haihe River were used to assess the contribution of climate variability and human activities to streamflow decrease. The hydrological regimes at the three catchments represented an overview of the hydrological regime of the entire basin.

4.3.1. Reconstruction of the "natural streamflow"

Table 3 summarized the performance of VIC model in the three catchments. The *Nsc* values were higher than 0.75 in Taolinkou catchment and were higher than 0.7 in Zhangjiafen and Guantai catchment. *Re* values were lower than 5% for the three catchments, except it in Guantai catchment during the verification period. Fig. 12a showed the simulated and observed monthly streamflow in the calibration and verification period. The results denoted good performance of the VIC model, although there were some differences between simulation and observation at the peak. In order to detect the simulation of VIC model in every month, the observed and simulated average monthly streamflow were shown in Fig. 12b. Generally, the simulation curve corresponded to the observation curve well. Overall, the calibration and verification accuracy of VIC model was acceptable for monthly streamflow simulation in the three catchments.

Table 3
Performance of the VIC model for monthly streamflow simulation in the Taolinkou, Zhangjiafen, and Guantai catchment.

Catchment	Period	Year	*Nsc*	*Re* (%)
Taolinkou	Calibration period	1957–1972	0.93	4.80
	Verification period	1973–1980	0.76	−4.66
Zhangjiafen	Calibration period	1954–1970	0.73	3.00
	Verification period	1971–1980	0.70	−0.94
Guantai	Calibration period	1955–1966	0.73	−2.87
	Verification period	1967–1970	0.75	14.06

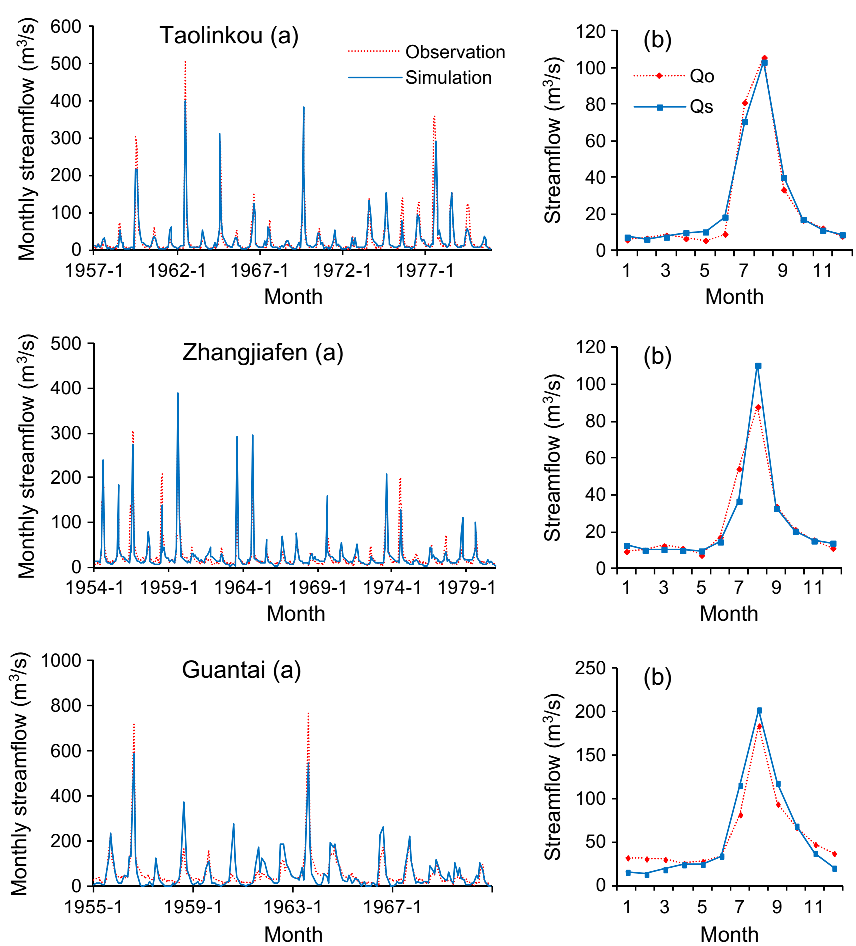


Fig. 12. Observed and simulated monthly streamflow in the calibration and verification period of the Taolinkou, Zhangjiafen, and Guantai catchment (a, time series; b, multi-year monthly average).

Based on the sufficient accuracy of streamflow simulated by the VIC model, the "natural streamflow" was reconstructed for the whole period in the Taolinkou, Zhangjiafen, and Guantai catchment (Fig. 13). The beginning of the significant differences between the observed and simulated annual streamflow was consistent with the break point of observed annual streamflow. The gap between the observation and simulation represented the impact of human activities on streamflow (Wang et al., 2008).

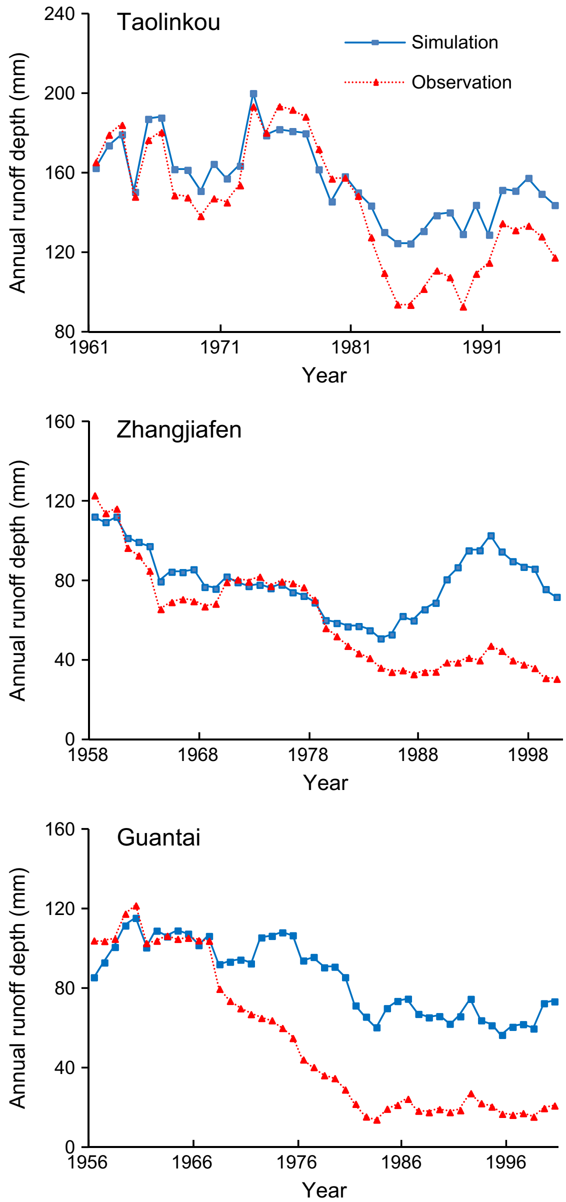


Fig. 13. Difference between simulated and observed annual streamflow, which were smoothed with a 9-year moving average filter for the whole periods in the Taolinkou, Zhangjiafen, and Guantai catchment.

4.3.2. Contribution of climate variability and human activities to streamflow decrease

By the comparison of the meteorological variables in two periods divided by the break point, precipitation had decreased by 69.63 mm (9.9%), 45.11 mm (9.5%), and 54.54 mm (9.2%), and mean temperature had increased by 0.9, 0.76, and 0.64 °C, in the Taolinkou, Zhangjiafen, and Guantai catchment, respectively (Table 4). In the Taolinkou catchment, the observed average annual streamflow decreased by 73.51 mm from 177.08 mm to 103.57 mm in the "natural period" and "impacted period", respectively. Meanwhile, the average annual "natural streamflow" reconstructed by the VIC model was 173.73 mm and 130.72 mm in the "natural period" and "impacted period", respectively, and decreased by 40.01 mm. That meant climate variability and human activities accounted for 58.5% (43.01 mm/73.51 mm) and 41.5%, respectively, of the annual streamflow decrease in the Taolinkou catchment between the two periods (Fig. 14). Similarly, the contribution of climate variability accounted for 40.1% and 26.1%, and human activities accounted for 59.9% and 73.9% to the streamflow decrease in the Zhangjiafen and Guantai catchment, respectively.

Meanwhile, the monthly contribution of climate variability and human activities to streamflow decrease was analyzed and expressed in Fig. 15. Overall, monthly contribution was consistent with the annual results. In the Taolinkou catchment, the lower contribution of climate variability was in February to April. For the Zhangjiafen and Guantai catchment, the contribution of climate variability in August was the biggest monthly ones. That was because the most extensive decrease of precipitation was in August for the two catchments. That would lead to a high decrease of

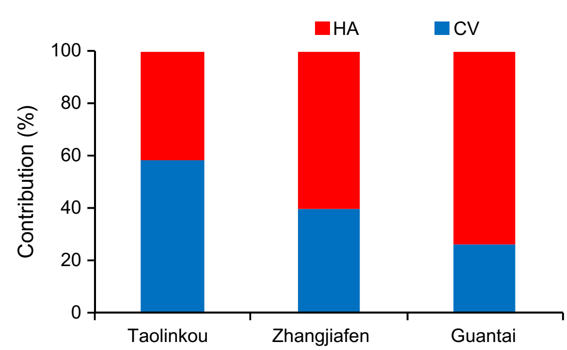


Fig. 14. Contribution of climate variability and human activities for decreasing annual streamflow during the two periods divided by the break point in the Taolinkou, Zhangjiafen, and Guantai catchment.

Table 4
Changes of annual mean temperature, precipitation, and streamflow during the two periods in the Taolinkou, Zhangjiafen, and Guantai catchment.

Catchment	Period	Year	T_{mean} (°C)	*P* (mm)	*Qo*[a] (mm)	*Qs*[a] (mm)
Taolinkou	Natural period	1957–1979	6.98	703.97	177.08	173.73
	Impacted period	1980–2000	7.88	634.34	103.57	130.72
	Change		0.90	−69.63	−73.51	−43.01
Zhangjiafen	Natural period	1954–1979	8.70	477.24	92.63	93.11
	Impacted period	1980–2004	9.46	432.13	34.99	70.02
	Change		0.76	−45.11	−57.64	−23.09
Guantai	Natural period	1951–1972	12.80	593.04	98.99	95.89
	Impacted period	1973–2004	13.44	538.5	26.01	76.85
	Change		0.64	−54.54	−72.98	−19.04

[a] *Qo*, observed annual streamflow; *Qs*, simulated annual streamflow using the VIC model.

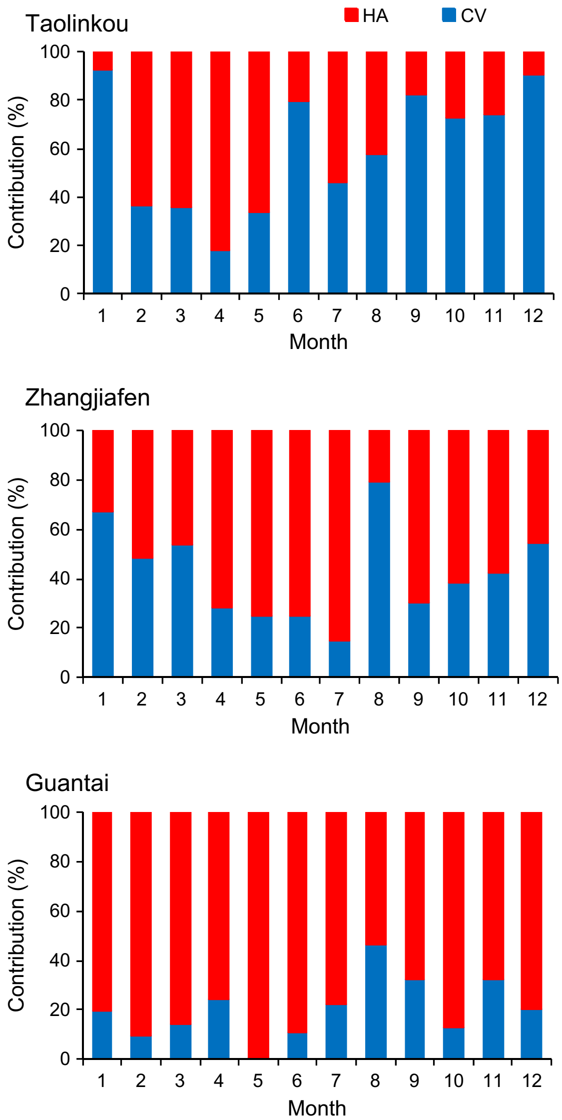


Fig. 15. Contribution of climate variability and human activities for decreasing monthly streamflow in the Taolinkou, Zhangjiafen, and Guantai catchment. (HA, human activities; CV, climate variability.)

streamflow and result in high percentage of the contribution from climate variability.

Using the "natural period" as the base line period, the contribution of climate variability on streamflow decrease was estimated in each year during the "impacted period" (Fig. 16). From 1980 to 1988, the contribution of climate variability in Taolinkou catchment was higher than 50% and as similar as it in Zhangjiafen catchment. But after 1988, in Zhangjiafen catchment, the contribution of climate variability decreased rapidly to lower than 50%, with a slight rebound after 1996; otherwise, the contribution of climate variability still fluctuated near 50% in Taolinkou catchment. Early 1980s was the beginning period of China's land reform, which motivated farmers to increase agricultural product by increasing agricultural activities that resulted in increased agricultural water use (Yang and Tian, 2009). That also happened in Zhangjiafen catchment (i.e., Baihe River). Meanwhile, the annual precipitation increased in 1982–1995 and decreased in 1996–2001. That was consistent with the trend for contribution of climate variability in Zhangjiafen catchment. In Guantai catchment, the contribution of climate variability was always lower than 50% after 1973, with an increasing trend after 1978. That was because most of the small reservoirs were built before 1975 in Guantai catchment that led to a streamflow decrease.

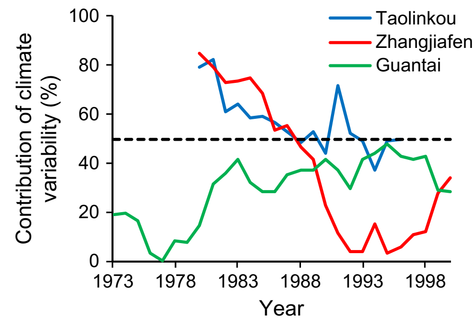


Fig. 16. Time series (smoothed with a 9-year moving average filter) of the contribution of climate variability to streamflow change in the Taolinkou, Zhangjiafen, and Guantai catchment. (The base line was "natural period".)

4.3.3. Comparison of the results with other studies

Taolinkou catchment had the largest contribution of climate variability, followed by Zhangjiafen catchment, and then Guantai catchment. Meanwhile, climate variability was the main factor for streamflow decrease in Taolinkou catchment; however, human activities were the main factors for streamflow decrease in Zhangjiafen and Guantai catchments. That was consistent with Liu et al. (2004) and Wang et al. (2009), but was different with the result of Ma et al. (2010) who pointed out that climate variability accounted for about 51–55% of the decrease of inflow into Miyun Reservoir. That was mainly due to the different break point using, different time period of datasets, different hydrological models, etc. Wang et al. (2009) divided the data series in 1961–1966 and 1973–2001 into two sub-periods (1961–1966 & 1973–1979 and 1980–2001) by 1980. Ma et al. (2010) divided the data series in 1956–2005 into two sub-periods (1956–1983 and 1984–2005) by 1984. From 1980 to 1990, because of the increase in the impact of human activities, the contribution of climate variability on streamflow decrease had been decreasing constantly in the Zhangjiafen catchment (Fig. 16). The break point used by Wang et al. (2009) was before Ma et al. (2010). Therefore, the contribution of climate variability investigated by Wang et al. (2009) was lower than that pointed by Ma et al. (2010).

4.3.4. Uncertainty analysis

The major sources of uncertainty in the analysis of attribution for streamflow decrease depended on the detection of the break point of streamflow and the reconstruction of "natural streamflow" with the VIC model. They were influenced by the hydro-meteorological data, model parameters, and model structure. (1) Precipitation data from limited number of meteorological stations could not really represent the regional precipitation. (2) There were some unavoidable errors for the calibration of model parameters. (3) The VIC model does not simulate all physical processes of the hydrological cycle at a catchment scale. Although the VIC model had satisfying results, the reconstructed annual streamflow in the "natural period" still had a slight difference compared to the observed annual streamflow. Quantitative uncertainty of attribution analysis would be further investigated in future studies.

5. Conclusions

During the last 60 years, there were statistically significant increasing and decreasing trends for mean temperature and precipitation in the Haihe River basin, respectively, that is, the HRB had been becoming warmer and drier. Meantime, the local human activities had become more and more extensive. Observed annual and monthly streamflow was detected as statistically significant decreasing trends in 12 hydrological stations located in different parts of the HRB. That was mainly attributed to two driving factors: climate variability and human activities. Using the break point of the annual streamflow, the whole period was divided into two periods: "natural period" (before the break point) and "impacted period" (after the break point).

Three catchments located in different parts of the HRB were used as the case study area for the quantitative assessment of the attribution for streamflow decrease. They are the Taolinkou catchment in the Luanhe River, Zhangjiafen catchment in the north of Haihe River, and Guantai catchment in the south of Haihe River. Using the VIC model, which was calibrated in the "natural period", the "natural streamflow" without the impact of human activities was reconstructed for the whole period. The differences of the "natural streamflow" between the "natural period" and "impacted period" indicated the impact of climate variability on streamflow decrease. Another part of streamflow decrease was because of human activities. The results indicated that Taolinkou catchment (58.5%) had the largest contribution of climate variability, followed by Zhangjiafen catchment (40.1%), and then Guantai catchment (26.1%). That was to say, climate variability was the major driving factor for streamflow decrease in the Luanhe River; on the other hand, human activities was the main driving factor for streamflow decrease in the north and south part of the Haihe River.

The results could be useful for water resources planners and managers to understand the changing process of hydrological cycle and driving factors for streamflow decrease and could also be a reference for water resources planning and management in the HRB.

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