Quantitative assessment of the impact of climate variability and human activities on runoff changes: a case study in four catchments of the Haihe River basin, China

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Abstract:
Quantitative evaluation of the effect of climate variability and human activities on runoff is of great importance for water resources planning and management in terms of maintaining the ecosystem integrity and sustaining the society development. In this paper, hydro-climatic data from four catchments (i.e. Luanhe River catchment, Chaohe River catchment, Hutuo River catchment and Zhanghe River catchment) in the Haihe River basin from 1957 to 2000 were used to quantitatively attribute the hydrological response (i.e. runoff) to climate change and human activities separately. To separate the attributes, the temporal trends of annual precipitation, potential evapotranspiration (PET) and runoff during 1957–2000 were first explored by the Mann–Kendall test. Despite that only Hutuo River catchment was dominated by a significant negative trend in annual precipitation, all four catchments presented significant negative trend in annual runoff varying from –0.859 (Chaohe River) to –1.996 mm a−1 (Zhanghe River). Change points in 1977 and 1979 are detected by precipitation–runoff double cumulative curves method and Pettitt’s test for Zhanghe River and the other three rivers, respectively, and are adopted to divide data set into two study periods as the pre-change period and post-change period. Three methods including hydrological model method, hydrological sensitivity analysis method and climate elasticity method were calibrated with the hydro-climatic data during the pre-change period. Then, hydrological runoff response to climate variability and human activities was quantitatively evaluated with the help of the three methods and based on the assumption that climate and human activities are the only drivers for streamflow and are independent of each other. Similar estimates of anthropogenic and climatic effects on runoff for catchments considered can be obtained from the three methods. We found that human activities were the main driving factors for the decline in annual runoff in Luanhe River catchment, Chaohe River catchment and Zhanghe River catchment, accounting for over 50% of runoff reduction. However, climate variability should be responsible for the decrease in annual runoff in the Hutuo River catchment. Copyright © 2012 John Wiley & Sons, Ltd.

KEY WORDS climate change; human activities; Haihe River basin; hydrological response

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INTRODUCTION

According to the latest report of the Intergovernmental Panel on Climate Change (IPCC), the Fourth Assessment Report (IPCC, 2007), the average global surface temperature has increased by 0.74 °C over the last 100 years. Concurrently, rainfall has decreased by 0.3% per decade over much of the Northern Hemisphere’s sub-tropical regions during the 20th century (Chen et al., 2007). One of the most significant potential consequences of climate change may be alterations in regional hydrological cycles (Huntington, 2006). In addition to global climate change, increases in human activities due to the sharp growth in population such as cultivation, irrigation, afforestation, deforestation and urban construction, have also introduced variability in the flow regime and subsequent changes to the amount of water available, in terms of both spatial and temporal distributions (Yang et al., 2004; Brown et al., 2005). For example, afforestation causes the decline in streamflow (Brown et al., 2005; Lane et al., 2005; Shao et al., 2009). Moreover, other land use changes such as terraces and irrigation can also lead to change in the water cycle and affect runoff (Li et al., 2007; Scanlon et al., 2007; Ma et al., 2008; Yang and Tian, 2009). Water resource managers and planners are eagerly seeking to support sustainable natural resources development, especially at catchment scale (Wei and Zhang, 2010). That is particularly evident when climate change and anthropogenic activities dramatically and extensively alter the hydrological processes and functions of catchment (Schindler, 2001). Therefore, investigations on the impacts of climate variability or climate change and human-induced land use change on hydrology and water resources have recently drawn considerable concerns (e.g. Lane et al., 2005; Siriwardena et al., 2006; Tutjea et al., 2007; St. Jacques et al., 2010). Particularly in China, due to the strong warming and the significant regional precipitation variation...
coupled with drastic agricultural and industrial development during the past decades (Piao et al., 2010), more attention has been paid to understand the influence and relative importance of climate variation and human activities on hydrological cycle and water resources (e.g. Li et al., 2007; Huo et al., 2008; Ma et al., 2008; Zhang et al., 2008; Cong et al., 2009; Liu et al., 2009; Wang et al., 2009; Yang and Tian, 2009; Zheng et al., 2009; Liu et al., 2010; Ma et al., 2010; Wang et al., 2010; Wei and Zhang, 2010; Zhao et al., 2010; Jiang et al., 2011). Nonetheless, quantifying the individual effects of climate variability and human activities on hydrological regime is a challenge. Furthermore, regional impacts of climate change and human activities on hydrology vary from place to place and need to be investigated for a local scale.

Traditionally, paired catchment and physically based hydrological model are used to measure the effect of natural and human factors on the water cycle. However, paired catchments are not always available for it is difficult to locate suitable controls and the investigations are expensive to conduct (Fohrer et al., 2005; Wei and Zhang, 2010; Zhao et al., 2010). In addition, physically based hydrological models, such as distributed hydrology soils and vegetation model, soil and water assessment tool and the variable infiltration capacity model, are always limited due to the time-consuming calibration and validation process, requirement of large data sets (e.g. topography, vegetation and hydro-climatic data) and complexity and uncertainty in model structure and parameter estimation. Therefore, simple water balance hydrological model provides alternative choice. Moreover, some new methods have been developed and widely used in many regions to estimate the effect of climate variability or human activities, such as regression analysis method, hydrological sensitivity analysis method and elasticity method. For example, Huo et al. (2008) and Zhang and Lu (2009) employed regression analysis to estimate the impact of human activities on streamflow in the Shiyang River basin and the lower Xijiang, respectively. The hydrological sensitivity method, developed by Dooge et al. (1999) and Milly and Dunne (2002) to describe first-order effect of changes in precipitation and potential evaporation on streamflow, was also adopted to study hydrologic responses to changes in climate and hence separate the effect of climate change on streamflow from that of human activities (e.g. Jones et al., 2006; Zhang et al., 2008; Liu et al., 2009; Zhao et al., 2010). Furthermore, climate elasticity method proposed by Schaake (1990), which is similar to the hydrological sensitivity method, has been continually extended and improved (e.g. Fu et al., 2007; Zheng et al., 2009). This climate elasticity method has also been widely used to assess the impact of climate variability (e.g. Zheng et al., 2009; Ma et al., 2010). A general approach can be summarized for these methods as that one effect, usually from climate variability, was estimated first and the remaining effect was attributed to other factors such as human activities (Zhao et al., 2010). For a given river basin, before application of these methods, advanced statistical methods (e.g. non-parametric tests and time series analysis) and graphical methods (e.g. double mass curves, single mass curves and flow duration curves) are always used to determine the spurious change points and the baseline period (Wei and Zhang, 2010; Jiang et al., 2011).

The Haihe River basin is an important economic center of China with an important role in the sustainable development of the economy and ecology. However, in recent years, sharply increasing water shortages in this basin hindered its economy development and resulted in severe environmental and ecological problems (Liu and Xia, 2004). To date, a number of studies had reported that the streamflow of the Haihe River basin or its tributary has dramatically decreased during recent years (e.g. Yao et al., 2003; Zhang and Yuan, 2004; Cui and Cui, 2007; Ren, 2007). Human activities including construction of reservoir and dam, irrigation with river water or groundwater, man-made land use change and climate change that happened in recent years have been believed to be responsible for the decline in runoff in the Haihe River basin. Yang and Tian (2009) identified that human activities rather than climatic change are the main driving factor of runoff decline in eight catchments of the Haihe River basin. However, to the best of our knowledge, systematically quantifying the relative contributions of climatic variability and human activities to runoff change in the Haihe River basin has not been reported.

The objectives of our study are (1) to detect statistically significant trends and change points in annual streamflow with statistical and graphic method and (2) to estimate the proportion of streamflow change attributing to climatic and human activities influence with three different methods. This paper is organized as follows. The study area and data are given in the next section, followed by the description of methods used. The results and discussion, including change points determination, quantification of climate variability and human activities, comparison among the results of these three methods, are presented before the major conclusions.

STUDY AREA, BACKGROUND AND DATA PROCESSING

The Haihe River is located in the eastern part of northern China, between 112°E–120°E and 35°N–43°N (Figure 1). The Haihe River basin, the largest water system in northern China, has a total drainage area of 318 000 km² and covers Beijing, Tianjin, most parts of Hebei and parts of Shandong, Henan, Shanxi and Inner Mongolia. The elevation within the basin ranges from 0.4 to 3047 m above the sea level, and the topography descends significantly from northwest to southeast. Among the entire area, plateaus and mountains comprise 189 000 km², accounting for nearly 60% of the area, and plains cover 129 000 km², accounting for about 40%. The climate of the Haihe River basin is of the temperate continental monsoon type. The annual precipitation ranges from 379.2 to 583.3 mm and annual mean...
temperatures are between \(-4.9\) and \(15^\circ C\) (Yang and Tian, 2009). Summer (June–August) is the main flooding season for the Haihe River basin. The basin has a tremendous conflict between water supply and demand, with the water volume per capita of \(305\, m^3\) from 1956 to 1998, merely \(1/7\) of the national average and \(1/24\) of the world average (Xia et al., 2006). The rapid economic development and the urban population explosion in this region, especially after China’s reform and opening-up policy occurred in 1979, intensified the issue of water shortages and resulted in many severe environmental and ecological problems (Yuan et al., 2005). Table I shows that the gross domestic product (GDP), town population, food production and the level of urbanization after 1980 in the Haihe River basin.

Accelerated development of food production, GDP, urbanization and agriculture during 1980–2000 in the Haihe River basin can be easily seen by their high increase rates presented in Table I. A huge amount of water was thus consumed by agricultural irrigation, industrial production, daily life and municipal engineering after 1980. There are several forms of human activity with direct or indirect influences on runoff change in the Haihe River basin. Direct human activities mainly include the soil conservation and water control works, increasing water demand, whereas indirect influences refer to land cover and land use changes over the Haihe River basin.

Mini-dams have been constructed during 1958–1975 in almost all the valleys to control the soil erosion (Gao et al., 2002). The construction of mega-reservoirs was largely made after 1960s for flood control and water storage for agricultural and domestic water demands (Zhang, 2003). For example, in Ziya River, Huangbizhuang reservoir with 1.21 billion \(m^3\) of storage was built in 1963. In Luanhe River, Panjiakou reservoir with 2.63 billion \(m^3\) of storage was built in 1985 (Ren, 2007). Mini-dams have been proved to have the capacity to affect runoff (Wang et al., 2009). Mega-reservoirs can result in enhancing water-withdrawing capacity of the local population and an increase in total evaporation and leakage from the reservoirs. In addition, in this basin, rainfall often does not meet crop water demand; irrigation, which is increasingly reliant on groundwater pumping, has thus become an indispensable agronomic

<p>| Table I. Social and economic development in the Haihe River basin during the period of 1980–2000 |
|-------------------------------------------|-----------|----------|--------------|</p>
<table>
<thead>
<tr>
<th>Year</th>
<th>Town population (million)</th>
<th>GDP (billion yuan)</th>
<th>Food (10^4 ton)</th>
<th>Level of urbanization (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1980</td>
<td>22.89</td>
<td>159.2</td>
<td>2655</td>
<td>24</td>
</tr>
<tr>
<td>1985</td>
<td>28.15</td>
<td>265</td>
<td>3440</td>
<td>27</td>
</tr>
<tr>
<td>1990</td>
<td>33.64</td>
<td>382.1</td>
<td>4202</td>
<td>29</td>
</tr>
<tr>
<td>1995</td>
<td>38.35</td>
<td>705.2</td>
<td>4816</td>
<td>32</td>
</tr>
<tr>
<td>2000</td>
<td>45.12</td>
<td>1163.3</td>
<td>4576</td>
<td>36</td>
</tr>
<tr>
<td>Average annual growth rate</td>
<td>3.45%</td>
<td>10.46%</td>
<td>2.76%</td>
<td>2.05%</td>
</tr>
</tbody>
</table>

practice as it significantly enhances harvest (Yang and Tian, 2009). During the past decades, land use/cover has changed dramatically. Before 1985, large expanses of natural forest/grassland were transformed into agricultural lands. However, the reverse trend has been encouraged by the government since 1990 due to the huge impact of the land transformation on the environment (Wang and Wang, 2007). It can be seen that most of activities occurred at different socio-economic periods. Therefore, determining the abrupt change point based on the associated human activities could be conductive to understanding the driving factors of runoff decline (Gerstengarbe and Werner, 1999).

Four catchments (i.e. Luanhe, Chaohe, Hutuo and Zhanghe) in the Haihe River basin were selected as the study area. The data used in this study include runoff data from four hydrological stations and meteorological data from seven meteorological stations distributed in each catchment for the period of 1957–2000 (Figure 1). The runoff data were obtained from the ‘Hydrological Year Book’ published by the Hydrological Bureau of the Ministry of Water Resources. The hydrological stations include Luanxian station (with the drainage area of 44 100 km² in the Luanhe River catchment), Daiying station (with the drainage area of 4701 km² in the Chaohe River catchment), Xiaojue station (with the drainage area of 15 580 km² in the Hutuo River catchment) and Guantai station (with the drainage area of 17 800 km² in the Zhanghe River catchment). The meteorological data with sunshine duration and relative humidity were obtained from the China Meteorological Administration. In addition, potential evapotranspiration is estimated using the Penman–Monteith equation recommended by the Food and Agriculture Organization of the United Nations (Allen et al., 1998).

METHODOLOGY

Trend test and break point analysis method

Mann–Kendall test. The rank-based Mann–Kendall test (Mann, 1945; Kendall, 1975) was used to detect trends in the hydro-climatic series in this study. The method was highly recommended by the World Meteorological Organization and widely used (e.g. Zhang et al., 2008; Yang and Tian, 2009; Wang et al., 2011a,b) to assess the significance of monotonic trends in hydrological series, for it has an advantage of not assuming any distributional form for the data and has the same power as its parametric competitors. Meanwhile, Sen’s slope method (Sen, 1968; Hirsch et al., 1982) was used to estimate the trends magnitudes (slopes) based on Kendall’s tau.

Double mass curve method. The double mass curve (DMC), frequently used in paired studies to detect hydrological changes caused by human activities, is the plot of the accumulated values of one variable against the accumulated values of the another related variable for a concurrent period (Searcy and Hardison, 1960). It is a straight line if two variables are proportional, and the slope of this line will present the ratio between the two variables. A change in the gradient of the curve may indicate that the original relationship between variables was broken. DMC can be used to check the consistency of hydrological records and has recently become an effective tool for detecting the changes of hydrological regime due to anthropogenic disturbances (e.g. Huo et al., 2008; Zhang and Lu, 2009; Zhang et al., 2009). In this study, DMC between precipitation and runoff was employed as an auxiliary confirmation of the change points when human activities imposed the influences on the river.

Pettitt’s test. The Pettitt’s test (Pettitt, 1979) is a non-parametric approach to determine the occurrence of a change point. This approach is a rank-based and distribution-free test for detecting a significant change in the mean of a time series when the exact time of the change is unknown. Pettitt’s test has been widely used to detect changes in the hydrological as well as climatic records (e.g. Verstraeten et al., 2006; Zhang and Lu, 2009; Zhang et al., 2009). We will use the Pettitt’s test to identify the change point of the runoff series as a reconfirmation of the change points detected by DMC.

General framework for separating effects of climate variability and human activities on streamflow

For a given catchment, the streamflow can be modeled as a function of climate variables and human activities by (Zhang et al., 2008; Zheng et al., 2009)

\[ Q = f(C, H) \]  

where \( Q \) is streamflow, \( C \) represents climate factors on hydrological cycle, and \( H \) is a factor that represents the integrated effects of human activities on streamflow. Following Equation (1), changes in streamflow due to climate variability and human activities can be approximated as

\[ \Delta Q = f_C \Delta C + f_H \Delta H \]  

where \( \Delta Q, \Delta C \) and \( \Delta H \) are changes in streamflow, climate and human activities, respectively, with \( f_C = \frac{\partial Q}{\partial C} \) and \( f_H = \frac{\partial Q}{\partial H} \).

As a first-order approximation, Equation (2) can be written as (Zhang et al., 2008)

\[ \Delta Q = \Delta Q_C + \Delta Q_H \]  

where \( \Delta Q_C \) and \( \Delta Q_H \) represent changes in streamflow due to climate variability and human activities, respectively. Although climate variability and human activities interact with each other, for a small basin, climate variability is mainly controlled by external forces. Therefore, these two factors were regarded as independent variables at basin scale (Wang et al., 2009; Jiang et al., 2011). \( \Delta Q \) can be...
estimated by subtracting the observed average streamflow during the baseline period \( \bar{Q}_{\text{obs}} \) from the observed average annual streamflow during the changed period \( \bar{Q}^{\text{obs}}_2 \). Consequently, separating the effect of climate change from that of human activities can be achieved by this framework if \( \Delta Q_c \) or \( \Delta Q_H \) is known.

**Estimating the impact of climate variability or human activities on streamflow**

**Description of different methods.** According to the aforementioned framework, the first step of separating the effects is to estimate the impact of climate change or human activities on streamflow. The physical-based hydrological model is usually a good choice to measure the effect of natural and human factors on streamflow. However, in this study, the limited information and the available data sets fail to meet the minimal requirements for physical-based hydrological model. Instead, a simple hydrological water balance model and statistical methods are used to estimate the effects of climate variability or human activities on annual streamflow.

**Hydrological model method.** For the effect of human activities on runoff to be estimated, the hydrological model was first calibrated based on observed runoff in the baseline period, and the natural runoff without human activities was reconstructed for the human-induced period. Consequently, the effect of human activities on runoff can be calculated as follows:

\[
\Delta Q_H = \bar{Q}^{\text{obs}}_2 - \bar{Q}^{\text{obs}}\quad \text{(4)}
\]

where \( \bar{Q}^{\text{obs}}_2 \) indicates the reconstructed runoff for the changed period, and \( \Delta Q_H \) and \( \bar{Q}^{\text{obs}} \) are defined as before. The two-parameter monthly hydrological model proposed by Xiong and Guo (1999) was used in this study. The model has only two parameters to be calibrated and requires only the monthly areal precipitation, pan evaporation and air temperature. The model outputs include monthly streamflow, actual evapotranspiration (AET) and soil moisture content index.

The model has been tested in more than 100 small- and medium-size basins with different types of climate in China and has proved to be quite efficient in simulating monthly runoff with its simple structure (Xiong and Guo, 1999; Guo et al., 2002; Guo et al., 2005). Because of its simplicity and good performance, the two-parameter monthly water balance model and statistical methods are used to estimate the effects of climate variability or human activities on annual streamflow.

\[
E(t) = C \times EP(t) \times \tan h[P(t)/EP(t)]
\]

where \( E(t) \), \( EP(t) \) and \( P(t) \) represent monthly AET, monthly pan evaporation and monthly rainfall, respectively, and \( C \) is the first model parameter. Soil moisture content can be reflected indirectly by rainfall and potential \( EP(t) \), because of feedback mechanism of soil-plant-atmosphere system, although the term of soil moisture content does not appear in Equation (5).

The monthly runoff is closely related to the soil water content via

\[
Q(t) = S(t) \times \tan h[S(t)/SC]
\]

where \( Q(t) \) is the monthly runoff, \( S(t) \) is the water content in soil, and the second model parameter \( SC \) represents the field capacity of basins, with the unit of millimeter. The actual monthly evapotranspiration \( E(t) \) can be determined through Equation (5) by the monthly rainfall \( P(t) \) and the monthly pan evaporation \( EP(t) \). The quantity of the remaining water in the soil at the beginning of the \( t \)th month is \( [S(t-1)+P(t)-E(t)] \), after loss through evapotranspiration \( E(t) \), with \( S(t-1) \) being the water content at the end of the \( (t-1) \)th month and at the beginning of the \( t \)th month. Equation (6) is then used to calculate the \( t \)th month runoff \( Q(t) \) as

\[
Q(t) = [S(t-1) + P(t) - E(t)] \times \tan h\{S(t-1) + P(t) - E(t)/SC\}
\]

Finally, the water content at the end of the \( t \)th month was calculated according to the water conservation law:

\[
S(t) = S(t-1) + P(t) - E(t) - Q(t)
\]

Three statistics, namely the correlation coefficient (\( R \)), the Nash–Sutcliffe coefficient (NSCE) and Relative Bias (BIAS), were used to evaluate the performance of the regression model and are defined as

\[
R = \frac{\sum_{i=1}^{N} (Q_{\text{obs}}(i) - \bar{Q}_{\text{obs}})(Q_{\text{sim}}(i) - \bar{Q}_{\text{sim}})}{\left[ \sum_{i=1}^{N} (Q_{\text{obs}}(i) - \bar{Q}_{\text{obs}})^2 \right]^{1/2} \left[ \sum_{i=1}^{N} (Q_{\text{sim}}(i) - \bar{Q}_{\text{sim}})^2 \right]^{1/2}}
\]

\[
\text{NSCE} = 1 - \frac{\sum_{i=1}^{N} (Q_{\text{obs}}(i) - Q_{\text{sim}}(i))^2}{\sum_{i=1}^{N} (Q_{\text{obs}}(i) - \bar{Q}_{\text{obs}})^2}
\]

\[
\text{BIAS} = \frac{\sum_{i=1}^{N} (Q_{\text{obs}}(i) - Q_{\text{sim}}(i))}{\sum_{i=1}^{N} Q_{\text{obs}}(i)}
\]

where \( N \) is the number of data points, \( Q_{\text{obs}}(i) \) is the observed runoff (millimeter per month) at time step \( i \), \( Q_{\text{sim}}(i) \) is the simulated runoff (millimeter per month) at time step \( i \), and \( \bar{Q}_{\text{obs}} \) and \( \bar{Q}_{\text{sim}} \) are the means of the observed and simulated values (millimeter per month), respectively.

**Hydrological sensitivity analysis method.** Hydrological sensitivity can be described as the percentage change in
mean annual runoff in response to the change in mean annual precipitation and potential evapotranspiration. The water balance for a basin can be described as

\[ P = E + Q + \Delta S \]  \hspace{1cm} (12)

where \( P \) is precipitation, \( E \) is AET, \( Q \) is streamflow, and \( \Delta S \) is the change in soil water storage. On the mean annual time scale, the change \( \Delta S \) can reasonably be neglected, that is, \( \Delta S \) can be assumed as zero for a long period (i.e. 10 years or more).

Budyko (1974) considered that the available energy and water are the primary factors determining the rate of evapotranspiration and developed a framework for estimating AET based on dryness index. Following a similar assumption to Budyko (1974), a simple model (called Zhang’s curve) developed by Zhang et al. (2001) to estimate the AET is consistent with previous theoretical work and shows good agreement over the world (Zhang et al., 2001, 2004; Li et al., 2007; Liu et al., 2009; Shao et al., 2012):

\[ E = \frac{1 + w(PET/P)}{1 + w(PET/P) + (PET/P)^{-1}} \]  \hspace{1cm} (13)

where \( PET \) is the potential evapotranspiration and \( w \) is the plant-available water coefficient related to vegetation type (Zhang et al., 2001). The details of the relationship can be found in Zhang et al. (2001). In this study, the parameter \( w \) is calibrated by comparing the long-term annual AET from Equation (12).

Perturbations in both precipitation and PET can lead to changes of water balance. It can be assumed that a change in mean annual runoff is determined by the following expression (Koster and Suarez, 1999; Milly and Dunne, 2002):

\[ \Delta Q = \beta \Delta P + \gamma \Delta PET \]  \hspace{1cm} (14)

where \( \Delta Q \), \( \Delta P \) and \( \Delta PET \) denote changes in runoff, precipitation and PET, respectively, and \( \beta \) and \( \gamma \) are the sensitivity coefficients of runoff to precipitation and PET, expressed as (Li et al., 2007)

\[ \beta = \frac{1 + 2x + 3wx}{(1 + x + wx^2)^2} \]  \hspace{1cm} (15)

\[ \gamma = \frac{1 + 2wx}{(1 + x + wx^2)^2} \]  \hspace{1cm} (16)

where \( x \) is the mean annual index of dryness (equal to \( PET/IP \)).

**The climatic elasticity model.** In addition to the hydrological sensitivity analysis method, the climate elasticity model was widely employed to assess the climate variability impact (e.g. Ma et al., 2010). The concept of climate elasticity was introduced by Schaaake (1990) and then improved constantly (e.g. Sankarasubramanian et al., 2001; Fu et al., 2007; Zheng et al., 2009). The climate elasticity of runoff can be defined by the proportional change in runoff divided by the proportional change in a climatic variable such as precipitation. The precipitation elasticity of runoff was thus expressed as

\[ \varepsilon_p = \frac{\Delta Q}{\Delta P} \frac{Q}{P} \]  \hspace{1cm} (17)

where \( P \) and \( Q \) are precipitation and runoff, respectively. Sankarasubramanian et al. (2001) proposed a non-parametric approach, the median descriptive statistics, to estimate the climate elasticity directly from observed data. Although the approach was tested and found to be robust via Monte Carlo experiments for three basins in the United States, it is weak when the sample size is small. Zheng et al. (2009) proposed an alternative non-parametric estimator of climate elasticity to overcome the problem associated with small sample size. The elasticity \( \varepsilon \) of runoff \( Q \) to climatic variable \( X \) can be expressed as the product of the correlation coefficient \( \rho_{X,Q} \) and the ratio between coefficients of variation of runoff \( C_Q \) and climatic variable \( C_X \). Following Zheng et al. (2009), the estimator of precipitation elasticity of runoff can be expressed as

\[ \Delta Q/\bar{Q} = \varepsilon_p \Delta P/\bar{P} \]  \hspace{1cm} (18)

where \( \Delta Q_i/\bar{Q} \) and \( \Delta P_i/\bar{P} \) are changes of the annual runoff and the precipitation with respect to long-term average of runoff \( Q \) and precipitation \( P \), respectively. The values of \( \varepsilon_p \) were calculated using observed precipitation as well as runoff data before the year of change points detected by statistical method. Changes in annual runoff after the change points could be estimated from the annual precipitation data during the post-change period using Equation (18).

**Calibration and validation for different methods.** According to change points detected in runoff, the study period for all the catchments can be divided into two periods, pre-change period and post-change period. Pre-change period, when few human activities affecting runoff in the four catchments, was treated as a baseline period to calibrate and validate the parameters for different methods.

The baseline period was divided into two phases to determine the two-parameter hydrological model parameter. The model parameters were estimated by minimizing the absolute values of BIAS and ensuring the NSCE and correlation coefficient close to 1. \( w \) is the key model parameter for hydrological sensitivity analysis method. Most of the catchments are located in the mountainous area of the Haihe River basin. Before the 1980s, the forest coverage rate in these regions is over 50% (Ren, 2007). Zhang et al. (2001) considered that the plant-available coefficient \( w \) was set to 2.0 for forest and 0.5 for pasture. It is difficult to assign the parameter \( w \) for the mixed vegetation, which always exists in a real catchment, because of the difficulty to accurately separate herbaceous and forest cover for individual catchments. In this study, different with the way to set \( w \) value (e.g., Li...
et al., 2007; Huo et al., 2008; Liu et al., 2010), the parameter $w$ is calibrated by comparing long-term annual AET calculated by using the Zhang’s curve and the water balance equation (WBE) for the pre-change period. According to non-parametric estimator of climate elasticity proposed by Zheng et al. (2009), the precipitation elasticity $e_P$ can be estimated by annual runoff and annual precipitation data during the pre-change period. With the calibrated $e_P$, climate elasticity model can be used to simulate the runoff change due to climate variability during the post-change period.

According to Equation (4), runoff change contributed by local human activities, which represented as the additional runoff change, can be obtained from the difference between reconstructed natural runoff and observed runoff. Consequently, with the human-induced runoff change determined by hydrological model method and the climate-induced runoff change calculated by hydrological sensitivity analysis method and climate elasticity method, the effect of climate variability and human activities can be quantitatively evaluated on the basis of the general framework.

RESULTS

Trends and change points analysis for hydro-climatic series

Observed annual precipitation, runoff and calculated PET series for the four catchments during the period of 1957–2000 are presented in Figure 2. All the catchments exhibited a large variation in their runoff, whereas the changes in precipitation and PET appear to be more stationary. Table II further showed the statistical results of trends in precipitation, runoff and PET based on the Mann–Kendall test. Although annual precipitation in all the catchments decreased, the statistically significant trends can only be identified in the Hutuo River catchment. Similarly, only the Luanhe River catchment was dominated by significant trends in PET. Different from precipitation and PET, which have no clear trends, annual runoff in all four catchments presented significant negative trends with even remarkable negative trends (with a confidence level of 99%) in three catchments, at the rates from $-0.859$ (Chaohe River) to $-1.996$ mm a$^{-1}$ (Zhanghe River).

The DMC method was employed to further investigate the change points of runoff series. Figure 3 shows the

![Figure 2. Long term variations of precipitation, potential evapotranspiration (PET) and runoff series in the four catchments of the Haihe River basin](image-url)

<table>
<thead>
<tr>
<th>Catchments</th>
<th>$z$-test</th>
<th>Significance</th>
<th>Slope ($\beta$) (mm a$^{-1}$)</th>
<th>$z$-test</th>
<th>Significance</th>
<th>Slope ($\beta$) (mm a$^{-1}$)</th>
<th>$z$-test</th>
<th>Significance</th>
<th>Slope ($\beta$) (mm a$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luanhe River</td>
<td>$-2.64$</td>
<td>***</td>
<td>$-1.766$</td>
<td>$-0.56$</td>
<td>ns</td>
<td>$-1.133$</td>
<td>$-4.52$</td>
<td>***</td>
<td>$-2.167$</td>
</tr>
<tr>
<td>Chaohe River</td>
<td>$-1.73$</td>
<td>*</td>
<td>$-0.859$</td>
<td>$-1.15$</td>
<td>ns</td>
<td>$-1.343$</td>
<td>$-0.62$</td>
<td>ns</td>
<td>$-0.222$</td>
</tr>
<tr>
<td>Hutuo River</td>
<td>$-3.57$</td>
<td>***</td>
<td>$-1.201$</td>
<td>$-2.42$</td>
<td>**</td>
<td>$-5.170$</td>
<td>$0.46$</td>
<td>ns</td>
<td>$0.785$</td>
</tr>
<tr>
<td>Zhanghe River</td>
<td>$-3.83$</td>
<td>***</td>
<td>$-1.996$</td>
<td>$-1.55$</td>
<td>ns</td>
<td>$-2.725$</td>
<td>$-1.32$</td>
<td>ns</td>
<td>$-0.577$</td>
</tr>
</tbody>
</table>

***, ** and * indicate confidence levels of 99%, 95% and 90%, respectively; ns indicates confidence level under 90%. |

double cumulative curve of annual precipitation–runoff over the four catchments. The relationships between precipitation and runoff can be presented nearly two straight lines with different slopes before and after 1979 for the Luanhe River catchment, the Chaohe River catchment and the Hutuo River catchment, and before and after 1977 for the Zhanghe River catchment, indicating that there may be an abrupt change in the runoff series. Furthermore, we use Pettitt’s test to detect the change points in runoff series. The results by Pettitt’s test (Figure 4) present the significant change points in 1979 for the Luanhe River catchment and the Hutuo River catchment and in 1977 for the Zhanghe River catchment and marginally significant change point in 1979 for the Chaohe River catchment, further confirming the change points detected by DMC method. For the Chaohe River catchment, break point at 1979 for the runoff record has also been found by order clustering analysis method in the literature (Xie et al., 2005; Wang et al., 2009). Overall, the change points identified for annual runoff occurred intensively between late 1970s and early 1980s (listed in Table III). Accordingly, the study period for all the catchments can be divided into two periods (i.e. pre-change period and post-change period) by the change points.

The means and standard deviations of the annual runoff in the pre-change period and post-change period are analyzed to better understand the characteristics of the runoff change. The ratio of the mean annual runoff for the post-change period relative to that for the pre-change period varied from 36.27% to 66.27%, indicating large reductions in the annual runoff during the post-change period.
period. The significant differences between the means of the two samples during the pre-change and post-change periods can be found at 90% confidence level for all catchments using the $t$-test. Concurrently, using $F$-test, there are statistically significant differences between the standard deviations of the two samples at 95% confidence level for all the catchments except the Chaohe River catchment. In addition, the increasing coefficient of variation can be found in three catchments, indicating that the runoffs in these catchments vary more during the post-change period. These changes are consistent with the fact that the factors influencing runoff become more complex during the post-change periods. In addition, the differences in the correlation of precipitation and runoff for the two periods (Figure 5) were investigated to further understand the effects of climate and other factors on runoff during the two periods. For all the catchments, the correlations between precipitation and runoff for the pre-change period are stronger than that for the post-change period.

**The results of calibration and validation**

**Hydrological model method.** The model was calibrated using the historical data from January 1961 to December 1975 for Luanhe River catchment, Chaohe River catchment and Hutuo River catchment, and from January 1961 to December 1970 for Zhanghe River catchment. Correspondingly, the validation periods for the Luanhe River catchment, Chaohe River catchment and Hutuo River catchment are from January 1976 to December 1980 and for the Zhanghe River catchment is from January 1971 to December 1977. Figure 6 presents the

![Figure 5. Correlation between precipitation and runoff for pre-change period and post-change period](image)

Table III. Summary for the annual runoff change points analysis

<table>
<thead>
<tr>
<th>Catchments</th>
<th>Change point</th>
<th>Pre-change period</th>
<th>Post-change period</th>
<th>Changes (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luanhe River</td>
<td>1979 ***</td>
<td>106.5 57.5 0.54</td>
<td>51.6** 33.9** 0.66</td>
<td>51.55</td>
</tr>
<tr>
<td>Chaohe River</td>
<td>1979 ns</td>
<td>69.2 40.3 0.58</td>
<td>44.1* 22.0* 0.50</td>
<td>36.27</td>
</tr>
<tr>
<td>Hutuo River</td>
<td>1979 **</td>
<td>58.5 27.9 0.48</td>
<td>28.7** 21.7** 0.76</td>
<td>50.94</td>
</tr>
<tr>
<td>Zhanghe River</td>
<td>1977 **</td>
<td>84.5 49.0 0.58</td>
<td>28.5** 21.8** 0.76</td>
<td>66.27</td>
</tr>
</tbody>
</table>

Pre-change and post-change periods were defined by the change points listed in the table. ** and * indicate confidence levels of 95% and 90%, respectively. ns indicates confidence level under 90%.

CV, coefficient of variation; SD, standard deviation.
simulated and measured runoffs for the calibration and validation period. It can be seen that the model was calibrated generally well to the measured runoff depth, and the calibrated model performed well for the validation data, even though there are over or under estimates in some peak runoff. The optimized parameter values and statistics for evaluating the performance model are summarized in Table IV. During the calibration period, the correlation coefficient \((R)\) ranges from 0.89 to 0.93, the NSCE coefficient ranges from 0.83 to 0.86, and all the absolute values of BIAS coefficients are lower than 3%.

Although the model performance during the validation period was not as good as that in calibration period, with the larger BIAS and smaller \(R\) and NSCE, the model results presented in Figure 6 and Table IV are overall acceptable, suggesting also that two-parameter model was applicable to estimate the effect of climate variability and human activities in the four catchments of the Haihe River basin. After the two-parameter model is benchmarked with the hydro-meteorological conditions of the baseline period (i.e. the pre-change period), meteorological data including precipitation and pan evaporation...
data for the human-induced period (i.e., the post-change period) are used as input to simulate natural runoff without consideration of catchment characteristics change or artificial water intake based on the validated model parameter. The natural runoff series for the catchments during the post-change period can thus be reconstructed and the effects of climate variability and human activities can be quantitatively estimated on the basis of the general framework.

**Hydrological sensitivity analysis method.** The calibrated $w$ value and the runoff sensitivity coefficients to precipitation $\beta$ and PET $\gamma$ are shown in Table V. The comparison of AET calculated by Zhang’s curve and WBE for the four catchments is shown in Figure 7. All the $R^2$ values are greater than 0.87, especially for the Hutuo River catchment with $R^2$ values reaching 0.98. Concurrently, the simulated results for all the catchments present small mean absolute error. Generally, all the scatter points calculated by WBE and simulated by Zhang’s curve are concentrated around the 1:1 line (Figure 7) and all the $w$ values are between 0.5 and 2 (Table V), indicating that the results simulated by Zhang’s curve are realistic and acceptable. For all the catchments, the absolute value of runoff sensitivity coefficients to precipitation is larger than that to PET (Table V), revealing that the change in runoff was more sensitive to change in precipitation than to change in PET in this region. With the runoff sensitivity coefficients to precipitation and PET calibrated, runoff change caused by climate variability can be estimated by Equation (14), and quantitatively estimating the effects of climate variability and human activities on runoff can be thus achieved by Equation (3).

**Climate elasticity method.** Taking the Luanhe River catchment as an example, regarded as the slope in the linear regression model of the change of runoff against the change of precipitation in Equation (18), the precipitation elasticity $e_p$ is estimated to be 1.81 (Figure 8), indicating that a 10% change in precipitation will cause an 18.1% change in runoff in the Luanhe River catchment. The precipitation elasticity of four catchments was calculated and listed in Table V. The values of $e_p$ for the Luanhe River catchment, Chaohu River catchment, Hutuo River catchment and Zhanghe River catchment were obtained as 1.81, 2.21, 1.68 and 1.52, respectively. The results indicate that the strongest and weakest response of runoff to precipitation change can be found in the Chaohu River catchment and the Zhanghe River catchment, respectively.

**Effects of climate variability and human activities on runoff**

Figure 9 presents the comparison between simulated runoff based on the two-parameter model and observed runoff for the post-change period. Compared with that during the pre-change period (Figure 6), the more obvious and larger difference between reconstructed and observed runoffs in the monthly runoff processes were found during the post-change period (Figure 9), indicating runoff during the post-change periods should be driven by increased human activities in these regions. The quantitative effects derived from three different methods are shown in Table VI.

For all the catchments, the hydrological model method, hydrological sensitivity analysis method and climate elasticity method provided similar estimates of the changes in runoff for post-change period due to climate variability and human activities. Human activities were dominant factors for runoff change across all the catchments except the Hutuo River catchment. Taking the Luanhe River catchment as an example, human activity should be responsible for 61%, 67% and 57% runoff change computed by hydrological model, hydrological sensitivity analysis and climate elasticity method, respectively, whereas the percentages due to the climate variability were 39%, 33% and 43%, respectively. The Hutuo River catchment is the only catchment where runoff reduction during the post-change period should be mainly attributed to climate variability (70%, 72% and

---

### Table IV. Model parameters and performance assessment of the two-parameter model

<table>
<thead>
<tr>
<th>Catchments</th>
<th>Parameter values</th>
<th>Period</th>
<th>$R$</th>
<th>NSCE</th>
<th>BIAS (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luanhe River</td>
<td>0.972 650</td>
<td>Simulation period (1961–1975)</td>
<td>0.91</td>
<td>0.84</td>
<td>−2.96</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Validation period (1976–1979)</td>
<td>0.85</td>
<td>0.75</td>
<td>3.07</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Simulation period (1961–1975)</td>
<td>0.92</td>
<td>0.85</td>
<td>1.12</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Validation period (1976–1979)</td>
<td>0.83</td>
<td>0.73</td>
<td>−4.26</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Simulation period (1961–1970)</td>
<td>0.93</td>
<td>0.86</td>
<td>0.10</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Validation period (1971–1977)</td>
<td>0.79</td>
<td>0.62</td>
<td>4.20</td>
</tr>
</tbody>
</table>

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### Table V. Model parameter for hydrological sensitivity analysis method and precipitation elasticity for climate elasticity method

<table>
<thead>
<tr>
<th>Catchments</th>
<th>Hydrological sensitivity analysis</th>
<th>Climate elasticity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\beta$ $\gamma$</td>
<td></td>
</tr>
<tr>
<td>Luanhe River</td>
<td>1.32 0.32</td>
<td>−0.16 1.81</td>
</tr>
<tr>
<td>Chaohu River</td>
<td>1.07 0.23</td>
<td>−0.11 2.21</td>
</tr>
<tr>
<td>Hutuo River</td>
<td>1.13 0.29</td>
<td>−0.14 1.68</td>
</tr>
<tr>
<td>Zhanghe River</td>
<td>1.15 0.28</td>
<td>−0.13 1.52</td>
</tr>
</tbody>
</table>
69% detected by hydrological model, hydrological sensitivity analysis and climate elasticity method, respectively, which directly corresponds to the fact that only the Hutuo River catchment is dominated by the significant decreasing trends in precipitation. The generally consistent results in quantifying the effects provided confidence in the methods used to separate the effects of climate change and human activities. Furthermore, to present the temporal patterns of the yearly climate variability effect, the annual time series of $\Delta Q_C$ for the post-change period were calculated by the hydrological model method, hydrological sensitivity analysis method and climate elasticity method (Figure 10). Although there are some differences in annual runoff change simulated by the three methods for some years, especially for the times when precipitation is high, the overall processes of $\Delta Q_C$ present a similar simulation for all the catchments. The phenomenon has been found that the effect of climate variability is sensitive to the annual precipitation. When the precipitation is high, a positive effect of climate variability on runoff can be easily found. Similar conclusions were also found in some earlier studies in other area of China (e.g. Laohuhe River catchment; Jiang et al., 2011).

**DISCUSSION**

Remarkable downward trends in runoff can be found in four catchments of the Haihe River basin despite the precipitation presents significant decreasing trends only in one catchment. This implies that runoff in most catchments might be affected by other factors (human activities) besides the precipitation. Concurrently, the fact that the regression lines (Figure 5) for the post-change period always lie below that for the pre-change period means that in post-change period, the same annual precipitation in the pre-change period produces less runoff, also suggesting that runoff should be driven by increased human activities in the study area. Overall, despite that no clear and consistent trends in precipitation and PET were identified, the runoff presents statistically significant negative trends in annual runoff for all four catchments, indicating that there are other factors for explaining the abrupt change in the annual runoff. Water-related human activities including agricultural irrigation, dam construction and industry development are usually considered to be responsible for the sharp decline in runoff. The change points of runoff in the four catchments
detected by DMC and Pettitt’s test happened in the late 1970s, which corresponds to the start of China’s land reform when the absolute responsibility for productively managing the lands were returned to farmers. Therefore, increasing agricultural land and related agricultural water use as well as water control works may be the main driving factors of runoff decline. This finding agrees with previous studies (e.g. Gao et al., 2002; Yang and Tian, 2009).

In this study, a simple two-parameter water balance model was selected as the hydrological model for making hydrological prediction. Certainly, distributed physically based hydrological model may be preferred and even the most optimal choice for hydrological effect study (Legesse et al., 2003). However, as a matter of fact, there are always limitations in practice for distributed hydrological model to be applied at basin scale because of its complexity in model setup, time consumption in calibration and validation, as well as data set requirements involving topography, vegetation and soil hydraulic properties and so on (Liu et al., 2009; Wei and Zhang, 2010).

Figure 9. Comparison between monthly measured runoff and simulated runoff by the two parameter model for the post-change period.
The simple water balance model needs only small data quantity, which usually includes only basic meteorological data such as precipitation and temperature and normal hydrological data such as runoff series. Normally, the simple water balance model is not expected to provide enough information compared with distributed physically based model and even to work as good as physically based distributed model. Nevertheless, our results show that it did not affect the performance of simple water balance model in terms of quantifying the climate and anthropogenic effects on runoff. The hydrological sensitivity analysis method has been considered and proved as the more flexible method for the advantage of being applicable to large basins where paired catchments are not practical (Zhao et al., 2010).

The consistent results with other methods in this study and literature (e.g. Jiang et al., 2011) justify again that hydrological sensitivity analysis can be an alternative approach and provides independent assessment of climate and anthropogenic effects on runoff. The climate elasticity method is similar to the hydrological sensitivity analysis method (Dooge et al., 1999). However, the difference between the hydrological sensitivity analysis method and climate elasticity employed in this study mainly represents that (1) climate elasticity needs less data compared with the hydrological sensitivity method and (2) climate elasticity parameter can be directly estimated by hydro-climatic data without parameter adjustment based on non-parametric estimator. We only use precipitation elasticity to estimate the effect on runoff in the present study because runoff responds directly to precipitation. The elasticities of other climate variables (such as PET) estimated using different hydrological models are more likely to be different for the different methods used by different models to simulate PET (Chiew, 2006). Therefore, precipitation elasticity \( \varepsilon_p \) is

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Table VI. Effects of climate variability and human activity on mean annual runoff for post-change period using different estimation method

<table>
<thead>
<tr>
<th>Catchments</th>
<th>Climate variability</th>
<th>Human activity</th>
<th>Climate variability</th>
<th>Human activity</th>
<th>Climate variability</th>
<th>Human activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luanhe River</td>
<td>39</td>
<td>61</td>
<td>33</td>
<td>67</td>
<td>43</td>
<td>57</td>
</tr>
<tr>
<td>Chaohue River</td>
<td>46</td>
<td>54</td>
<td>34</td>
<td>66</td>
<td>35</td>
<td>65</td>
</tr>
<tr>
<td>Hutuo River</td>
<td>70</td>
<td>30</td>
<td>72</td>
<td>28</td>
<td>69</td>
<td>31</td>
</tr>
<tr>
<td>Zhanghe River</td>
<td>31</td>
<td>69</td>
<td>35</td>
<td>65</td>
<td>36</td>
<td>64</td>
</tr>
</tbody>
</table>

---

Figure 10. Climate variability effects on runoff (\( \Delta Q_C \)) determined by hydrological model method, hydrological sensitivity analysis and climate elasticity method for post-change period, respectively.
commonly used to investigate the impacts of climate change on annual streamflow (e.g. Sankarasubramanian et al., 2001; Sankarasubramanian and Vogel, 2003; Niemann and Eltahir, 2005; Chiew, 2006; Novotny and Stefan, 2007). Moreover, non-parametric estimator for $\varepsilon_P$ was regarded as more appropriate with smaller bias and more robust than modeling approaches (Chiew, 2006).

It should be noted that there are uncertainties associated with assessing effects of climate variability and human activities on runoff. Although the estimating effects are relatively consistent, there is still a certain variation for catchments with different methods (Table VI). Firstly, there are still limitations for the methods used in this study. The two-parameter model is easy to satisfy the data requirement but its disadvantages are also apparent. It provides less information about detailed description of hydrological process compared with complex hydrological model. Furthermore, the hydrological sensitivity analysis and climate elasticity method are only for the effect of the changes in runoff with changes in mean annual precipitation. However, runoff can be influenced by changes in other precipitation characteristics, such as seasonality, intensity and concentration. In addition, occurrence of extreme runoff may also affect the accuracy of the hydrological sensitivity analysis method (Zhao et al., 2010). Secondly, uncertainty may come from the approximation in the framework to separate the effect. It should be noted that the framework used to estimate proportional contribution of climate variability and human activities to runoff is based on the assumption that human activities is independent of climate change (Zheng et al., 2009). However, the effects of human activities and climate are inter-related with each other and are not readily separable. Climate change may influence the human activities such as land use and thus change runoff (Zheng et al., 2009). Conversely, extensive urbanization and expanded population may cause increase in temperature and consequently result in change in hydrological regime (Wang et al., 2010). Therefore, despite that human activities and climate system interact with each other, even in baseline period, it is not considered as such in the present study. Finally, uncertainties may arise from limited hydro-climatic variables observation data and model parameters. Scarcity meteorological station data may limit the simulation accuracy of the hydro-climatic variables such as PET and runoff. Moreover, uncertainity in model parameters can also inevitably affect the simulation results (Li et al., 2010; Jiang et al., 2011). Therefore, further studies should be conducted in future to improve the results of quantification of climate and anthropogenic effects with consideration of these uncertainties.

**SUMMARY**

Global and regional climate variability (e.g. increased temperatures and reduced precipitation) is regarded as an important factor affecting hydrological processes. Concurrently, irrigation-based human activities have been identified as the main factors causing significantly declined runoff in most catchments of the Haihe River basin (Yang and Tian, 2009). It is hence useful to separate the effects of climate variability from that of human activities. In this study, we employ three methods (i.e. hydrological model method, hydrological sensitivity method and climate elasticity method) to quantitatively assess the impacts of climate variability and human activities on runoff in four catchments (i.e. the Luanhe River catchment, the Chaohu River catchment, the Hutuo River catchment and the Zhanghe River catchment) of the Haihe River basin. A statistically identified change point (derived comprehensively from double cumulative curve and Pettitt’s test) was first used to determine the baseline period. A two-parameter model has been calibrated and validated based on hydro-climatic data during the pre-change period. Meanwhile, the parameters $w$, $\beta$ and $\gamma$ in the hydrological sensitivity analysis method are successively calibrated within the pre-change period, and the precipitation elasticity $\varepsilon_P$ of climate elasticity method is also determined with precipitation and runoff data during the same period. The effects of human activities on runoff were evaluated as a difference between measured runoff and simulated runoff with no consideration of local human activities on the basis of two-parameter model. Concurrently, the effects of climate variability on runoff during the post-change period can be estimated with the hydrological sensitivity analysis method and climate elasticity with the calibrated parameters. The climate and human activity effects can consequently be separated by the general framework based on the assumption that climate and human activities are dominant drivers for runoff change. The results show that three methods provide generally consistent estimates of the contributions of climate variability and human activities to runoff, indicating that the period separation, the selected methods and conceptual framework are appropriate.

Significant downward trends in runoff can be found in all the catchments, especially for Luanhe River, Hutuo River and Zhanghe River, which are dominated by significant decreasing trends at 99% confidence level, whereas significant downward trend in precipitation can only be found in the Hutuo River catchment. The change in the gradient of precipitation–runoff double cumulative curves can be found in 1979 for the Luanhe River catchment, Chaohu River catchment and Hutuo River catchment and in 1977 for the Zhanghe River catchment, indicating that the relationship between precipitation and runoff has changed abruptly. As a result, the annual runoff during 1957–2000 can be divided into two periods named pre-change and post-change periods accordingly. Human activities should be mainly responsible for the runoff reduction in the Luanhe River catchment (accounting for 61%, 67% and 57% by hydrological model method, hydrological sensitivity method and climate elasticity method, respectively), Chaohu River catchment (accounting for 54%, 66% and 65%, respectively) and Zhanghe River catchment (accounting for 69%, 65% and 64%, respectively), whereas 70%, 72% and 69% of runoff
reduction in the Hutuo River catchment were attributed to climate variability.

This study presents a quantitative assessment of the effects of climate variability and human activities on runoff in four catchments of the Haihe River basin. In conjunction with other findings of the hydro-climatic variables change (e.g. Yang and Tian, 2009; Wang et al., 2011a,b), an ongoing crisis in water supply with decreasing water resource amount and increasing water demand in the Haihe River basin has been portended by the results of this study. Furthermore, the results of the present study can serve as a reference for regional water resources management and planning, and at the same time, also put forward a practically possible proposition for local administrative managers to reasonably arrange the local actions and to reduce the negative effect of climate change to local water resources.

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