Runoff changes and their potential links with climate variability and anthropogenic activities: a case study in the upper Huaihe River Basin, China
Ye Zhu, Wen Wang, Yi Liu and Hongjie Wang

ABSTRACT
The impacts of climate variability and anthropogenic activities on hydrological processes have been of wide concern in the hydrology community during recent decades. In this study, specific investigations of individual impacts of climate variability and anthropogenic activities on runoff during 1964–2010 are conducted for the upper Huaihe River Basin at Huaibin (HB) and its five sub-catchments. The non-stationary relationship between precipitation and runoff was firstly analyzed, and according to change point detection results, long-term series for each catchment was divided into pre-change period and post-change period, respectively. Then, the climate variability and human activities that occurred in the whole HB catchment were analyzed. Finally, using two quantitative evaluation methods, the individual impacts of climate variability and human activities for each catchment were assessed. The results showed that for the whole HB catchment, runoff changes during the whole post-change period are mainly attributed to climate variability, as for its sub-catchments except the Xinxian catchment. As for decadal behaviors, runoff generally suffered more human-induced impacts in dry decades (1990s) than wet decades (1980s and 2000s). These results reflected the complex role of climate variability and human activities in influencing the runoff regime, which could be considered in local water resources management.

Key words | anthropogenic activities, climate variability, Huaihe River Basin, runoff changes

INTRODUCTION
Climate variability and anthropogenic activities are two important factors affecting regional water resources. In northern hemisphere sub-tropical regions, affected by the combined effects of rising temperature and reduced precipitation (e.g. Chen et al. 2007), problems associated with water scarcity are becoming worse. Global warming may give rise to the intensification of regional water cycles (Huntington 2006), resulting in frequent occurrence of natural disasters such as floods (Milly & Dunne 2002) and droughts (Sheffield & Wood 2008). Concurrently, human activities in the form of cultivation, irrigation, drainage, urbanization and flood prevention measures have also induced variability in temporal and spatial distributions of water resources and flow regimes (e.g. Ren et al. 2002). Thus, regional patterns of runoff are complex under coupled impacts of climate variability and human activities.

As for China, observed annual runoff of the six large basins in the eastern regions has generally decreased during the past 50 years, with dramatic reductions observed in northern China (Zhang et al. 2007) which largely impede local economic development. On these grounds, strategies associated with alleviating contradictions between water shortage and growing human demands are highlighted and some preliminary evaluations have been performed (Li et al. 2007; Ye et al. 2013). However, due to the diversity of climatic conditions and human activities (related to local development strategy), runoff changes exhibit high spatial-temporal variability. Even among sub-catchments in a river...
basin, the main driving force of runoff variation may differ, such as in the Haihe River Basin (Wang et al. 2015). Hence, conducting the quantitative assessment at a local scale would be helpful to establish a wide spectrum of runoff change mechanisms.

The Huaihe River Basin is located in the north and south climate transitional zone. With a total length of 1,000 km, it flows through five provinces (Henan, Hubei, Anhui, Jiangsu and Shandong) controlling a drainage area of 270,000 km². Owing to poor management, problems of water shortage, water pollution and environmental degradation have become increasingly severe in recent decades. Given this, two different mechanisms-based methods have been adopted in this study – statistical analysis-based hydrological sensitivity analysis and process-based hydrological model simulation method – to assess the impact of climate variability and human activities on runoff changes. The catchment located in the upper Huaihe River Basin, together with its five sub-catchments, are selected as a case study. The objectives of this study are: (1) to comprehensively investigate the runoff change from a perspective of varied rainfall–runoff relationship; (2) to systematically analyze climate variability and human activities that have occurred in this region; and (3) to quantitatively estimate the individual contribution of climate change and human activities to runoff variation with two different mechanisms-based methods.

STUDY AREA, DATA AND METHODS

Study area

The upper Huaihe River Basin at Huaibin (referred to as the HB catchment hereafter) has a drainage area of 16,005 km² (Figure 1). It is bounded by the Dabie Mountain to the south and Huang-Huai Plain to the north. The elevation ranges from 27 to 1,031 m above sea level and topography generally decreases from the west to the east. Affected by the monsoon climate, the mean annual (1964–2010) temperature and precipitation are 15.4 °C and 1,076 mm, respectively, and approximately 60% of annual precipitation falls between July and September. In the present study, five sub-catchments within the HB catchment (Dapoling...
(DPL), Changtaiguan (CTG), Xinxian (XIN), Huangchuan (HC) and Xixian (XX) catchments) are selected for hydro-meteorological analysis. Relevant hydrological information is listed in Table 1. In addition, five large reservoirs and a medium-sized reservoir (Xiangshan) in and around the HB catchment are shown in Figure 1 considering their potential impact on runoff. Specific information on these six reservoirs is listed in Table 2. Obviously, the DPL catchment, within which there are no large reservoirs, is a good selection for hydrological model simulation among these catchments. Accordingly, a comparison of hydrological model simulation and hydrological sensitivity analysis method was conducted in the DPL catchment for evaluating the effectiveness of the two methods.

**Data used**

Observed daily discharges of six runoff stations (i.e. DPL, CTG, XIN, HC, XX and HB) and precipitations at 59 gauging sites are used for hydrological analysis (see Figure 1 for geographic distributions). Discharges at the six streamflow gauging stations are converted to catchment runoff by averaging the runoff amounts over the area of each catchment.

Daily meteorological variables at five standard meteorological stations from 1964 to 2010, including mean temperature ($T_{\text{mean}}$), maximum and minimum temperature ($T_{\text{max}}$ and $T_{\text{min}}$), wind speed (WS), sunshine duration (SD) and relative humidity (RH), were retrieved from the China Meteorological Data Sharing Service System (http://cdc.cma.gov.cn). Areal rainfall was calculated by interpolating daily precipitations of 59 rain gauges with the inverse distance weighting method (Bartier & Keller 1999), and potential evapotranspiration (PET) was calculated using the Penman–Monteith equation recommended by FAO (Allen et al. 1998).

Socio-economic records for Xinyang City are collected from the ‘Henan Province Statistical Yearbook’. Other geographical data used in the study include: three land cover images (1 km in spatial resolution) for 1985, 1995 and 2000 provided by the Chinese Academy of Sciences; digital elevation data with a 3 arc-second (about 90 m) spatial resolution retrieved from the shuttle radar topography mission (SRTM) digital elevation model (http://srtm.cgiar.org/); and soil data with a 30 arc-second (about 1 km) spatial resolution downloaded from the Harmonized World Soil Database (http://www.isric.org).

**Methodology**

**Trends analysis and change point detection**

The rank-based non-parametric method, i.e. Mann–Kendall (MK) test (Mann 1945; Kendall 1975), was employed for monotonic trend detection due to its advantages of non-restriction on data distribution and robustness against the...
interference of outliers. Significant trends are identified when the absolute value of the statistic $Z$ exceeds 1.96 or 2.576, corresponding to 5% and 1% significance level, respectively.

For change point detection, the cumulative curve of precipitation and runoff method was employed. Normally, the cumulative curve of precipitation and runoff follows a straight line before the change point occurs, and the point of non-conformity is recognized when the consistency of hydrological series is broken (shown as the variation in the gradient of the cumulative curve). Moreover, the order cluster analysis method (OC) was employed to detect the change point. The long time series can be divided into two parts by the possible change point, and the point which makes the sum of the square deviation of the two divided series least is identified as the change point. The detailed procedure for this test can be found in Jiang et al. (2011). For both test methods, pre-change period and post-change period are identified on the basis of detected change points.

Conceptual framework for separating effects of climate change and human activities

For a given basin, runoff change is regarded as the joint effects of climate change and human activities. Based on the hypothesis of independence between these two factors, a conceptual framework for separating effects is established as follows:

$$\Delta Q_{\text{tot}} = Q_{2}^{\text{obs}} - Q_{1}^{\text{obs}}$$  \hspace{1cm} (1)

$$\Delta Q_{\text{tot}} = \Delta Q_{\text{clim}} + \Delta Q_{\text{hum}}$$  \hspace{1cm} (2)

$$I_{\text{clim}} = \frac{\Delta Q_{\text{clim}}}{|\Delta Q_{\text{clim}}| + |\Delta Q_{\text{hum}}|} \times 100\%$$  \hspace{1cm} (3)

$$I_{\text{hum}} = \frac{\Delta Q_{\text{hum}}}{|\Delta Q_{\text{clim}}| + |\Delta Q_{\text{hum}}|} \times 100\%$$  \hspace{1cm} (4)

where $\Delta Q_{\text{tot}}$ represents total changes of runoff; $|\Delta Q_{\text{tot}}|$ is the absolute value of $\Delta Q_{\text{tot}}$; $Q_{2}^{\text{obs}}$ and $Q_{1}^{\text{obs}}$ stand for observed runoff in the changed period and the baseline period, respectively; $\Delta Q_{\text{clim}}$ and $\Delta Q_{\text{hum}}$ denote the individual change of runoff resulting from climate change and human activities, respectively; $I_{\text{clim}}$ and $I_{\text{hum}}$ are the percentage of the climate change and human activities on runoff changes, respectively.

Therefore, the separate effects of the climate change and human activities can be obtained with this framework if $\Delta Q_{\text{clim}}$ or $\Delta Q_{\text{hum}}$ is known. In this study, quantitative assessments are implemented by calculating $\Delta Q_{\text{hum}}$ or $\Delta Q_{\text{clim}}$ with the hydrological model simulation method and hydrological sensitivity analysis method, respectively.

Hydrological model simulation method

The hydrological model simulation method is performed by firstly calibrating hydrological models with meteorological forcings in the baseline period. Then, keeping optimized parameters unchanged, the simulation driven by meteorological forcings during the changed period is defined as the reconstructed runoff series for which no human interferences are involved. Accordingly, human-induced impacts on runoff can be obtained by computing the difference between reconstructed and observed runoff series in changed periods. It can be described as follows:

$$\Delta Q_{\text{hum}} = Q_{2}^{\text{rec}} - Q_{2}^{\text{obs}}$$  \hspace{1cm} (5)

where $Q_{2}^{\text{rec}}$ represents the reconstructed runoff in changed periods.

The physically based distributed hydrology soil and vegetation model (DHSVM) was employed for hydrological simulation. At each time step, simultaneous simulations of energy and water balances are carried out in every grid cell within the watershed, and runoffs generated on the basis of saturation and infiltration excess mechanism according to a user-defined infiltration capacity. Meanwhile, individual grid cells are hydrologically linked through a quasi-three-dimensional saturated subsurface transport scheme. A detailed description of DHSVM can be found in Wigmosta et al. (1994).

For model implementation, DHSVM was run at a 3-hour time step over a digital elevation model (DEM) with 200-m grid spacing. Daily forcings (precipitation, maximum and minimum temperature, RH and WS) are disaggregated to 3-hour intervals by procedures provided by Nijssen et al. (2001). For model performance evaluation,
two statistics are employed: coefficient of efficiency (NSCE) (Nash & Sutcliffe 1970) and BIAS.

**Hydrological sensitivity analysis method**

This method is proposed on the basis of the water balance equation which can be described as

\[ P = Q + E + \Delta S \]  

where \( P, Q, E \) are precipitation, runoff and actual evapotranspiration, respectively; \( \Delta S \) denotes the change in water storage. Usually, for a long period (e.g. 10 years or more), \( \Delta S \) can be neglected.

Because \( E \) is largely determined by precipitation and PET, by neglecting \( \Delta S \) the change in mean annual runoff can be determined by perturbations in precipitation and PET, which is described as (Koster & Suarez 1999; Milly & Dunne 2002)

\[ \Delta Q_{\text{clim}} = \beta \Delta P + \gamma \Delta PET \]  

where \( \Delta P \) and \( \Delta PET \) represent the change in precipitation and PET, respectively; \( \beta \) and \( \gamma \) denote the sensitivity of runoff to a 1-unit change in precipitation and PET, respectively.

In this study, a sensitivity analysis framework developed by Donohue et al. (2011) was adopted, which can directly assess the sensitivity with no limitation for sequence length. The framework originates from Choudhury’s equation (Choudhury 1999)

\[ Q = P - \frac{P \times PET}{(P_n + PET^n)^{1/n}} \]  

where the parameter \( n \) (dimensionless and typically ranges from 0.6 to 3.6) describes the partition of \( P \) between \( E \) and \( Q \), and represents the sum effect of all processes not encapsulated in \( P \) and PET.

Then, the sensitivity coefficients \( \beta \) and \( \gamma \) can be defined as the partial derivatives of Equation (8), expressed as

\[ \beta = 1 - \frac{E}{P} \left( \frac{PET^n}{P^n + PET^n} \right) \]  

\[ \gamma = - \frac{E}{PET} \left( \frac{P^n}{P^n + PET^n} \right) \]

Similarly, relevant calibration of the model was conducted in the baseline period with two criteria: BIAS and correlation coefficient (CC).

**RESULTS**

**Non-stationary relationship between precipitation and runoff**

The runoff is potentially influenced by the combined effects of climate variability and human activities, shown as non-stationary responses of runoff to precipitation (Zhang et al. 2014). In this section, runoff change patterns are analyzed from the perspective of the varied relationship between runoff and precipitation, including the trends of long-term series, cumulative curves and the decadal runoff coefficient (RC).

To compare long-term precipitation and runoff change intuitively, the annual precipitation anomaly series and runoff anomaly series of all six catchments are plotted in Figure 2. For the whole HB catchment (Figure 2(f)), while both precipitation and runoff anomaly series experienced significant annual fluctuations, the precipitation series exhibits a stronger downward trend than the runoff series, and the cases are the same for DPL, CTG and XX catchments (Figure 2(a), 2(b), 2(e)). For the XIN catchment (Figure 2(c)), however, runoff shows a stronger downward trend than precipitation, and an adverse pattern is found in the HC catchment (Figure 2(d)), where runoff exhibits an upward trend while precipitation has little change.

Cumulative curves of annual precipitation, cumulative curves of annual runoff and the OC analysis method are used to detect change points. Consistent results are given by the two methods, and break points for each catchment are marked in Figure 3. It is shown that for the two headwater catchments (DPL and CTG), break points occurred in 1990, relatively later than the other catchments where breakpoints all occurred in the 1970s; i.e. 1976 for XIN.
Figure 2 | Time series of precipitation and runoff anomaly for the six catchments during 1964–2010.
Figure 3  | Cumulative curves of precipitation and runoff for the six catchments within the HB catchment.
catchment, 1979 for HC catchment and 1973 for XX and HB catchments. Based on the change point detection results, the temporal span for each catchment is divided into two parts: the pre-change period (baseline period) and post-change period. Moreover, to evaluate the impact of decadal precipitation oscillation (Ma 2007) on runoff, post-change period was further divided into four periods: between change point and 1979; 1980s (1980–1989); 1990s (1990–1999); and 2000s (2000–2010).

RC is calculated for the baseline and post-change periods, respectively, for each catchment. Table 3 summarizes the statistics of RC for all six catchments. For DPL, CTG, XX and HB catchments, RC regularly oscillated with the lowest value in the 1990s, indicating the least runoff generation in unit precipitation during that period. For the XIN catchment, RC increased slightly in the 1980s in comparison with the baseline period, then decreased in the following two decades (1990s and 2000s). RC in HC catchment showed unique variations with consistently higher values in the whole post-change periods than in the baseline period.

### Potential climate variability and anthropogenic activities

Climate variability and anthropogenic activities are regarded as two main driving forces that result in runoff changes. In this section, we analyze runoff-related climatic variables, historical land cover data, and local socio-economic indices, trying to explore their potential links with runoff changes for the whole HB catchment.

#### Climate variability analysis

Precipitation and PET, which govern regional water and energy budgets, respectively, are two crucial factors influencing runoff patterns. Since most catchments experienced their first breakpoints during the 1970s (Figure 3), precipitation and PET in the period before 1980 are used as benchmarks, and statistics in the three changed decades (1980s, 1990s and 2000s) are compared with the benchmarks so as to detect decadal climate variability.

For assessing decadal precipitation variations, decadal spatial patterns of precipitation distribution for the whole HB catchment are plotted in Figure 4, from which a decadal drying and wetting alternation is found. Except for the HC catchment, all other catchments suffered their driest decade in the 1990s. Most parts in the northern HB catchment encountered their wettest decade in the 2000s, while the 1980s is the wettest in southern parts (including XIN and HC catchments). In addition, seasonal precipitations (in December–January–February (DJF), March–April–May (MAM), June–July–August (JJA) and September–October–November (SON)) of the whole HB catchment in different decades are compared, shown in Figure 5. It is clear that seasonal precipitation in the 1980s, 1990s and 2000s tended to present higher variability than that before the 1980s, especially in JJA, SON and DJF. Meanwhile, compared with the period before the 1980s, precipitation in JJA increased during two wet decades (1980s and 2000s), and decreased in SON and DJF for the dry decade (1990s).

PET, which represents comprehensive energy conditions, exhibits a significantly negative trend with a confidence level of 99% during 1964–2010 (Figure 6). Six PET-related meteorological variables, $T_{\text{mean}}, T_{\text{min}}, T_{\text{max}}, \text{WS}, \text{RH}$ and SD, also presented significant trends with a confidence level of 99%. WS and SD are the two most significantly changed variables that jointly contributed to PET drops.

| Table 3 | RCs of all catchments in different periods |
|---|---|---|---|---|
| DPL | (1964–1989) 0.36 | – | 0.31 | 0.38 |
| CTG | (1964–1989) 0.35 | – | 0.30 | 0.34 |
| XIN | (1967–1976) 0.45 | 0.47 | 0.38 | 0.34 |
| HC | (1964–1979) 0.33 | 0.42 | 0.38 | 0.39 |
| XX | (1964–1973) 0.34 | 0.38 | 0.32 | 0.36 |
| HB | (1964–1973) 0.32 | 0.35 | 0.30 | 0.36 |

Numbers in brackets denote the baseline period of each catchment.
Anthropogenic activities detection

The non-stationary relationship between precipitation and runoff indicates that runoff in these catchments may be potentially affected by human activities besides precipitation. Three land cover maps from 1985, 1995 and 2000, provided by the Chinese Academy of Science, are used in this study for change analysis. According to the original classification system, the HB catchment has 17 land cover types in total. To facilitate land cover comparison among different years and hydrological model simulation, the three maps were re-classified into seven types (Figure 7).

For the whole HB catchment, main land cover changes between 1985, 1995 and 2000 could be generalized as shifts between dry farmland and paddy field. Compared with 1985, paddy field increased from 20.37 to 30.10% in 1990, then decreased to 20.80% in 2000, accompanied with adverse changes for dry farmland. As for small areas

Figure 4 | Spatial distribution of precipitation during four periods: (a) before 1980s (1964–1979); (b) 1980s; (c) 1990s; (d) 2000s.
(such as the DPL and XIN catchments), the land cover changes in 1995 are particularly significant compared with the other 2 years, which may be exaggerated to some extent due to the limitation of satellite image interpretation. However, the potential error of 1995’s classification did not affect the hydrological simulation results since only 1985’s land cover was used for hydrological simulations.

On the other hand, for a reservoir regulated region, the influence of water conservancy constructions should not be ignored. As shown in Figure 8, except for DPL catchment, the remaining areas are highly disturbed by dozens of water conservancy facilities, including large and medium-sized reservoirs, irrigation stations and canals, barrages and hydropower stations. The driving force behind these hydraulic structures is the growing demand for water resources for social development. Figure 9 shows that population, gross domestic product, industrial added value and grain yield of the Xinyang administrative region all have generally undergone sustainable growth since 1964. Some apparent drops are found in the grain yield series, which is possibly caused by meteorological droughts, such as in 2001 when many parts of China suffered severe drought (Yu et al. 2013), but they do not influence the overall upward trend of grain yield. These four rising socio-economic indices suggest that more water would be withdrawn and consumed for the purpose of domestic usage, industrial

Figure 5 | Boxplots for seasonal precipitation of the HB catchment during four periods: (a) March-April-May; (b) June-July-August; (c) September-October-November; (d) December-January-February.
consumption and irrigation depletion during changed periods.

**Quantitative evaluation**

**Calibration and validation for the two quantitative evaluation methods**

Considering the geographic advantage of no large reservoir regulation in the DPL catchment, the hydrological model simulation method was applied in this area for separating effects of climate variability and anthropogenic activities, which also serves as a validation for the hydrological sensitivity analysis method. According to change point detection results, the 1980s still belongs to the baseline period for DPL catchment, when the hydrological conditions were considered as relatively stable. On these grounds, it is reasonable to calibrate DHSVM model during 1980s and then apply the model in changed periods to obtain reconstructed runoff series. Figure 10 shows the monthly simulation results for calibration (1980–1985) and validation (1986–1989) periods. Generally, the calibrated results are satisfactory with NSCE above 0.9 and absolute values of bias lower than 1%, suggesting that DHSVM is capable of capturing natural variability of the observed hydrograph.

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**Figure 6** | Evolution of PET and its six meteorology-related variables over 1964–2010; red solid lines represent significant detected trends.

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For the hydrological sensitivity analysis method, calibration was conducted in all six catchments during each baseline period, and Table 4 lists relevant fitted parameters and calibration results. The fitted $n$ varied between 1.29 and 1.61, reflecting different properties of the six catchments. With sensitivity coefficients $\beta$ uniformly larger than $\gamma$, it reveals that the change in runoff is more sensitive to precipitation than to PET within this region. The calibration results for all catchments are generally satisfactory according to the two criteria (BIAS and CC).

**Separated impacts of climate variability and human activities on runoff**

Individual impacts of climate variability and human activities on runoff are quantitatively assessed for each catchment using the hydrological model simulation method and the hydrological sensitivity analysis method, respectively, and the results are presented in Table 5. For DPL catchment, the results of both methods are comparable; both showed that climate variability was the dominant factor. The closeness of the results by the two methods indicates the effectiveness of both methods in evaluating the individual impacts of climate variability and human activities on runoff. According to results given by the hydrological sensitivity analysis method, the reduction of runoff for the entire HB catchment during the whole post-change period (1974–2010) was mainly attributed to climate variability, accounting for 60%, while human activities accounted for the remaining 40%. Similar patterns are found in another two main stream catchments, CTG and XX, for which annual runoff changes are largely determined by climate variability.
variability as well. This suggests that even though there are dozens of water conservancy constructions, their impacts on runoff changes do not exceed those of climate variability at the decadal scale. This is quite different from the adjacent basins, such as the Yellow River Basin and the Haihe River Basin, where human activities influence runoff greatly (Li et al. 2011; Wang et al. 2013). The possible reason is that precipitation in the Yellow River Basin and Haihe River Basin can hardly satisfy local water demand even in their wet years, while the HB catchment is generally self-sufficient in wet years and the demands of water diversion in the form of irrigation are not strong. But in dry years, when precipitation cannot largely meet the requirements, more water would be withdrawn through these conservancy facilities. As shown in Table 5, DPL, HC, XX and HB catchments suffered more impacts of human activities in their driest decade of the 1990s than in the wet decades (1980s and 2000s).

Human interferences in the XIN catchment are more intensive than in the other catchments. Table 5 shows that human activities contributed 98% of runoff reduction during the post-change period, while climate variability accounted for 2%. The regulation of Xiangshan Reservoir was possibly responsible for most of the runoff reduction in this catchment. With a controlling area of 72.8 km², the reservoir governs 27% of the XIN catchment area, and its storage capacity accounts for 56% of mean annual runoff. Apart from irrigation (Table 2) and hydropower generation (Figure 8), the stored water also serves to meet domestic usage, industrial consumption and ecological landscape requirements of the XIN County (more than half of its area is outside the XIN catchment). With the development of the economy in XIN County, the water demands would increase gradually. For instance, according to the local survey, the total abstraction from Xiangshan Reservoir in 2010 was up to $0.44 \times 10^8$ m³, equivalent to 29% of mean annual runoff of this catchment.

In contrast to the dramatic runoff reduction in the XIN catchment, the runoff of the HC catchment experienced unusual increases. For the post-change period, climate variability and human activities contributed 64% and 36% of runoff increments, respectively. The water resources allocation in this catchment is rather complex; since the Pohe Reservoir (inside the HC catchment) can hardly meet local requirements, two large reservoirs outside the catchment (i.e. Wuyue Reservoir and Nianyushan Reservoir) contribute considerable amounts of water to this region. The large irrigation canal conveys water from the Wuyue Reservoir (Figure 8), and for Nianyushan Reservoir, approximately $0.5 \times 10^8$ m³ of water on average was transported from the lateral channels of its western irrigation canal (assessed from local official websites, http://xsgk.xinyang.gov.cn/huangchuan/slj). Owing to the lack of detailed observations
Figure 9  | Socio-economic records of Xinyang City during 1964–2010: (a) population; (b) gross domestic product; (c) industrial added value; (d) grain yield.

Figure 10  | DHSVM-simulated monthly results during baseline period for the DPL catchment.
of these reservoirs, it is hard to quantify the specific effect of each one.

**EFFECTS OF MODELING UNCERTAINTY ON EVALUATION RESULTS**

Although close results were derived by the hydrological model simulation and hydrological sensitivity analysis method in the DPL catchment, which indicates the feasibility of the two methods at this basin scale, the effects of modeling uncertainty in each evaluation method should not be ignored. For the hydrological model simulation method, a major concern is the rainfall–runoff simulation uncertainty introduced by heavy data requirements for the distributed modeling. As shown in Figure 10, the simulation bias of streamflow discharge is $-0.81\%$ for the calibration period and $0.84\%$ for the validation period, equivalent to

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**Table 4** | Parameters and calibration results for the hydrological sensitivity analysis method

<table>
<thead>
<tr>
<th>Parameters</th>
<th>DPL</th>
<th>CTG</th>
<th>XIN</th>
<th>HC</th>
<th>XX</th>
<th>HB</th>
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</thead>
<tbody>
<tr>
<td>$n$</td>
<td>1.38</td>
<td>1.45</td>
<td>1.29</td>
<td>1.61</td>
<td>1.57</td>
<td>1.59</td>
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<tr>
<td>$\beta$</td>
<td>0.64</td>
<td>0.65</td>
<td>0.72</td>
<td>0.72</td>
<td>0.64</td>
<td>0.63</td>
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<tr>
<td>$\gamma$</td>
<td>-0.25</td>
<td>-0.25</td>
<td>-0.37</td>
<td>-0.32</td>
<td>-0.26</td>
<td>-0.27</td>
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<tr>
<td>Calibration</td>
<td>CC</td>
<td>0.95</td>
<td>0.94</td>
<td>0.88</td>
<td>0.91</td>
<td>0.9</td>
</tr>
<tr>
<td>Results</td>
<td>BIAS (%)</td>
<td>-0.97</td>
<td>-0.49</td>
<td>-0.45</td>
<td>-0.17</td>
<td>-0.94</td>
</tr>
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</table>

**Table 5** | Impacts of climate variability and human activities on streamflow changes for all six catchments derived from the two evaluation methods

<table>
<thead>
<tr>
<th>Method</th>
<th>Periods</th>
<th>Contribution</th>
<th>DPL</th>
<th>CTG</th>
<th>XIN</th>
<th>HC</th>
<th>XX</th>
<th>HB</th>
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<td>Hydrological model simulation method</td>
<td>1990s</td>
<td>$\Delta Q_{\text{clim}}$ (mm)</td>
<td>-88.1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>$\Delta Q_{\text{hum}}$ (mm)</td>
<td>-18.1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>$I_{\text{clim}}$ (%)</td>
<td>-83</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>$I_{\text{hum}}$ (%)</td>
<td>-17</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2000s</td>
<td>$\Delta Q_{\text{clim}}$ (mm)</td>
<td>19.5</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>$\Delta Q_{\text{hum}}$ (mm)</td>
<td>-2.5</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<td></td>
<td>$I_{\text{clim}}$ (%)</td>
<td>89</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>$I_{\text{hum}}$ (%)</td>
<td>-11</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<td>$I_{\text{clim}}$ (%)</td>
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<td>$I_{\text{hum}}$ (%)</td>
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<td>$I_{\text{clim}}$ (%)</td>
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<td>36</td>
<td>-17</td>
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less than 3 mm of runoff. The bias is rather small when comparing with the volume of runoff changes caused by climate variability and human activities. As the bias of the simulated water amount is the major consideration in the assessment of the impacts of climate variability and anthropogenic activities, such a small bias caused by modeling uncertainty would not affect our analysis results significantly.

The hydrological sensitivity analysis method requires only meteorological inputs and therefore is more easily manipulated, though it has some distinct drawbacks such as the oversimplified modeling structure in which seasonal variability of hydrological factors is ignored. Nonetheless, this limitation does not influence the application of the hydrological sensitivity analysis method substantially. As shown in Table 5, the DPL catchment was evaluated with the two methods and the difference between each derived attribute result was less than 6% (e.g. for the 1990s, the hydrological model simulation method shows climate variability is responsible for 83% of runoff changes, while the figure is 78% for the hydrological sensitivity analysis method). The bias generally has little impact on the role of climate variability and human activities. The hydrological sensitivity analysis method also provides an alternative for the assessment in data-scarce basins where the hydrological model simulation method cannot work well.

In the framework of the hydrological sensitivity analysis method, estimation of $n$ is a crucial step since it governs the accuracy of simulated runoff $R$, and also affects the value of $\beta$ and $\gamma$. Figure 11 illustrates the sensitivity of streamflow to the variation of $n$ (0.5–4.0) for each catchment. The dotted line in each graph denotes the basin-wide fitted $n$ value of 1.59.

![Figure 11](https://iwaponline.com/hr/article-pdf/46/6/1019/370950/nh0461019.pdf)

**Figure 11** Streamflow sensitivities of (a) $R$, (b) $\beta$ and (c) $\gamma$ to the variation of $n$ (0.5–4.0) for each catchment. Scatters in plot (a) represent the fitted values of $n$ for each catchment. The dotted line in each graph denotes the basin-wide fitted $n$ value of 1.59.
two sensitivity coefficients $\beta$ and $\gamma$ (Donohue et al. 2011). Figure 11 shows the sensitivity of $R$, $\beta$ and $\gamma$ to the variation of $n$. Taking the whole HB catchment as an example, the fitted $n$ value is 1.59, corresponding to 359 mm yr$^{-1}$ of runoff. If $n$ is set to 1.54 and 1.64, the simulated runoff would be 369 mm yr$^{-1}$ and 348 mm yr$^{-1}$, respectively (Figure 11(a)). That is, the simulated runoff would increase (decrease) by approximately 10 mm yr$^{-1}$ for every 0.05 decrease (increase) in $n$, equivalent to 3% of mean annual runoff. On the other hand, since the absolute values of simulated water amounts bias in all six catchments are less than 1% (Table 4), the error for corresponding estimated $n$ would never exceed 0.05. Likewise, 0.05 ranges of $n$ values would produce less than 0.01 of value differences in $\beta$ and $\gamma$ (Figure 11(b) and 11(c)), meaning that 100 mm yr$^{-1}$ change in precipitation or PET would lead to no more than 1 mm yr$^{-1}$ change in runoff. Therefore, based on Equation (7), we can conclude that the minor error of $n$ values has little impact on the framework of the hydrological sensitivity analysis method. Meanwhile, from Figure 11 it is found that the curves reflecting the sensitivity of runoff to $n$ of the main stream catchments (DPL, CTG, XX and HB) are rather close, indicating similar hydrological sensitivity among these catchments. Only the XIN catchment shows a significant difference, which may be related to the higher precipitation received compared with other catchments; therefore with the same $n$ value more precipitation would be partitioned to runoff.

CONCLUSIONS

Using meteorological data at one meteorological observation site, precipitation data at 59 gauging sites and streamflow discharge data at six gauging stations during 1964–2010, runoff changes in the upper Huaihe River basin at HB together with five sub-catchments (i.e. DPL, CTG, XIN, HC and XX) were analyzed using the method of trend detection, the precipitation and runoff cumulative curves method, and the OC analysis method. Then, the potential impacts of climate variability and human activities within HB catchment on runoff were analyzed with two quantitative evaluation methods: the DHSVM-based hydrological model simulation method; and the hydrological sensitivity analysis method. The investigation results show the following:

1. A long-time series of runoff for the whole HB catchment showed no significant trends but fluctuated considerably at annual scale. Among its five sub-catchments, except the HC catchment in which runoff even increased under the condition of decreased precipitation, annual runoff generally decreased during 1964–2010, with varying degrees of reduction. Breakpoint for the two headwater catchments (DPL and CTG) both occurred in 1990, relatively later than other catchments, for which the first breakpoints emerged in the 1970s. Decadal variation of RC indicated the varied runoff response to precipitation between the pre-change and post-change periods.

2. Generally decadal drying and wetting alternations are found in the HB catchment, with the lowest amounts observed in the 1990s for most sub-catchments. Comparing with the period before the 1980s, seasonal precipitation in the 1980s, 1990s and 2000s presented a higher variability, with considerable increments of summer precipitation in the 1980s and 2000s. Annual PET significantly decreased during 1964–2010 with certain increments in the 1990s which was possibly caused by the rising SD. These findings suggest that the 1990s was the driest decade both in water and energy conditions. Meanwhile, investigations on land cover changes and socio-economic indices imply that more water would be abstracted and consumed in the post-change period.

3. Quantitative evaluation on separated effects of climate variability and human activities showed that for the whole HB catchment, climate variability played a dominant role, and runoff changes in the other four catchments DPL, CTG, HC and XX were also mainly induced by climate variability. As for the XIN catchment, runoff change was mainly attributed to human activities, accounting for 98%. Generally, runoff in most catchments suffered more reduction in dry decades (1990s) than wet decades (1980s and 2000s) due to enhanced impacts of climate variability and human activities. These results reflected the complexity of climate variability and human activities induced impacts on runoff.
regime, such as differences among catchments and decades. In these upstream catchments of the Huaihe River Basin, the runoff change should be highlighted and policy makers should make reasonable management interventions to guarantee the sustainable utilization of local water resources.

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