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Haihe River discharge to Bohai Bay, North China: trends, climate, and human activities

Qi Wei, Conghui Sun, Guanghong Wu and Ling Pan

ABSTRACT

Trends in annual precipitation and river discharge (1956–2012) were analyzed using the Mann–Kendall test and Sen's method to evaluate the impact of climate variation and human activities on the Haihe River discharge to Bohai Bay. Compared to observations before 1965, two obvious decreases in annual river discharge occurred after 1965 and after 1980. Considering 1956–1965 as the baseline period, it was established that the reduction in Haihe River discharge to the Bohai Sea was 52.9% and 81.9% during 1966–1980 and 1981–2012, respectively. Compared to the baseline period, the reductions in annual precipitation in 1966–1980 and 1981–2012 were 7.1% and 14.2%, respectively. Following the increase in population, industrial activity, and irrigated areas, water consumption has increased rapidly, from 51.9 mm in 1965 to 124.8 mm in 1980 and 126.4 mm in 2000. These results indicate that the reduction in discharge in the Haihe River basin during 1966–1980 and 1981–2000 could be attributed to climatic variations (33.2% and 41.4%, respectively) and human activities (66.8% and 58.6%, respectively). The results also indicate that salinity in Bohai Bay increased following the decrease in discharge from the Haihe River.

Key words | climate variation, Haihe River Basin, human activity, river discharge, trend analysis

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INTRODUCTION

It is widely recognized that runoff is influenced by both climatic variations and human activities (Bao *et al.* 2012; Zhao *et al.* 2014). Climatic variations, e.g. precipitation and potential evaporation, have a significant impact on river runoff. Human activities, such as land-use changes, irrigation, and dam construction, also lead to significant hydrological alterations (Milliman & Meade 1983; Carriquiry & Sánchez 1999; Frihy *et al.* 2003; Walling 2006; Wang *et al.* 2006; Wanders & Wada 2015). In recent decades, considerable effort has been devoted to elucidating the impact of both climatic variations and human activities on water resources (Milliman *et al.* 2008). Some studies have investigated the effects of human activities and climatic variations on the discharge of major Chinese rivers (Xu *et al.* 2010), including the Yellow River (Cuo *et al.* 2013), the Yangtze River (Xiong *et al.* 2013), and the Pearl River (Zhang *et al.* 2008).

The Haihe River basin in China, which is politically important and culturally and economically advanced, has experienced severe water shortages, considerable water pollution, and ecological deterioration (Wang *et al.* 2010). Therefore, a greater understanding of human and climatic influences on this river is needed. Several studies have analyzed decreasing trends in runoff in other rivers within the Haihe River basin. For example, Wang *et al.* (2013) found that human activities were mainly responsible for runoff reduction in the Luan River catchment (accounting for 57–67% of total reduction). Xu *et al.* (2013) concluded that the impact of local human activities accounted for 79.5% of the estimated decrease in annual inflow to the Panjiakou Reservoir in the Luan River basin. Wang *et al.* (2009) estimated the contribution of land-use change to runoff reduction to be 68% and 70% for the Chao and Bai rivers,

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respectively. Ma *et al.* (2010) reported that climatic variability accounted for 51–55% of the decrease in runoff into the Miyun Reservoir on the Chao and Bai rivers. Wang *et al.* (2013) found that human activities constituted the main driving factor for the decline in annual runoff within the Chao River catchment (accounting for 54–66% of the total decline). Jiang *et al.* (2014) reported that the dramatic decline in streamflow in the Yongding River within the Haihe River basin was not the result of precipitation variability, but was more likely due to upstream human drivers. Wang *et al.* (2013) found that human activities were mainly responsible for runoff reduction in the Zhang River (accounting for 64–69% of the total reduction) and that climatic variability was responsible for the decrease in annual runoff in the Hutuo River (accounting for 69–72% of the total decrease). Lei *et al.* (2014) investigated spatiotemporal changes in runoff across the mountainous region of the Haihe River basin, which were driven by variations in climatic factors and CO_2 concentration, and found that precipitation dominated runoff changes in most of the mountainous region (66%). The results of these studies quantifying the relative contributions of climatic variability and human activity to runoff reduction are inconsistent, mainly due to the different case study areas and the different temporal scope of the data sets. Most of these studies were concerned with runoff in specific rivers or sub-basins, and few have investigated the trends in water fluxes to Bohai Bay across the entire basin or have linked discharge reduction to increasing salinity in Bohai Bay.

The discharge of larger rivers to the sea is an important component of the global water cycle, which directly influences marine ecosystems in estuaries and neighboring seas (Ludwig *et al.* 2009). González-Ortegón *et al.* (2015) reported that in the Mediterranean climate zone, recurrent droughts and increased water demand generally lead to less freshwater flow to estuaries. This water scarcity may alter the proper function of estuaries as nursery areas for marine species and as a permanent habitat for estuarine species.

Water resource management in the Haihe River basin faces great challenges due to recent climate changes and extensive human activities. Changes in the discharge of the Haihe River to Bohai Bay concern both the public and the scientific community. The objectives of the present study were to investigate variations in the discharge of the Haihe River to Bohai Bay across the entire basin, to quantify the contributions from climatic variations and human activities to discharge variation, and to investigate links between the reduction in river discharge and salinity variation in Bohai Bay.

METHODS

Study area

The Haihe River basin encompasses Beijing, Tianjin, the greater part of Hebei, and parts of Shandong, Henan, Shanxi, and Inner Mongolia. The basin has an area of approximately 3.18×10^5 km^2, encompassing mountains and plateaus (1.89×10^5 km^2, 60%) and plains (1.29×10^5 km^2, 40%) (Figure 1). It contains more than 300 tributaries that are distributed like a fan over vast areas of northern China and flow eastward, emptying into Bohai Bay. The entire basin includes three primary river systems: the Luan River sub-basin (the northern part; 17% of the total area), the Haihe River sub-basin (the middle part; 74% of the total area), and the Tuhaimajia River sub-basin (the southern part; 9% of the total area). In 1963, the Haihe River basin was affected by a severe flood, and since then, ten additional outlets to Bohai Bay have been opened to increase flood-diversion capacity (Committee for the Compilation of Haihe River 1997). Land-cover types in the Haihe River basin include forests, grasslands, water bodies, wetlands, floodplains, barren land, built-up land, and croplands. Vegetation cover in the basin increased slightly during 1998–2011 to reach 65–73%. Soil types in the basin include chestnut soil in the plateau, brown-earth soil in the mountains, and fluvo-aquic and saline soil in the plain (Ren *et al.* 2007).

Data collection

Data sets of annual river discharge from the Haihe River basin, which includes the ten additional outlets to Bohai Bay, were obtained from Ren *et al.* (2007) and the Haihe River Water Conservation Commission (2013). The outlets provide access to the three river systems, which include 14 sub-basins (Figure 1). Further information on the discharge

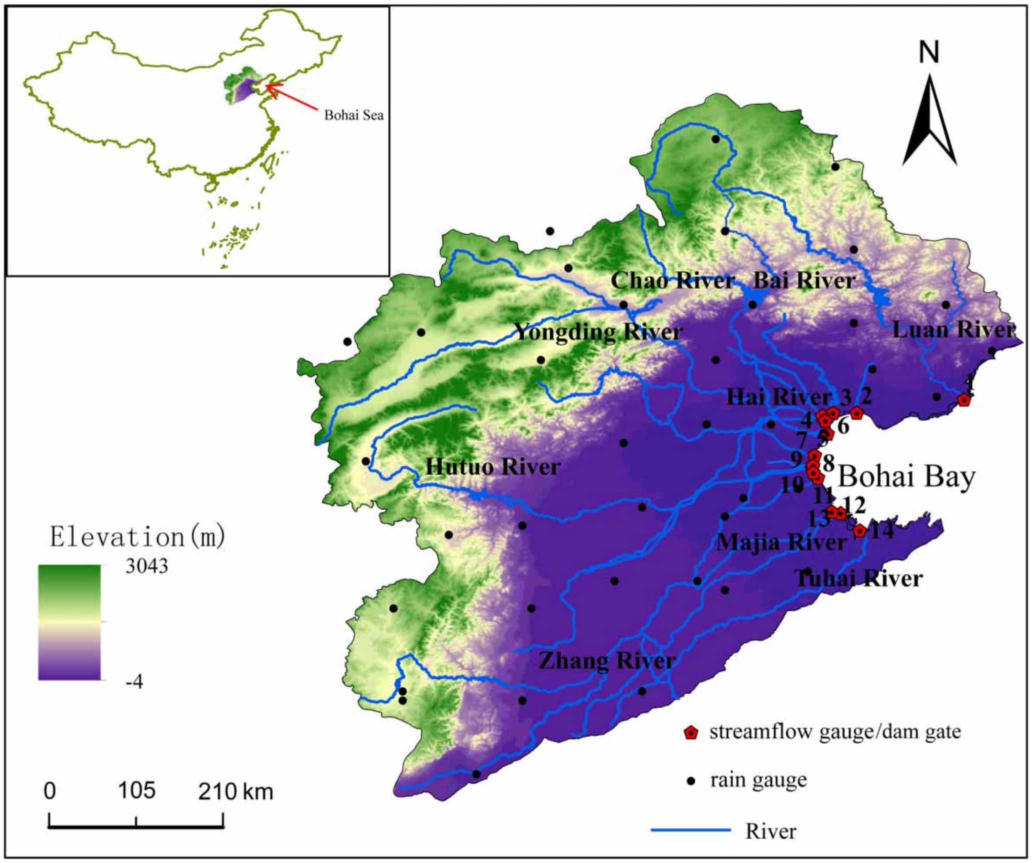

Figure 1 | Study area, its river system, and gauge stations. 1, Luan River; 2, Dou River; 3, Jiyun River; 4, Caobaixin River; 5, Yongdingxin River; 6, Hai River; 7, Duliujian River; 8, Ziyaxin River; 9, Canglang Canal; 10, Beipaishui River; 11, Nanpaishui River; 12, Zhangweixin River; 13, Majia River; 14, Tuhai River.

and gauge stations (dam gates) was presented in Ren *et al.* (2007). The climate data sets used in the present study were obtained from the China Meteorological Data Sharing Service System (http://cdc.nmic.cn). Temperature and precipitation data from 43 meteorological stations (Figure 1) were collected and processed into annual data sets using an inverse distance weighting interpolation tool. Data sets for salinity in Bohai Bay were obtained from the Chinese Science and Technology Resources Portal (http://www.escience.gov.cn/).

Mann–Kendall trend detection

The Mann–Kendall (M–K) test is a non-parametric test commonly used to detect the significance of trends in hydrometeorological time series data, which requires only that the data be independent (Mann 1945; Kendall & Gibbons 1990; Gocic & Trajkovic 2013; Bawden *et al.* 2015). The test is simple, robust, and supports multiple observations per time series. Hence, it was used to detect trends in the time series data for annual river discharge and annual precipitation in the present study.

The M–K test is given as:

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} \operatorname{sgn}(x_j - x_k),\ \ k = 2,\ 3,\ \ldots,\ n \tag{1}$$

$$\operatorname{sgn}(x_j - x_k) = \begin{cases} +1, & \text{if} \quad (x_j - x_k) > 0 \\ 0\,, & \text{if} \quad (x_j - x_k) = 0 \\ -1, & \text{if} \quad (x_j - x_k) < 0 \end{cases} \tag{2}$$

where x_j and x_k represent the data points at times j and k ($j > k$), respectively. As the test is based on the ranks of the time series data, a correction is made for the effects of the tied data on the variance of S using the following equation:

$$\mathrm{Var}(S)=\frac{1}{18}\left[n(n-1)(2n+5)-\sum_{i=1}^{m}t_i(t_i-1)(2t_i+5)\right] \quad (3)$$

where n is the number of data points, t_i is the number of ties for the i-th value, and m is the number of tied values. From this, the standardized test statistic Z is obtained using an approximation:

$$Z=\begin{cases}\dfrac{S-1}{\sqrt{\mathrm{Var}(S)}}, & \text{if } S>0\\ 0, & \text{if } S=0\\ \dfrac{S-1}{\sqrt{\mathrm{Var}(S)}} & \text{if } S<0\end{cases} \quad (4)$$

A positive Z value indicates an increasing trend, and a negative value indicates a decreasing trend. The null hypothesis is rejected at the significance level α if $|Z|\geq Z_{(1-\alpha/2)}$, where $(1-\alpha/2)$ is the value of the standard normal distribution with an exceedance probability $\alpha/2$. The $|Z|$ critical values of 1.28, 1.64, and 2.32 were used for the probabilities of 90%, 95%, and 99%, respectively.

Trend slopes (as change per year) were investigated using a robust non-parametric slope estimator developed by Sen (1968):

$$\beta=\frac{x_j-x_k}{j-k},\ \text{for all } j>k \quad (5)$$

where β is the slope estimator and x_j and x_k are data values at time j and k, respectively. Further details of the method used in hydro-meteorological time series were explained in Gocic & Trajkovic (2013).

M–K change-point analysis

M–K change-point analysis is used for determining the approximate year of the beginning of the significant trends at the 95% and 99% confidence levels. For a time series $x_1, x_2, x_3 \ldots x_n$, the M–K rank statistic is defined as:

$$S_k=\sum_{i=1}^{k}r_i\ (2\leq k\leq n) \quad (6)$$

$$r_i=\begin{cases}1, & x_i>x_j\\ 0, & x_i\leq x_j\end{cases}\ (j=1,2,3,\ \ldots\ i) \quad (7)$$

The mean and variance of the test statistic (S_k) are:

$$\begin{cases}E[S_k]=\dfrac{k(k-1)}{4}\\ \mathrm{Var}[S_k]=\dfrac{k(k-1)(2k+5)}{72}\end{cases}(2\leq k\leq n) \quad (8)$$

The test statistic (UF_k) is calculated using the following formula:

$$UF_k=\frac{S_k-E[S_k]}{\sqrt{\mathrm{Var}[S_k]}}\ (1\leq k\leq n). \quad (9)$$

The values of UF_k constitute a forward sequence curve (UF). For the given α significance level and $U\alpha$ (the critical value of the standard normal distribution), if $UF_k>U\alpha$, then the forward sequence curve (UF) has a trend with a significance level of α. The |UF| critical values of 1.96 and 2.58 were used for the probabilities of 95% and 99%, respectively. The same equation was then used for the inversed series ($x_n, \ldots, x_3, x_2, x_1$) for the backward sequence values of the statistic UB_k ($k=n, n-1, \ldots, 1$), which yields a backward sequence curve (UB). The intersection point of UF and UB within the confidence interval is the time when a change point occurred. Further details of the method are explained in Some'e *et al.* (2012).

Estimating the impact of climatic variations on river discharge

Changes in discharge caused by climatic variations and human activities, when considered as independent variables, can be represented as follows:

$$\Delta Q_{\mathrm{Total}}=\Delta Q_{\mathrm{Climate}}+\Delta Q_{\mathrm{Human}} \quad (10)$$

The relative climatic and human impacts can be quantified using the following formula:

$$\text{Human contribution}=\frac{\Delta Q_{\mathrm{Human}}}{\Delta Q_{\mathrm{Total}}}\times 100\% \quad (11)$$

$$\text{Climate contribution} = \frac{\Delta Q_{\text{Climate}}}{\Delta Q_{\text{Total}}} \times 100\% \tag{12}$$

where ΔQ_{Total} is the total change between two different periods estimated as the difference between observed discharges in the two periods, $\Delta Q_{\text{Climate}}$ is the change in discharge caused by climatic variation, and ΔQ_{Human} is the change in discharge caused by human activities.

The two periods were obtained by dividing the study period using inflection points. To quantify and separate the effects of the two factors, only one of the variables ($\Delta Q_{\text{Climate}}$ or ΔQ_{Human}) needs to be quantified. Several statistical methods have been widely used to model the rainfall–runoff relationship. In the present study, simple linear regression during different periods was used to estimate annual runoff (natural discharge). Therefore, changes in discharge caused by climatic variations ($\Delta Q_{\text{Climate}}$) could be quantified. Further details of simple linear regression were explained in Helsel & Hirsch (2002).

RESULTS

Trends and change point of river discharge

Trends and trend slopes of annual precipitation and river discharge (1956–2012) in the Haihe River basin are presented in Table 1. The results show decreasing trends in annual river discharge in this basin for 1956–2012 (negative test Z values, significant at the 99.5% confidence level). Owing to the combined effects of climatic factors and human activities, annual river discharge decreased at an average rate of -0.69 mm yr^{-1} (Table 1). Furthermore, it can be seen that the trends in river discharge detected by the M–K test and Sen's slope estimator are almost consistent.

The M–K plots for Haihe River discharge are shown in Figure 2(a). According to the M–K change-point analysis, a negative trend in annual values can be seen beginning in 1966 and reaches confidence levels greater than 95% and 99% around 1981 and 1983, respectively. Note that a significant trend is detected when the UF_k curve exceeds the

Table 1 | Trend analysis of annual river discharge and precipitation time series

	Mann–Kendall test			**Sen's slope estimator**		
Time series	**Test *Z***	**Trend direction**	**Significant**	**Sen's slope**	**Trend direction**	**Significant**
Discharge	−4.26	Down	***	−0.69	Down	***
Precipitation	−1.76	Down	*	−1.39	Down	

*** and * indicate that the computed probability is greater than the level of significance (99.5% and 95%, respectively).

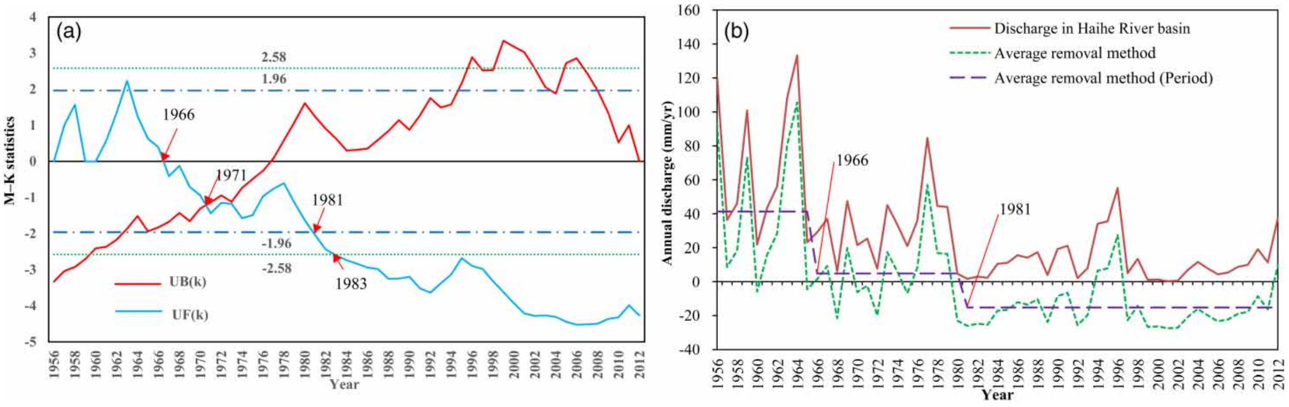

Figure 2 | (a) Sequential values of UF_k and UB_k from Mann–Kendall change-point analysis; (b) annual river discharge from the Haihe River basin to Bohai Bay.

absolute value of the critical value on a time series graph, i.e., 1.96 and 2.58 at the 95% and 99% confidence levels, respectively. Consequently, to quantify the changes over time, the data were split into three periods (Period I: 1956–1965, Period II: 1966–1980, and Period III: 1981–2012).

The average removal method was used to analyze the annual river discharge time series (Figure 2(b)). The results of the average removal method indicate a significant downward trend for annual river discharge in 1966–1980 and a slight downward trend in 1981–2012. Considering 1956–1965 as the baseline period, the reduction was estimated to be at least 52.9% (36.5 mm) and 81.9% (56.5 mm) for the periods 1966–1980 and 1981–2012, respectively.

The average removal method is a simple but effective technique. It has reliable, stable performance and it can remove annual trends, and the scaling behavior is maintained throughout the entire region under study (Zhang *et al.* 2011). The results indicate that strong fluctuations occurred in 1956–1980 due to natural climatic characteristics, but that the oscillations were relatively stable in 1981–2012 because of the response of river discharge to human activities. The results also show that after about 1981, the rivers in the basin became regulated, and the flood hazard in the lower reaches was reduced because of damming, reservoir storage, and flood control measures.

The mean annual river discharges to Bohai Bay from the entire basin and its three individual sub-basins in the past six decades is shown in Figure 3. Compared with the 1950s, the Haihe River discharge to Bohai Bay in the 1960s, 1970s, 1980s, 1990s, and 2000s decreased to 77.7%, 53.2%, 15.2%, 27.2%, and 11.5%, respectively. The lowest river discharge was found in the 1980s. Trends based on the M–K test of river discharge for each sub-basin were also detected (Table 2). Different trends were observed in the northern, middle, and southern parts of the Haihe River basin. The Haihe River discharge to Bohai Bay shows a downward trend. However, the results show that although the river discharge in the northern and central parts of the Haihe River basin decreased significantly at the 99% confidence level over the past six decades, no trend in river discharge was identifiable in the southern parts. The Tuhaimajia River sub-basin is located in the southeastern region of the Haihe River basin. It is 428 km long, with an area of approximately 2.87×10^4 km^2, and accounts for 9% of the total Haihe River basin area. No damming or water storage activities were found in this sub-basin (Committee for the Compilation of Haihe River 1997).

Table 2 | Trend analysis of annual discharges from the entire basin and its three individual sub-basins

Time series	Test *Z*	Trend direction	Significant
The entire basin	−4.26	Down	***
The Luan River sub-basin	−2.63	Down	**
The Haihe River sub-basin	−2.82	Down	**
The Tuhaimajia River sub-basin	0.38	No trend	

*** and ** indicate that the computed probability is greater than the level of significance (99.5% and 99% respectively).

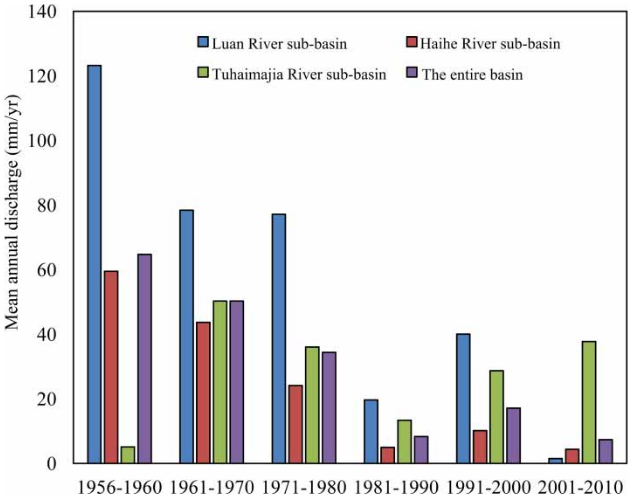

Figure 3 | Annual discharges to Bohai Bay in the three sub-basins of the Haihe River basin (1956–2010).

River discharge-salinity relationship

The entry of rivers into seawater exerts a profound influence on the dynamics of the local marine ecosystem. Note that evaporation and precipitation have an indisputable influence on salinity variation. However, it is generally believed that the magnitudes of the influences of evaporation and precipitation on sea surface salinity are similar, and that river discharge plays a major role in defining the salinity distribution of coastal waters (Liu 2011).

The Haihe River discharge and salinity in Bohai Bay are plotted in Figure 4. A significantly increasing trend can be

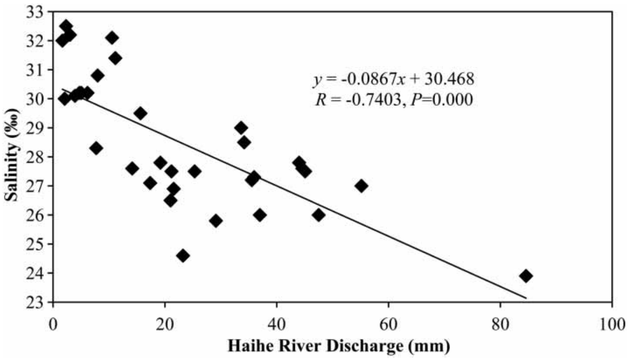

Figure 4 | Linear relationship between annual discharge and salinity in Bohai Bay, northern China.

seen in the salinity data series using the M–K test (positive test Z values $= 2.26$, significant at 95% confidence level) and Sen's method ($Q = 0.086$, significant at 95% confidence level). Pearson's correlation analysis was also performed to determine the relationship between Haihe River discharge and salinity in Bohai Bay, and a significant correlation ($R = -0.74$, $P < 0.000$) was found between salinity and river water fluxes to Bohai Bay. The results indicate that salinity in Bohai Bay increases with decreases in Haihe River discharge.

Climatic variations

Climate change and human activities are widely regarded as the two main drivers of runoff change. Climatic variations include changes in precipitation and potential evaporation, which together affect river runoff. Table 1 shows that precipitation in the Haihe River basin presented a downward trend in 1956–2012 (negative test Z values, significant at the 95% confidence level). Precipitation in the Haihe River basin has decreased at an average rate of -1.39 mm yr^{-1} without statistical significance.

M–K plots for the annual precipitation of the Haihe River basin are shown in Figure 5(a), and they show that the negative test Z values began around 1970. However, the negative annual trend in the Haihe River basin did not become significant in 1965–2012. Annual precipitation in the Haihe River basin is plotted in Figure 5(b) and shows a slight decline in 1956–2012. Considering 1956–1965 as the baseline period, the reductions in annual precipitation in the Haihe River basin were 7.1% and 14.2% (42.8 mm and 83.1 mm) in 1966–1980 and 1981–2012, respectively. The fluctuations over larger time scales revealed by the average removal method are not lost, and the oscillations of annual precipitation remained constant in 1956–2012. There were differences in fluctuations between river discharge and precipitation in 1956–2012; the coefficients of variation for annual river discharge and annual precipitation were estimated as 3.3% and 17.7%, respectively.

Contributions of climatic variations and human activities

Considering 1956–1965 as the baseline period, mean annual precipitation in the Haihe River basin decreased by 7.1% (42.8 mm) and 14.2% (83.1 mm) in 1966–1980 and 1981–2000, respectively. The observed annual Haihe River

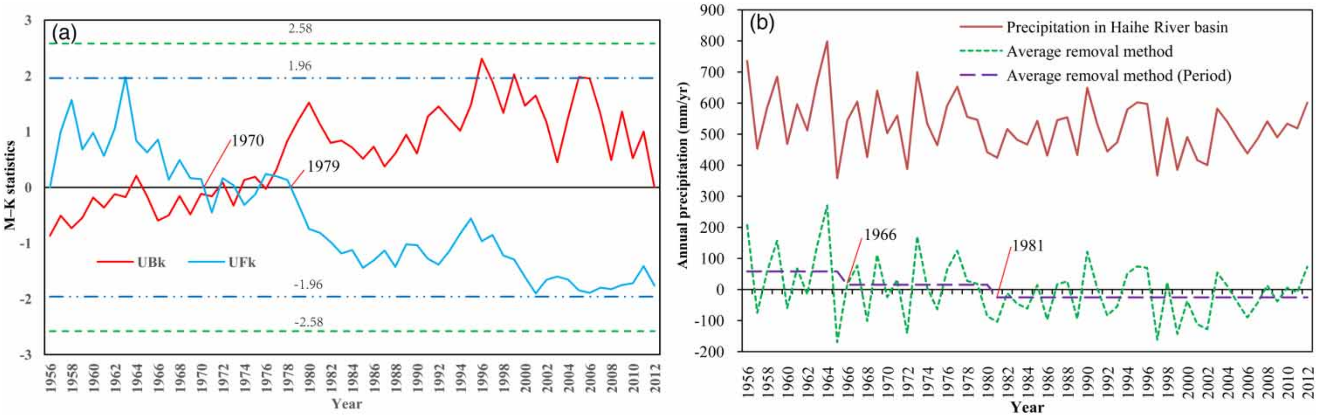

Figure 5 | (a) Sequential values of UF_k and UB_k from Mann–Kendall change-point analysis; (b) annual precipitation in the Haihe River basin.

discharge to Bohai Bay decreased by 52.9% and 81.9% in 1966–1980 and 1981–2000, respectively, and the absolute changes ($\Delta Q_{\mathrm{Total}}$) were 36.5 and 56.5 mm. Decreasing precipitation could partially explain the reduction in river discharge within the basin; however, increased water consumption in the upper reaches of the basin through damming and water storage is also seen as important.

Simple linear regression was used to reconstruct the natural discharge in the Haihe River basin (Figure 6). The adjusted R^2 (0.838) of the simple linear regression is greater than 0.81, and the coefficients of the explanatory variables are significant ($P < 0.000$), indicating that the fitted model is satisfactory. However, it should be mentioned that uncertainty is inevitable while using simple linear regression to reconstruct the discharge affected by climate change. Simple linear regression we established only considers an important meteorological variable (rainfall), without considering other factors such as land-cover change. The difference between simulated discharge (natural discharge) and observed discharge after 1965 can be attributed to human activities. Mean annual discharge as reconstructed by the simple linear regression was 69.0 mm, 56.9 mm, and 45.6 mm in 1956–1965, 1966–1980, and 1981–2012, respectively, and decreased by 12.1 mm and 23.4 mm ($\Delta Q_{\mathrm{Climate}}$) in 1966–1980 and 1981–2012, respectively. Therefore, the contributions to the decrease in river discharge in the Haihe River basin by climatic variations accounted for 33.2% and 41.4%, respectively, whereas human activities accounted for 66.8% and 58.6%, respectively.

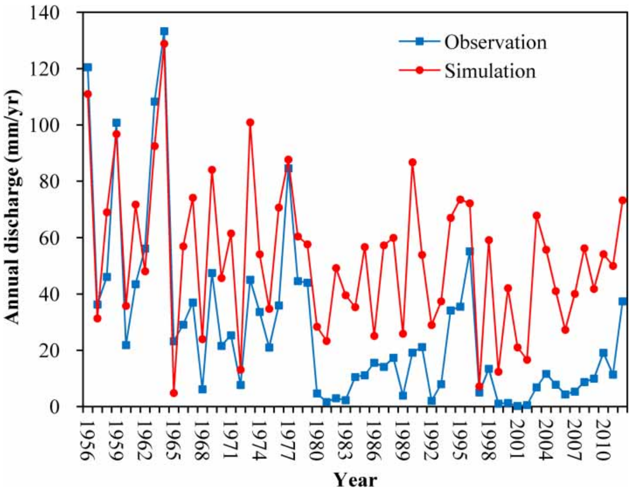

Figure 6 | Simulated and observed annual discharge of the Haihe River basin (1956–2012).

The annual river discharge and precipitation in the Haihe River basin in 1956–2012 exhibited similar downward trends, but they have shown different rates of decrease. Note that, in general, human activities such as water consumption (related to agricultural irrigation, population increase, and industrial development) through damming and reservoir storage are known to induce hydrological changes. Despite the complexities of the impacts of human activities on runoff, some of these activities are discussed below.

Human activities

The population within the Haihe River basin has grown from 63.12 million in 1952 to 70.18 million in 1965, passed 104.1 million in 1985, and reached 134.2 million in 2005. In addition, the gross domestic product (GDP) of the Haihe River basin increased by 170 times during this period and reached 2,575,000 million RMB in 2005 (Ren *et al.* 2007). The increase in urbanization rate from 16% in 1952 to 37.4% in 2005 also reflects increases in population and industry (Figure 7(a)). The Haihe River basin includes 120,000 km^2 of farmland and 75,440 km^2 of irrigated land. Water resource development and utilization in the Haihe River basin can be divided into three phases, as follows. (1) In 1952–1965, water resource development (damming and reservoir storage) was common, with more than 1900 reservoirs constructed in the mountainous and plateau areas of the upper reaches of the basin. (2) In 1966–1980, water consumption increased substantially, and many river engineering projects for water drainage and flood control were undertaken. More than 50 diversion works were constructed for flood control, and over 9,000 km of levees were constructed along streams and rivers. (3) In 1981–2000, water exploration focused on the urban water supply and groundwater development: 6,170 water diversion works and 13,081 water-lifting devices were built, and an estimated 1.22 million shallow wells (less than 120 m deep) and 140 thousand deep wells (greater than 120 m deep) were drilled across the entire basin (Committee for the Compilation of Haihe River 1997; Ren *et al.* 2007). The

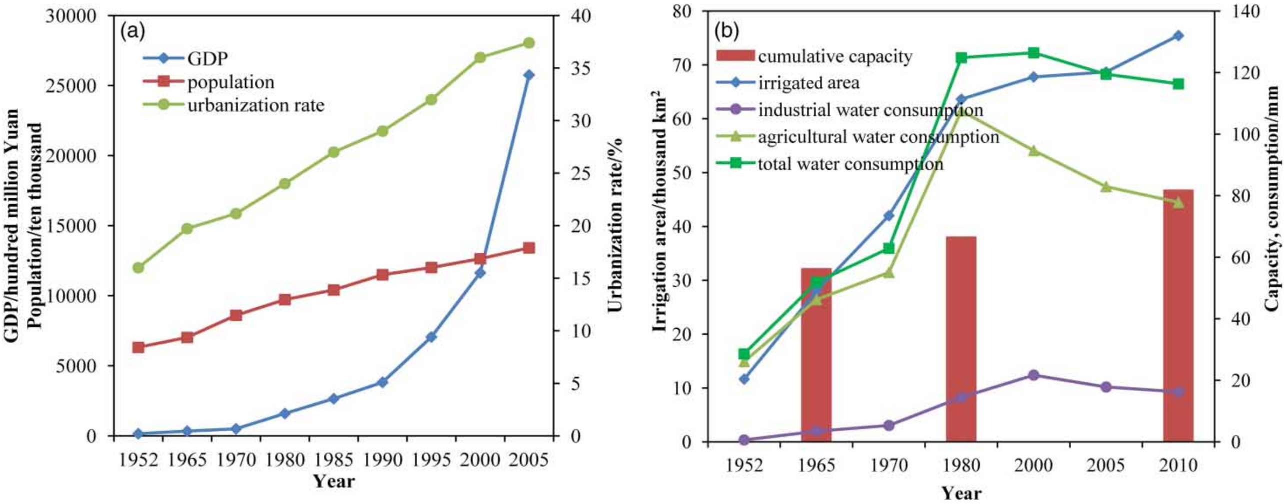

Figure 7 | Increases in (a) GDP, population, and urbanization rate and (b) damming and reservoir storage capacity, irrigated area, and total water consumption in the Haihe River basin over the last several decades.

rapid increase in population, industry, and farmland area has led to a tremendous increase in water supply requirements (Figure 7(a) and 7(b)). Consequently, the total water consumption in the Haihe River basin was only 28.6 mm in 1952, about 51.9 mm in 1965, 124.8 mm (240%) in 1980, and 126.4 mm (244%) in 2000. The irrigated area increased consistently throughout the period of record; agricultural water consumption rose until 1980, but decreased significantly from 1980 onwards. Total water consumption increased up to 1980, but declined slightly after that, and industrial water consumption decreased after 2000. Campaigns to encourage people to save water, and the implementation of water conservation technologies in agricultural irrigation and industry were responsible for these patterns.

To investigate the influence of human activities on discharge reduction, stepwise regression analysis was performed with the reduction in precipitation, the increase in irrigated area, urbanization rate, population, and GDP as predictors and the reduction in discharge as the dependent variable. The results showed that discharge reduction was related to precipitation reduction and irrigated area, which can be summarized as follows:

$$\Delta R = a \times \Delta P + b \times S + c \tag{13}$$

where ΔP represents the reduction in annual precipitation; S is the irrigated area; ΔR is the reduction in annual river discharge to the Bohai Sea; and a, b, and c are three parameters estimated by the least-squares technique. The estimated parameters were 0.224, 0.960, and 54.332 for a, b, and c, respectively. The associated probabilities under a two-tailed test were reported as 0.004, 0.006, and 0.005 for a, b, and c, respectively.

Water consumption in the Haihe River basin has increased approximately four-fold because of the doubling of the population and increased irrigation and industrial activity. Before 1980, most of the water withdrawn was for agricultural use (86–91%), with lesser amounts taken for industrial and domestic purposes (8–14%). However, since 1980, industrial and domestic uses have increased, but agricultural use has not changed to a great extent. Generally speaking, the reduction in annual precipitation and the increase in irrigated area were found to be the dominant variables impacting the change in discharge from the Haihe River basin.

DISCUSSION

It is clear that the contributions from climatic variations and human activities were different during the two periods studied. In 1966–1980, the contribution from human activities to river discharge into Bohai Bay was much greater than that from climatic variations; however, in 1981–2000, the contribution from climate variations increased. The effects of human activities on river discharge were closely consistent with water resource development and utilization in the Haihe River basin in 1966–1980 and 1981–2000.

The rainy season in the Haihe River basin is concentrated within a very short period (June–September). Precipitation during the rainy season in the basin accounts for 79.3% of annual precipitation. In periods of heavy rain, torrents in the numerous tributaries of the upper reaches rush into the low-lying middle and lower reaches, and therefore comprehensive measures have been taken to introduce permanent control of river water (Wu *et al.* 2011). The number of dams within the basin has increased to more than 1,900, which control 83% of the entire basin area with a combined storage capacity of $293.5 \times 10^8\,m^3$. Of these, 30 large dams (each with a storage capacity $>1 \times 10^8\,m^3$) have a total storage capacity of $243 \times 10^8\,m^3$. Nine large dams with a total storage capacity of $195.3 \times 10^8\,m^3$ were built between 1954 and 1983. The cumulative storage capacity is shown in Figure 7(b). In addition, 9,000 km of dikes have been built and ten additional outlets opened to the sea. These large dams and reservoirs regulate water discharge and reduce peak flows by storing water during the flood season and releasing it during the dry season, as required to service the consumption by industrial development and agricultural irrigation. Ying (2000) calculated the water storage index in the major Chinese rivers, which was defined as the ratio of reservoir storage capacity to annual runoff in the basin. The Haihe River has an index of 0.87 while the Yangtze and Pearl rivers have the same index of only 0.11.

Since 1952, land use in the Haihe River basin has changed as a result of increased anthropic pressure. The irrigated area in the Haihe River basin has increased approximately six-fold during this time. In agricultural areas, water-related activities refer mainly to water extraction for irrigation, which is defined as water directly lost to the basin, mainly through evapotranspiration. Water resources have been overexploited for agricultural irrigation and industrial production in the upper and middle reaches of the Haihe River basin. Owing to inadequate water resource management, runoff entering the lower reaches of the river has been reduced continuously in recent years. Such decreases in river discharge exert a negative impact on water resource utilization in Tianjin and pose challenges to water resource management.

Previous studies have shown that mean salinity in the Bohai Sea increased by 2.0 psu during the second half of the 20th century, mainly because of a sharp decrease in freshwater river discharge, but also because of large-scale climatic variations and water intrusions from the northern Yellow Sea (Mao *et al.* 2008). Liu (2011) reported that the salinity distribution in the Bohai Sea is changing, exhibiting an overall gradual increase because of the decrease or even disappearance of river discharges.

Land-use/land-cover changes have attracted substantial scientific interest in recent years because of their marked influence on the hydrological cycle (Lei *et al.* 2014, 2015). Urbanization within the basin, which is calculated to have increased from 16% in 1950 to 24% and 37.4% in 1980 and 2005, respectively (Figure 7(a)), has increased stream flow significantly. The increase in urbanized areas and rural housing land will lead to less infiltration and higher discharge (Franczyk & Chang 2009). The cultivated (irrigated) area has also increased, accounting for $63.6 \times 10^3\,km^2$ and $68.7 \times 10^3\,km^2$ in 1980 and 2005 and representing 20.0% and 21.6% of the total area, respectively (Figure 7(b)). Further increases in irrigation will cause decreases in river discharge in the basin. Simultaneously, increases in forested areas in recent decades will reduce annual runoff because conversions of land from other uses to forests lead to an increase in evapotranspiration (Wang & Wang 2009).

Rose & Peters (2001) used the comparative hydrological approach to reveal significant differences between runoff in an urbanized Atlanta watershed and six other less-developed Piedmont and Blue Ridge watersheds. Yao *et al.* (2009) summarized the observed daily rainfall and discharge in a basin in Japan and found that forest growth reduced low flows and annual runoff. According to an annual water balance, changes in runoff were influenced mainly by evaporation and percolation losses when precipitation was fixed, and deforestation and urbanization decreased evapotranspiration and percolation loss to depth and led to elevated runoff (Rose & Peters 2001; Yao *et al.* 2009). A comprehensive investigation into runoff responses to land-use change on an annual, monthly, and daily basis was conducted in China, and annual runoff was found to increase with reduced forest and increased cropland and urbanized area (Lin *et al.* 2015).

Quantifying the net impact of the land-use/land-cover contribution to runoff change remains challenging. Land-use/land-cover changes have greatly influenced the characteristics of the 20-year flood, and flooding still exists and is even more dangerous than 40 years ago in Beijing in the Haihe River basin (Yang *et al.* 2016). Schilling *et al.* (2010) reported convincing evidence that land-use/land-cover change had contributed to an increase in discharge from the Upper Mississippi River basin, but key details remain unresolved. Moreover, the impact of human activities on land cover and vegetation dynamics is related to climatic variations. In addition, it is difficult to analyze the effects of urbanization and land-cover changes, such as soil and water conservation, on trends in river discharge. Finally, the urbanization effect on the trends in extreme temperature indices should not be ignored.

The impact of other key hydrological processes known to influence river discharge, such as evapotranspiration, was estimated in a previous study (Xing *et al.* 2014). No coherent spatial patterns in evapotranspiration changes were seen in the Haihe River basin. Half the stations in the eastern and southeastern plain regions showed significant negative trends, whereas only three stations in the western mountains and plateau basin showed significant positive trends as a result of increasing air temperature and decreasing wind speed and net radiation (Xing *et al.* 2014). The decrease in evapotranspiration suggests a reduction in water availability and a change in the water cycle in seasons with the highest water demand.

In the present study, the socioeconomic data used were not annual data and did not span the entirety of the river discharge data set. Despite these limitations, the results demonstrate the downward trend in river discharge and the influence of climatic variations and human activities on river discharge in the Haihe River basin. Moreover, the results clarify the connection between river discharge and salinity in Bohai Bay. Salinity in Bohai Bay decreases with increasing freshwater inflow from the Haihe River basin because the inflows flush salt water from much of the estuary, and salinity increases when freshwater inflows decline. Salt transport in a complex estuarine system is a balance between seaward flux induced by river runoff and tidally induced diffusive landward flux (Vinita *et al.* 2015). Future studies should address how salinity and local marine ecosystems change in response to decreases in river discharge.

CONCLUSIONS

In the present study, trends in the Haihe River discharge to Bohai Bay over the past 60 years have been investigated, and the relative contributions of climatic variations and human activities to historical changes in river discharge have been quantified. The results showed a significant decreasing trend in river discharge to Bohai Bay, with a change point of 1965 and confidence levels greater than 95% around 1980. By considering 1956–1965 as the baseline period, decreases (52.9% and 81.9%) in river discharge were noted for 1966–1980 and 1981–2012. The reductions in annual precipitation in 1966–1980 and 1981–2012 were 7.1% (42.8 mm) and 14.2% (83.1 mm), respectively. However, by considering 1965 as the baseline year, the increases in water consumption in the Haihe River basin were at least 240% and 244% in 1980 and 2000, respectively. Although decreased precipitation in the Haihe River basin could partially explain the reduced river discharge to the Bohai Sea, increased water consumption also appears to have been important. The results indicate that climatic variations accounted for 33.2% and 41.4% of the reductions in river discharge in 1966–1980 and 1981–2012, respectively, and that human activities accounted for 66.8% and 58.6%, respectively, during the same periods. Damming and reservoir storage, which regulate water discharge and reduce peak flows by storing water during the flood season and releasing it during the dry season as required for consumption, were also significant in changing the river discharge. The results also indicate that salinity in Bohai Bay increased with decreasing river discharge. There is an urgent need to examine the influence of decreasing river discharge on local marine ecosystem dynamics.

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