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A comprehensive framework for quantifying the impacts of climate change and human activities on baseflow and direct runoff: Application across six diverse basins in China

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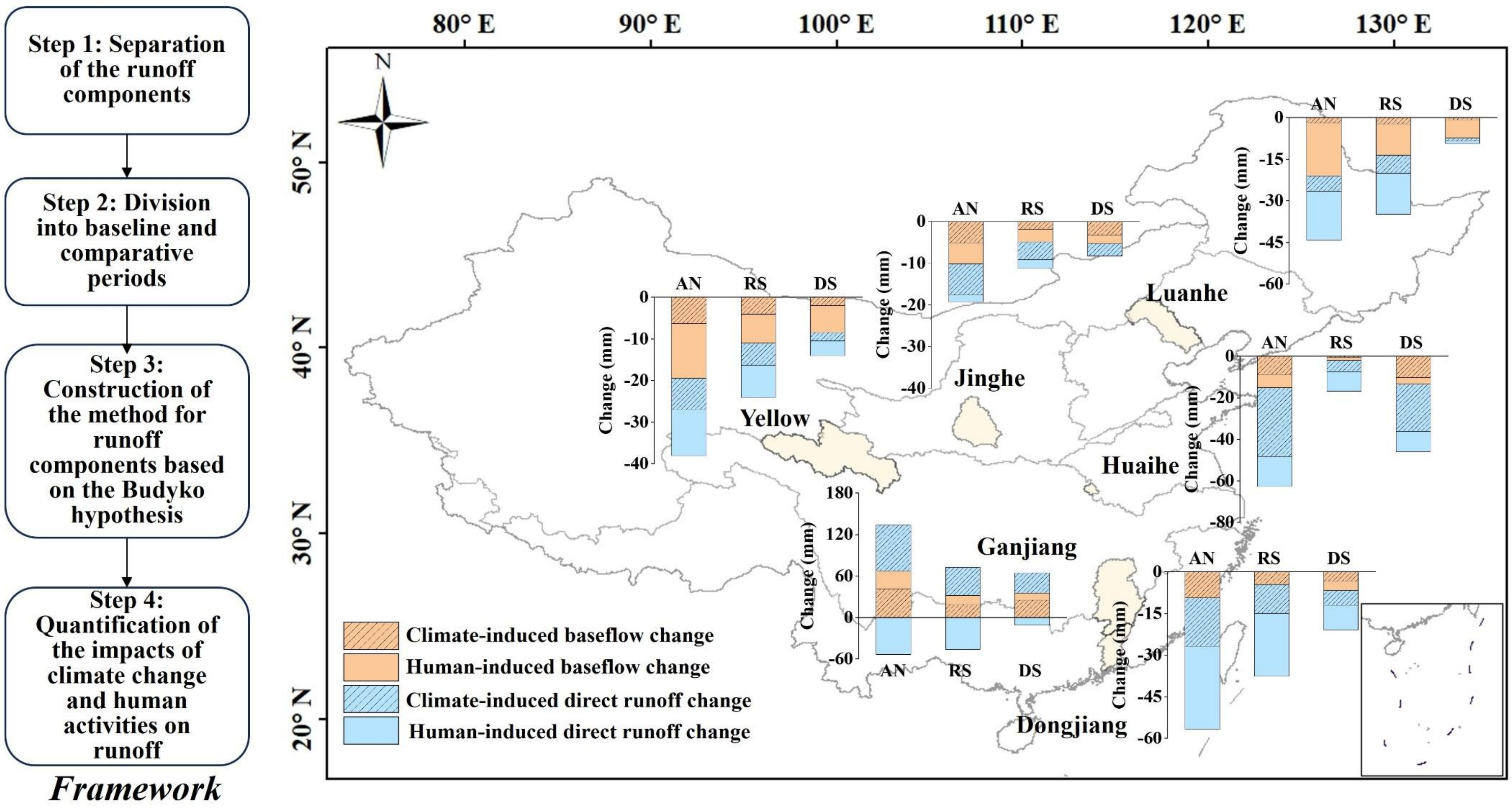
Abstract:	Study region The source region of the Yellow River, the Jinghe River, the Luanhe River, the Huaihe River, the Ganjiang River, and the Dongjiang River Study Focus Quantifying the impacts of climate change and human activities on runoff is essential for water resource protection and management. However, the respective effects on runoff components, specifically baseflow and direct runoff, remain insufficiently explored and quantified. This study proposes a comprehensive framework to quantify the contributions of the two factors to annual and seasonal baseflow and direct runoff changes, using an extended Budyko method. Six basins across China were selected to assess the framework's effectiveness. New Hydrological Insights for the Region Results indicate that Human activities are the primary factor contributing to the decline in annual baseflow and direct runoff in the Yellow River, Luanhe River, and Dongjiang River, while climate change has a more pronounced impact on baseflow and direct runoff in other basins. Moreover, the impacts of both factors on baseflow and direct runoff are greater during the rainy season compared to the dry season, except in the Huaihe River. This study demonstrates that the proposed framework effectively distinguishes the impacts of climate change and human activities on runoff components.
Opposed Reviewers:	

Highlights:

- A framework to quantify the impacts of climate change and human activities on runoff components is proposed.
- Baseflow and direct runoff changes across six basins in China exhibit divergence.
- Climate change and human activities have differential effects on baseflow and direct runoff.
- Climate change and human activities exert a greater impact on baseflow and direct runoff during the rainy season.

Graphical Abstract



A comprehensive framework for quantifying the impacts of climate change and human activities on baseflow and direct runoff: Application across six diverse basins in China

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Abstract

Study region

The source region of the Yellow River, the Jinghe River, the Luanhe River, the Huaihe River, the Ganjiang River, and the Dongjiang River

Study Focus

Quantifying the impacts of climate change and human activities on runoff is essential for water resource protection and management. However, the respective effects on runoff components, specifically baseflow and direct runoff, remain insufficiently explored and quantified. This study proposes a comprehensive framework to quantify

the contributions of the two factors to annual and seasonal baseflow and direct runoff changes, using an extended Budyko method. Six basins across China were selected to assess the framework's effectiveness.

New Hydrological Insights for the Region

Results indicate that Human activities are the primary factor contributing to the decline in annual baseflow and direct runoff in the Yellow River, Luanhe River, and Dongjiang River, while climate change has a more pronounced impact on baseflow and direct runoff in other basins. Moreover, the impacts of both factors on baseflow and direct runoff are greater during the rainy season compared to the dry season, except in the Huaihe River. This study demonstrates that the proposed framework effectively distinguishes the impacts of climate change and human activities on runoff components.

Keywords: Baseflow; Direct runoff; Climate change; Human activities; Attribution analysis

1. Introduction

Climate change and human activities trigger remarkable changes in hydrological cycle processes, resulting in severe water issues across the globe (Cui et al., 2023; Ansari Mahabadi and Delavar, 2024; Zaerpour et al., 2025). Runoff is the most important component of the hydrological cycle, as it transfers excess precipitation to the oceans and regulates water fluxes within hydrological systems (Kåresdotter et al., 2022). Therefore, quantitative evaluation of the impacts of climate change and human activities on runoff is essential for developing science-based strategies for sustainable water resource management and protection.

Numerous studies have investigated the contributions of climate change, human activities, or both, to runoff changes (Shen et al., 2017; Krajewski et al., 2021; Nguyen et al., 2024; Van Binh et al., 2025). For example, Shen et al. (2017) evaluated the attribute of the runoff change in 224 catchments across China from 1960 to 2010, and found that climate change was identified as the dominant driver in most catchments. In recent years, increasing attention has been given to the specific components of runoff, namely baseflow and direct runoff, to better understand the distinct effects of climate change and human activities on water resources (Tan et al., 2020; Saedi et al., 2022; Murray et al., 2023; Mo et al., 2025). Taking the Heihe River Basin in northwest China, as a case study, Zhang et al. (2019) distinguished the impacts of climate change and human activities on variations in streamflow, baseflow and surface runoff. Using long-term observational data from nine hydrological stations covering the period from the 1950s to 2018, Chen et al. (2024) assessed the contributions of climate change and human activities to the changes in baseflow and direct runoff in the Middle Reach of the Huai River. To the best of our knowledge, however, most previous studies have focused on individual basins or localized regions (Li et al., 2021; Mao et al., 2024). Moreover, limited attention has been given to the runoff components at shorter temporal scales, particularly at the seasonal scale. Therefore, further research is needed to provide a holistic understanding of the hydrological impacts of climate change and human activities on runoff components across China.

To date, several methodologies have been employed to separate the impacts of climate change and human activities on runoff, including statistical analysis, hydrological modeling, the Budyko framework, and paired catchment analysis (Dey and Mishra, 2017; Xu et al., 2022; Kazemi Garajeh et al., 2024). Among these, the Budyko framework has been extensively utilized due to its well-defined physical basis, concise mechanism, and relatively simple calculations (Kim and Chun, 2021; Wang et al., 2021). Within the Budyko framework, mean annual runoff is determined by the ratio of mean annual potential evapotranspiration to mean annual precipitation, as well as other watershed properties (Saha et al., 2020). Additionally, the Budyko framework has shown comparable reliability to more complex hydrological models (Xue et al., 2017). Recent developments have extended the framework to incorporate baseflow, with various baseflow Budyko functions developed by researchers such as Meira Neto et al. (2020), Cheng et al. (2021), and Chen and Ruan (2023). These baseflow Budyko functions offer practical approaches to quantify the impacts of climate change and human activities on baseflow and direct runoff changes. However, such studies remain relatively scarce.

In this study, we applied the baseflow Budyko functions proposed by Chen and Ruan (2023) to quantify the impacts of climate change and human activities on baseflow and direct runoff. China exhibits diverse climatic conditions, land surface characteristics, and population distributions, resulting in complex regional patterns of runoff variation (Liu et al., 2017; Yang et al., 2022). Thus, we selected six basins, namely the source region of the Yellow River, the Jinghe River, the Luanhe River, the Huaihe River, the Ganjiang River, and the Dongjiang River, to provide a holistic picture of the hydrological impacts of climate change and human activities on runoff components across China. In addition, hydro-climatic variables and human activities exhibit seasonal characteristics, such as rainfall seasonality, intense water withdrawals during irrigation periods, and reservoir operations during flood seasons (Alifujiang et al., 2021; Mahmoodi et al., 2022; Sushanth et al., 2023). The contributions of climate change and human activities were also examined at the seasonal scale.

The objectives of this study are: (1) to develop a framework to quantify the contributions of climate change and human activities to annual and seasonal baseflow and direct runoff; (2) to investigate the changes in meteorological factors and runoff components across the six selected basins; (3) to quantify the contributions of climate change and human activities to runoff component changes on both scales. The remainder of the paper is organized as follows: Section 2 introduces the study region and data used; Section 3 describes the methodology for quantifying the contributions of climate change and human activities to runoff component changes; Section 4 presents the results of the effects of climate change and human activities on the six basins; Sections 5 and 6 summarize the discussions and conclusions.

2. Study area and data sources

This study focuses on six river basins: the source region of the Yellow River, the Jinghe River, the Luanhe River, the upper reaches of the Huai River, the Ganjiang River, and the Dongjiang River (Fig. 1). The source region of the Yellow River (hereinafter referred to as the Yellow River), located in the northeastern Tibetan Plateau, covers a drainage area of 121,972 km^2. It experiences a wet, warm summer and a cold, dry winter. The Jinghe River, located in the Loess Plateau in northwest China, spans 43,216 km^2. The Luanhe River, located in the northeastern part of the Hai River Basin, has a drainage area of 44,900 km^2. Both basins fall within the temperate continental monsoon climate region. The upper reaches of the Huai River (hereinafter referred to as the Huaihe River), with a drainage area of 3,090 km^2 at the Changtaiguan hydrological station, belongs to the warm temperate semi-humid monsoon climate region. The Ganjiang River, with a drainage area of 81,158 km^2, is the seventh-largest tributary of the Yangtze River Basin. The Dongjiang River, a major tributary of the Pearl River Basin in South China, spans 25,325 km^2. The Ganjiang River and Dongjiang River belong to the subtropical moist monsoon climate zone, characterized by a moderate climate and sufficient rainfall.

The mean annual precipitation across the study basins ranges from 508 mm in the Jinghe River to 1,763 mm in the Dongjiang River (see Table 1). Precipitation predominantly occurs between June and August (Fig. 2). The Mean annual potential evapotranspiration ranges from 734 mm in the Yellow River to 1,101 mm in the Dongjiang River. The aridity index spans from 0.62 in the Dongjiang River to 1.84 in the Jinghe River. The mean annual runoff depth ranges from 37 mm in the Jinghe River to 938 mm in the Dongjiang River, with coefficients of variation ranging from 0.15 to 0.53. Additionally, high flows in these six basins primarily occur from June to August, driven by increased rainfall during this period.

Observed daily streamflow data from six-gauge stations were obtained from the local Hydrology Bureau (Table 1). These data cover the period from 1960 to 2010 for the Yellow River, Jinghe River, and Ganjiang River, from 1960 to 2000 for the Luanhe River, and from 1960 to 2007 for the Dongjiang River. Daily meteorological data spanning from 1960 to 2012, including precipitation, temperature, wind speed, relative humidity, and sunshine duration, were sourced from 48 observation stations operated by the National Climatic Centre of the China Meteorological Administration. The locations of hydrological and meteorological stations are shown in Fig. 1. In addition, potential evapotranspiration was computed using the Penman-Monteith method (Allen and Ingram, 2002). Spatially averaged meteorological data across the study basins were generated using the Thiessen polygon method (Thiessen, 1911).

3. Methodology

3.1. Baseflow separation methods

Since baseflow cannot be measured directly, four baseflow separation methods were employed in this study, i.e., the Boughton method, Jakeman method, Lyne-Hollick method, and Maxwell method (Lyne and Hollick, 1979; Boughton, 1993; Jakeman and

Hornberger, 1993; Chapman and Maxwell, 1996). These methods were applied to daily total runoff time series, and the average of their outputs was used as the daily reference baseflow to reduce uncertainties, as recommended by Zhang et al. (2020). The calculations were performed using the 'grwat' package in R software (Rets et al., 2022). The digital filter with a parameter of 0.925 was applied in the forward, backward, and forward directions. For further details on these methods, please refer to the relevant literature provided. Subsequently, daily direct runoff was computed as the difference between total runoff and the reference daily baseflow.

3.2. Change-point analysis

Identifying abrupt change points in runoff, which are significantly influenced by climate change and human activities, is of considerable importance. In this study, the Mann-Kendall and Pettitt’s tests were both selected to detect these change points and minimize errors or leakage from using a single method (Mann, 1945; Pettitt, 1979). The Mann-Kendall test, a nonparametric statistical method recommended by the World Meteorological Organization, was employed to preliminarily identify abrupt changes in annual total runoff, baseflow, and direct runoff time series. Subsequently, Pettitt’s test was used to confirm these identified change points. For detailed descriptions of both methods, please refer to the literature provided (Li et al., 2017; Ryberg et al., 2020).

3.3. Quantifying changes in runoff components based on Budyko hypothesis

Budyko framework. For an ideal basin, the long-term water-balance equation can be written as:

$$P=E+Q+\Delta S \tag{1}$$

where P, E, and Q represent precipitation, actual evapotranspiration, and runoff, respectively; ΔS represents the change in catchment water storage, which can be assumed to be zero over a long period (e.g., 5 and 10 years). Budyko (1974) proposed that the runoff coefficient (Q/P) is expressed as a function of the aridity index (φ, i.e. the ratio of the potential evaporation E_0 to P) (Monserud et al., 1993). Following this assumption, several mathematical models have been developed to describe the Budyko framework. A widely used Budyko function is Fu's equation (Fu, 1981) as follows:

$$\frac{Q}{P}=(1+\varphi^{\omega})^{\frac{1}{\omega}}-\varphi \tag{2}$$

where ω represents the catchment characteristics, which is correlated with vegetation cover, relative infiltration capacity, etc.

Climate elasticity method considering the runoff components. Chen and Ruan (2023) assumed that baseflow is proportional to subsurface water storage and direct runoff is proportional to precipitation and the relative subsurface water storage. They proposed that the baseflow index (BFI, the ratio of baseflow Q_b to total runoff Q) can be expressed as:

$$\frac{Q_b}{Q}=\frac{\alpha}{P+\alpha} \tag{3}$$

where α is catchment storage capacity. Combining Eqs. (2) and (3), Q_b and direct runoff (Q_d) can be expressed as functions of P, E_0, ω, and α:

$$Q_b=P\cdot\left(\left(1+\left(\frac{E_0}{P}\right)^{\omega}\right)^{\frac{1}{\omega}}-\frac{E_0}{P}\right)\cdot\frac{\alpha}{P+\alpha} \tag{4}$$

$$Q_d=P\cdot\left(\left(1+\left(\frac{E_0}{P}\right)^{\omega}\right)^{\frac{1}{\omega}}-\frac{E_0}{P}\right)\cdot\frac{P}{P+\alpha} \tag{5}$$

Here, we assumed that P is independent of E_0 and that both P and E_0 are independent of ω and α (Zhou et al., 2016). The changes in Q_b and Q_d caused by climate change can be estimated through the first-order differentiation of Eqs. (4) and

(5):

$$\Delta Q_b^C = Q_b \cdot \left(\varepsilon_{Q_b,\ P} \cdot \frac{\Delta P}{P} + \varepsilon_{Q_b,\ E_0} \cdot \frac{\Delta E_0}{E_0} \right) \tag{6}$$

$$\Delta Q_d^C = Q_d \cdot \left(\varepsilon_{Q_d,\ P} \cdot \frac{\Delta P}{P} + \varepsilon_{Q_d,\ E_0} \cdot \frac{\Delta E_0}{E_0} \right) \tag{7}$$

where ΔQ_b^C and ΔQ_d^C represent the changes in Q_b and Q_d induced by climate change between the pre- and post-impact periods, respectively; ΔP and ΔE_0 denote the changes in P and E_0, respectively; ε represents the elasticities of Q_b or Q_d to changes in P or E_0, indicating a 1% change in P or E_0 would change in Q_b or Q_d (Berghuijs et al., 2017). $\varepsilon_{Q_b,P}$, $\varepsilon_{Q_d,P}$, ε_{Q_b,E_P}, and ε_{Q_d,E_P} can be derived from Eqs. (4) and (5):

$$\varepsilon_{Q_b,\ P} = \frac{\partial Q_b/Q_b}{\partial P/P} = f(\varphi,\ \omega) - \frac{P}{P+\alpha} \tag{8}$$

$$\varepsilon_{Q_d,\ P} = \frac{\partial Q_d/Q_d}{\partial P/P} = f(\varphi,\ \omega) + \frac{\alpha}{P+\alpha} \tag{9}$$

$$\varepsilon_{Q_b,\ E_0} = \varepsilon_{Q_d,E_0} = \frac{\partial Q_b/Q_b}{\partial E_0/E_0} = \frac{\partial Q_d/Q_d}{\partial E_0/E_0} = g(\varphi,\ \omega) \tag{10}$$

where

$$f(\varphi,\ \omega) = \frac{(1+\varphi^{\omega})^{\frac{1}{\omega}-1}}{(1+\varphi^{\omega})^{\frac{1}{\omega}} - \varphi} \tag{11}$$

$$g(\varphi,\ \omega) = \frac{\varphi^{\omega} \cdot (1+\varphi^{\omega})^{\frac{1}{\omega}-1} - \varphi}{(1+\varphi^{\omega})^{\frac{1}{\omega}} - \varphi} \tag{12}$$

Thus, ΔQ_b^C and ΔQ_d^C runoff changes caused by climate change can be expressed as follows:

$$\Delta Q_b^C = \gamma \cdot Q_{b,1} \cdot \left(\left(\varepsilon_{Q_b,\ P} \right)_1 \cdot \frac{\Delta P}{P_1} + \left(\varepsilon_{Q_b,\ E_0} \right)_1 \cdot \frac{\Delta E_0}{E_{0,1}} \right) + (1-\gamma) \cdot Q_{b,2} \cdot \left(\left(\varepsilon_{Q_b,\ P} \right)_2 \cdot \frac{\Delta P}{P_2} + \left(\varepsilon_{Q_b,\ E_0} \right)_2 \cdot \frac{\Delta E_0}{E_{0,2}} \right) \tag{13}$$

$$\Delta Q_d^C = \gamma \cdot Q_{d,1} \cdot \left(\left(\varepsilon_{Q_d,\ P} \right)_1 \cdot \frac{\Delta P}{P_1} + \left(\varepsilon_{Q_d,\ E_0} \right)_1 \cdot \frac{\Delta E_0}{E_{0,1}} \right) + (1-\gamma) \cdot Q_{d,2} \cdot \left(\left(\varepsilon_{Q_d,\ P} \right)_2 \cdot \frac{\Delta P}{P_2} + \left(\varepsilon_{Q_d,\ E_0} \right)_2 \cdot \frac{\Delta E_0}{E_{0,2}} \right) \tag{14}$$

where γ is a coefficient (0-1), and set to 0.5 in this study as recommended by Zhou et al. (2016). The changes in Q_b and Q_d resulting from human activities (i.e., ΔQ_b^H and ΔQ_d^H) can be calculated by:

$$\Delta Q_b^H = \Delta Q_b - \Delta Q_b^C \quad (15)$$

$$\Delta Q_d^H = \Delta Q_d - \Delta Q_d^C \quad (16)$$

where ΔQ_b and ΔQ_d represent the observed changes in Q_b and Q_d, respectively. The percentage contributions of climate-induced (η_b^c) and human-activities-induced (η_b^h) baseflow changes are calculated as:

$$\eta_b^c = \frac{\Delta Q_b^c}{\Delta Q_b + \Delta Q_d} \times 100\% \quad \text{and} \quad \eta_b^h = \frac{\Delta Q_b^h}{\Delta Q_b + \Delta Q_d} \times 100\% \quad (17)$$

Similarly, the percentage contributions of direct runoff can be calculated.

Effective precipitation. Changes in water storage are usually negligible for long-term water balance. However, at the monthly or seasonal scales, water storage changes become significant and must be considered. Chen et al. (2013) proposed the concept of effective precipitation to extend the Budyko hypothesis to the seasonal scale. In dry months or seasons, effective precipitation includes both precipitation (P) and the depletion of stored water (ΔS) (i.e., $P_e = P + \Delta S$), while watershed storage is replenished by infiltrated rainfall in rainy months or seasons (i.e., $P_e = P - \Delta S$). Correspondingly, the seasonal aridity index is defined as the ratio of seasonal potential evaporation to seasonal effective precipitation.

In this study, the four months with the heaviest precipitation are defined as the rainy season, while the remaining months are defined as the dry season (Wu et al., 2017). Given the strong seasonal variation across the six basins, the months with the heaviest precipitation differ. Specifically, the heaviest precipitation months are June to September for the source region of the Yellow River, the Jinghe River, and the Luanhe River, May to August for the Huaihe River and Dongjiang River, and March to June for the Ganjiang River.

3.4. The monthly abcd model

The monthly abcd model proposed by Thomas (1981)was adopted to capture the dynamics of soil moisture and groundwater in the six basins. This model has been successfully applied in numerous basins with different climatic features (Wang and Tang, 2014; Bhasme et al., 2022; Maurer et al., 2022). It inputs precipitation and potential evaporation, and includes four parameters (i.e., a, b, c, and d). Parameter a ($0 \leq a \leq 1$) represents the propensity of runoff to occur before the soil is fully saturated; parameter b is the upper limit on the sum of evapotranspiration and soil moisture storage; parameter c is the fraction of streamflow from groundwater discharge; parameter d is the coefficient for the groundwater storage-discharge relationship. In this study, these four parameters, along with the initial water storage, underwent calibration.

Seventy percent of the observed monthly data were utilized for model calibration, while the remaining served as validation. The widely used SCE-UA method was employed to optimize the parameter values of the monthly model (Duan et al., 1994) . Meanwhile, the Nash Sutcliffe efficiency coefficient (NSE) and the correlation coefficient (R^2) were used to assess the performance of the model.

In addition, we used the baseflow index (BFI) to quantify the proportion of baseflow to total runoff at the seasonal scale. To assess the reliability of the seasonal estimates, we calculated the α separately for the rainy and dry seasons and compared their combined value with the annual value. The results indicated a negligible margin of error. For example, in the Yellow River Basin, the α values were 221 mm for the rainy season and 428 mm for the dry season, which closely approximated the directly calculated annual value of 667 mm. This consistency suggests that the method is suitable for seasonal-scale applications.

The flowchart of the comprehensive assessment framework for quantifying the contributions of climate change and human activities to runoff components in this study is presented in Fig. 3. It mainly consists of four procedures: (1) separation of the runoff components; (2) division into baseline and comparative periods; (3) construction of the method for runoff components based on the Budyko hypothesis; (4) quantification of the impacts of climate change and human activities on runoff.

4. Results

4.1. Baseflow separation

The averages of baseflow estimated using four separation methods are presented in Table 2 and Fig. 2. As shown in Table 2, annual baseflow ranged from 17.4 to 502.4 mm, and BFI varied from 0.34 to 0.56 across the six basins. The highest BFI was observed in the Yellow River with a value of 0.56, which can be attributed to enhanced groundwater recharge from snowmelt and rainfall. In contrast, the Huaihe River exhibited the lowest BFI at 0.34. In general, BFI values during the rainy season tend to be lower than those in the dry season, particularly in the Jinghe River, Luanhe River and Huaihe River. This can be explained by the fact that precipitation during the rainy season occurs in the form of high-intensity storms, which generate more direct runoff (see Fig. 2).

4.2. Variation of hydrometeorological variables

4.2.1. Detection changes of runoff components

Fig. 4 illustrates the abrupt change points in total runoff, baseflow, and direct runoff using the Mann-Kendall test for the six basins. The intersection of the UF and UB curves is considered the abrupt change point in the time series. The results indicate that the change points for total runoff, baseflow, and direct runoff occurred in 1989 for the Yellow River, 1996 for the Jinghe River, and 1979 for the Luanhe River. Pettitt's test confirmed these change points (Table 2). For the Huaihe River, the Mann-Kendall test detected potential change points in 1984, 1987, 1992, 1996, and 2001. Pettitt's test validated the change point in 1984, which was subsequently adopted. Similarly, change points were detected in 1972 for the Ganjiang River and 1984 for the Dongjiang River.

4.2.2. Change in hydro-meteorological variables

Based on the identified abrupt change point, the overall time series was divided into the pre-impact period and the post-impact period. Fig. 5 illustrates the changes in precipitation, potential evapotranspiration, total runoff, baseflow, and direct runoff between these two periods. The annual precipitation and total runoff exhibited a decreasing trend in all basins except for the Ganjiang River, with reductions ranging from -17.5 mm to -66.2 mm. For the Ganjiang River, the annual precipitation and total runoff increased by 100.9 mm and 80.7 mm, respectively. Potential evapotranspiration increased by 19.0 mm in the Yellow River and 52.2 mm in the Jinghe River, but decreased by up to 51.9 mm in other basins.

In terms of runoff components, the reduction magnitude of baseflow and direct runoff showed little difference for the Yellow River, Jinghe River, and Luanhe River. In the Huaihe River and Dongjiang River, the decrease in direct runoff was the predominant contributor to the reduction in total runoff, accounting for 75% and 85%, respectively. In contrast, the increase in baseflow was the primary factor contributing to the total runoff increase in the Ganjiang River (approximately 83%).

In general, the changes in hydro-meteorological variables during the rainy and dry seasons were consistent with annual changes, except for precipitation in the Yellow River and Luanhe River, potential evapotranspiration in the Huaihe River and direct runoff in the Ganjiang River. In addition, precipitation, total runoff, baseflow, and direct runoff exhibit larger changes during the rainy season than in the dry season in the Yellow River, Jinghe River, and Luanhe River. For example, total runoff in the Yellow River decreased by 24.1 mm during the rainy season and 14.0 mm during the dry season. In contrast, opposite trends were observed in the Huaihe River and Ganjiang River. In the Dongjiang River, the change in baseflow was smaller during the rainy season than in the dry season, but the changes in total and direct runoff are larger. For potential evapotranspiration, the Jinghe River, Luanhe River, and Ganjiang River exhibited larger changes.

4.3. Calibration and validation of the abcd model

The simulated and observed monthly runoff series for the calibration and validation periods are presented in Fig. 6. Both the simulated monthly runoff amounts and hydrograph shapes closely match with the observed values, indicating that the performance of the model is generally satisfactory for these basins. Table 3 displays the parameter values of the abcd model and the assessment criteria. The correlation coefficients during calibration and validation ranged from 0.816 to 0.949 across all basins. The NSE values exceeded 0.719 during calibration and 0.706 during validation, except for the Luanhe River. This lower performance is likely due to substantial changes in runoff characteristics following the abrupt change point in 1979. Overall, the model demonstrates acceptable performance, and is applicable for estimating the hydrological variables using the Budyko framework.

4.4. Effects of climate change and human activities on runoff components

4.4.1. Sensitivity of runoff alterations to P and E

Table 4 lists the values of α, ω, Φ, and ΔS for the pre- and post-impact periods. Parameter α ranged from 127.8 mm in the Jinghe River to 2,129.2 mm inthe Dongjiang River, and showed an overall increasing trend. Parameter ω ranged from 1.69 to 6.46, and exhibited an increasing trend across all basins. The aridity index Φ ranged from 0.45 to 2.04, with the aridity indices decreasing from north to south. Moreover, a lower value of Φ was observed during the rainy season and a higher value during the dry season. Overall, Φ increased from the pre-impact to the post-impact period in all basins except the Ganjiang River, indicating that climatic conditions became drier in most basins. ΔS ranged from 12.9 mm in the Huaihe River to 112.8 mm in the Luanhe River, a showing only slight variation between the two periods.

Fig. 7 presents the mean elasticity coefficients of baseflow and direct runoff with respect to precipitation and potential evapotranspiration at both annual and seasonal scales. The precipitation elasticity coefficient (ε_P) of runoff components is positive across all basins and time scales, ranging from 0.99 to 3.96. Moreover, ε_P exhibits clear spatial variability, being higher in the Jinghe River and Luanhe River and lower in the Ganjiang River and Dongjiang River. ε_P is also higher during the dry season compared to the rainy season, indicating that runoff was more sensitive to changes in precipitation during the rainy season. According to the climate elasticity method, the sum of the precipitation elasticity coefficient and the potential evapotranspiration elasticity coefficient is equal to 1. Therefore, changes in the potential evapotranspiration elasticity ε_E coefficient closely followed trends, and changes in the ε_E automatically followed the ε_P trends closely. However, a significant difference is that runoff was negatively correlated with ε_E across all basins. The absolute value of ε_E is smaller than that of ε_P, indicating that runoff is more sensitive to variations in precipitation than to changes in potential evapotranspiration. Notably, the absolute values of the elasticity coefficients in the post-impact period exceed those in the pre-impact period, suggesting that these basins have become more sensitive to climate change in recent decades.

4.4.2. Quantification of climate and direct human impacts on runoff

Figs. 8 and 9 illustrate the quantitative contributions of climate change and human activities to changes in baseflow and direct runoff on annual, rainy season, and dry season scales across the six basins. As shown in Fig. 8, human activities are identified as the primary factor contributing to the decline in annual baseflow and direct runoff in the Yellow River (-13.2 mm for ΔQ_b^H and -11.1 mm for ΔQ_d^H) and Luanhe River (-19.0 mm for ΔQ_b^H and -17.5 mm for ΔQ_d^H). In contrast, climate change had a greater impact on annual baseflow and direct runoff in the Jinghe River (-12.5 mm for ΔQ_b^C and ΔQ_d^C) and Huaihe River (-41.9 mm for ΔQ_b^C and ΔQ_d^C). In the Ganjiang River, climate change led to a combined increase of approximately 108.9 mm in $\Delta Q_b^H$and ΔQ_d^H; human activities resulted in Q_b^H increasing by 25.4 mm but Q_d^H decreasing by-53.6 mm. Opposite trends are detected in the Dongjiang River, and human activities led to a significant decrease in direct runoff (-29.0 mm for ΔQ_b^H and ΔQ_d^H).

At the seasonal scale, both climate change and human activities generally exerted a greater influence during the rainy season compared to the dry season, with the exception of the Huaihe River. Moreover, the dominant drivers of runoff change at the seasonal scale were consistent with those at the annual scale. For instance, human activities decreased baseflow by 7.0 mm in the Yellow River during the rainy season, while climate change decreased it by 4.0 mm, consistent with the causes of annual runoff changes. Climate change mainly decreased the direct runoff (22.8mm) during the dry season in the Huaihe River. It is notable that human activities have a relatively minor effect on baseflow during the rainy season in the Huaihe River and Dongjiang River.

In terms of relative contribution, climate change contributed 4.6 - 16.7% of annual baseflow changes and 12.6 - 52.9% of direct runoff changes in the Yellow River, Luanhe river, Huaihe river, and Dongjiang River (see Fig. 9). Whereas, human activities contributed -1.5 - 34.7% to baseflow changes. In the Jinghe River, climate change and human activities contributed equally to baseflow (26.3%) but contributed 39.0% and 8.4% to direct runoff, respectively. In the Ganjiang River, climate change contributed 51.4 - 83.6 % of baseflow changes and direct runoff increase, while human activities accounted for -66.4% of the direct runoff decrease. The contributions of climate change and human activities to baseflow and direct runoff vary across the six basins. For instance, climate change showed a slight change in contribution to direct runoff in the Jinghe River during the rainy season (26.3%) compared to the annual contribution (27%), but a significant decrease in the Luanhe River (from 52.9% to 33.3%). Moreover, the difference is most pronounced in the Ganjiang River.

Overall, human activities contributed to 52.0 - 82.8% of the total flow decrease (i.e. the sum of contributions of human activities on baseflow and direct runoff) in the Yellow River, Luanhe River and Dongjiang River on annual and seasonal scales. Climate change contributed to 53.6 - 79.0% of total runoff changes (i.e. the sum of contributions of climate change on baseflow and direct runoff) for the annual and seasonal scales in Jinghe River. For the Huaihe River, climate change contributed to 66.7% and 71.6 % of total runoff changes for the annual and dry season, respectively, and 36.4% for the rainy season. In the Ganjiang River, climate change contributed 135.0%, 222.5%, and 101.4% of total runoff changes during the annual, rainy, and dry seasons, respectively.

5. Discussions

5.1. Comparison of results with other studies

Table 5 lists the contributions of climate change to total runoff in six selected basins based on previous research using the Budyko framework, as well as the findings from this study (Li and Zhou, 2016; Pan et al., 2018; Wang et al., 2018). In general, climate change affects runoff in a consistent direction, either increasing or decreasing it, across the basins. However, there are differences in the magnitude of contributions. For example, Zheng et al. (2009) reported that climate change contributed 30% to runoff change in the source region of the Yellow River, whereas this study estimates a contribution of 36.1%; Yang et al. (2021) quantified the attribution of runoff change in the Jinghe River and showed that climate change accounted for 24.5 - 41.5% of runoff change, compared to 65.3% in the current study. These discrepancies may be due to differences in meteorological data sources, mathematical models, and the comparison of different time intervals. Since the total contribution of climate change and human activities sums to one, the contribution of human activities closely follows this trend. Overall, the contributions estimated in this study are consistent with the findings of previous studies.

Unlike previous studies, this study divided total runoff into baseflow and direct runoff to analyze their respective contributions. First, we found that the responses of the two components to environmental changes often diverge (see Fig. 5). For instance, the Yellow River, Jinghe River, and Luanhe River exhibit only minor differences in the magnitude of changes between baseflow and direct runoff. In contrast, other basins show more pronounced disparities. Specifically, the direct runoff of the Huaihe River decreased significantly, whereas the baseflow of the Ganjiang River increased substantially. The difference becomes even more pronounced at the seasonal scale.

Then, we proposed a comprehensive Budyko framework for quantifying the contributions of climate change and human activities to baseflow and direct runoff (see Fig. 3). The results showed that climate change and human activities have different effects on these two components across the six basins. For instance, human activities affect the baseflow and direct runoff of the Yellow River, while primarily impacting the direct runoff of the Dongjiang River. To further evaluate the impact of neglecting changes in runoff components on the contribution of climate change and human activities to runoff, we recalculated the contributions using the Budyko framework without considering these components. As shown in the last column of Table 5, the climate change contributions estimated with the components considered are higher than those without the components considered in all basins, with the percentage change ranging from 0.5 to 6.9%. These differences are attributed to the computation of elasticity coefficients based on different models (Eqs. (6) - (12)). For instance, the precipitation elasticity coefficient of baseflow and direct runoff are 1.3 and 2.3 using the baseflow Budyko hypothesis (Eqs. (4) and (5)), while the coefficient is 1.8 for total runoff (Eq. (2)) in the Yellow River.

Moreover, the contributions of climate change and human activities exhibit seasonal variation, particularly in watersheds with intensive human interventions. For instance, in the Ganjiang River, human activities led to a significant decrease in direct runoff (-171.3%) and an increase in baseflow (48.8%) during the rainy season. This phenomenon occurs because human activities, such as reservoir operations, involve storing water during the rainy season, which leads to an increase in direct runoff.

5.2. Sensitivity of runoff components to climate change

In the Budyko framework, the impact of climate change is considered through changes in precipitation and potential evapotranspiration. In this study, we found that the precipitation elasticity coefficients of baseflow and direct runoff were positive, while the potential evapotranspiration elasticity coefficients were negative. This indicates that an increase in precipitation tends to enhance the runoff components, whereas an increase in potential evapotranspiration tends to decrease them. Eqs. (8) - (9) show that $\varepsilon_{Q_d,P}$ exceeds $\varepsilon_{Q_b,P}$ by 1. This suggests that direct runoff is more sensitive to precipitation than baseflow. Harman et al. (2011) and Xu et al. (2012) reported higher precipitation elasticity for surface runoff and lower precipitation elasticity for subsurface flow. The analysis in this study confirmed these results. Moreover, the large absolute values of the precipitation elasticity coefficients indicate that the runoff components are more sensitive to precipitation changes than to potential evapotranspiration changes.

Fig. 10 depicts the theoretical lines of $f(\varphi, \omega)$ and $g(\varphi, \omega)$ for various values of ω. It can be observed that the $f(\varphi, \omega)$ is higher than 1, while $g(\varphi, \omega)$ is lower than 0. The absolute values of $\varepsilon_{Q_b,P}$, ε_{Q_b,E_0}, and ε_{Q_d,E_0} increase with φ holding all other parameters constant. These findings suggest that dry catchments exhibit high sensitivity of runoff to precipitation and potential evapotranspiration changes. In this study, we found that rivers in northern China generally display higher sensitivities of runoff to precipitation than those in southern China, especially during the dry season. This finding aligns with the conclusions of Berghuijs et al. (2017). Moreover, the absolute values of elasticity coefficients in the post-impact period exceeded those in the pre-impact period, indicating that both baseflow and direct runoff have become more sensitive to climate change in recent decades.

5.3. Limitations and uncertainty in this study

It should be noted that, due to data limitations, this study was conducted using six basins in China, which may not fully represent the country' diverse climatic and hydrological conditions. Further studies involving a larger number of basin necessary to produce more universally applicable results. The Budyko framework is a valuable approach for illustrating and understanding the impacts of climate change and human activities on runoff changes. Nevertheless, several sources of uncertainty must be acknowledged. Firstly, the Budyko framework typically assumes an independence between climate change and human activities. In reality, these factors are interdependent and interact within natural catchments. Furthermore, according to Chen and Ruan (2023), baseflow is proportional to subsurface water storage, while direct runoff is proportional to both precipitation and subsurface water storage. Simultaneously, precipitation and potential evaporation are considered independent of shape parameters ω and α. These assumptions should be carefully considered when applying the Budyko framework proposed in this study, as they can introduce uncertainties in model performance.

Furthermore, uncertainties in this study stem from parameters, modeling methods, and observational data. Firstly, the estimation of baseflow is subject to uncertainties (Yan and Xu, 2022; Narimani et al., 2023). The baseflow index varies from 0.25 to 0.6 using four separation methods in this study. Meanwhile, changes in water storage, significant at seasonal scales, were derived from the monthly model (Xin et al., 2019). However, this model tends to underestimate high flows and overestimate low flows, potentially leading to inaccuracies in water storage results (Liu et al., 2022; Baseri et al., 2023). Lastly, the quality of precipitation and runoff data, along with the method used to estimate potential evapotranspiration, constitutes additional sources of uncertainty. These factors collectively contribute to the overall uncertainty of the study's findings.

6. Conclusions

This study aims to comprehensively investigate changes in runoff components and to distinguish between the impacts of climate change and human activities. A framework was proposed and applied to six basins, namely, the Yellow River, the Jinghe River, the Luanhe River, the Huaihe River, the Ganjiang River, and the Dongjiang River. The primary findings of this study are summarized as follows:

(1) The proposed framework integrates baseflow separation methods, extends the Budyko equation, and incorporates a water storage method. It enables the separation of climate and direct human contributions to baseflow and direct runoff on annual and seasonal scales, requiring less data and reducing the simulation burden.

(2) The BFI varied from 0.34 to 0.56 across the six basins, and the dry season BFI tends to be higher than the rainy season. The decrease in direct runoff played a dominant role in the Luanhe River and Dongjiang River on annual and seasonal scales, while baseflow increased the total runoff in the Ganjiang River. In addition, the changes in runoff components varied across the basins at the seasonal scale.

(3) The performance of the monthly model was generally satisfactory for these basins, enabling accurate estimation of hydrological variables. The aridity index increased

from the pre-impact to the post-impact periods for all basins except the Ganjiang River on both annual and seasonal scales. The precipitation elasticity coefficient (ε_P) ranged from 0.99 to 3.96 exhibiting clear spatial and temporal variability, with higher values for direct runoff than baseflow.

(4) Human activities were identified as the primary factor for the decline in annual baseflow and direct runoff in the Yellow River, Luanhe River, and Dongjiang River. Climate change had a more significant impact on baseflow and direct runoff in the Jinghe River, Huaihe River, and Ganjiang River. Both climate change and direct human activities had a more pronounced impact on baseflow and direct runoff during the rainy season compared to the dry season across all basins, except the Huaihe River.

CRediT authorship contribution statement

Tong Cui: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing - original draft, Writing - review & editing. **Shuai Chen:** Conceptualization, Data curation, Formal analysis, Methodology, Resources, Software, Visualization, Writing - review & editing. **Chengju Shan:** Data curation, Methodology, Resources, Validation. **Debao Lu:** Formal analysis, Investigation, Methodology, Writing - review & editing. **Jiazhong Zheng:** Formal analysis, Methodology, Visualization. **Dongjing Huang:** Formal analysis, Methodology, Visualization. **Fuqiang Tian:** Conceptualization, Investigation, Methodology, Project administration, Supervision, Visualization, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Table 1 Hydrological conditions and streamflow data of the six basins in this study.

Basin	Station	Area (km^2)	Annual mean precipitation (mm)	Annual mean potential evapotranspiration (mm)	Annual mean runoff (mm)	Aridity index	Runoff ratio	Streamflow (daily)
Yellow	Tangnaihai	121972	525.4	733.6	165.1	1.40	0.31	1960-2010
Jing He	Zhangjiashan	43216	507.6	935.7	37.0	1.84	0.07	1960-2010
Luanhe	Luanxian	44100	526.5	890.7	79.1	1.69	0.15	1960-2000
Huaihe	Changtaiguan	3090	993.0	1173.8	347.1	1.18	0.35	1960-2012
Ganjiang	Waizhou	80948	1599.3	1022.4	844.4	0.64	0.53	1960-2010
Pearl	Boluo	25325	1762.7	1100.6	937.6	0.62	0.53	1960-2007

Table 2 Mean annual and seasonal baseflow, and baseflow index across the six basins and the identified change points.

Basin	Baseflow (mm)			BFI			Selected change point
	Annual	Rainy season	Dry season	Annual	Rainy season	Dry season	
Yellow	92.4	51.4	41	0.56	0.53	0.60	1989
JingHe	17.4	7.8	9.7	0.47	0.38	0.58	1996
Luanhe	36.8	23.7	13.1	0.47	0.41	0.61	1979
Huaihe	117.9	60.7	57.2	0.34	0.28	0.43	1984
Ganjiang	431.4	246.8	184.6	0.51	0.47	0.57	1972
Zhujiang	502.3	250.3	252.0	0.54	0.49	0.58	1984

Table 3 Model parameters and performance of the abcd model in the six basins.

Basin	Parameter values				Calibration		Validation	
	a	b	c	d	R2	NSE	R2	NSE
Yellow	0.942	364.66	0.155	0.04	0.904	0.812	0.891	0.790
JingHe	0.995	712.99	0.001	0.779	0.875	0.748	0.832	0.706
Luanhe	0.936	223.28	0.768	0.001	0.858	0.734	0.816	0.549
Huaihe	0.969	196.17	0.574	0.794	0.848	0.719	0.884	0.768
Ganjiang	0.969	508.73	0.401	0.843	0.949	0.898	0.943	0.858
Zhujiang	0.981	1322.9	0.231	0.071	0.929	0.863	0.942	0.886

Table 4 Values of hydrological, climate, and landscape variables before (pre-impact) and after (post-impact) the identified change points.

Parameter		Yellow	Jinghe	Luanhe	Huaihe	Ganjiang	Dongjiang
α (mm)	Pre-Anuual	666.72	301.18	475.75	510.02	1442.56	1979.97
	Post-Anuual	676.43	228.96	437.72	515.97	1748.65	2129.17
	Pre-Rainy	329.97	165.49	224.72	215.47	586.36	951.65
	Post-Rainy	344.45	127.80	223.40	223.93	744.29	1061.24
	Pre-Dry	349.49	364.29	387.86	324.88	950.75	1032.98
	Post-Dry	340.24	275.75	251.55	356.57	1075.20	1068.67
ω	Pre-Anuual	1.96	2.80	2.44	2.01	2.03	2.09
	Post-Anuual	2.14	2.99	3.02	2.10	2.14	2.21
	Pre-Rainy	2.07	3.09	2.44	1.92	2.13	3.62
	Post-Rainy	2.30	3.44	3.16	2.00	2.64	6.46
	Pre-Dry	1.87	3.39	2.63	2.12	2.05	1.69
	Post-Dry	2.02	3.52	2.98	2.27	2.06	1.75
Φ	Pre-Anuual	1.36	1.78	1.68	1.14	0.70	0.62
	Post-Anuual	1.44	2.04	1.72	1.22	0.62	0.63
	Pre-Rainy	1.16	1.80	1.43	1.11	0.50	0.51
	Post-Rainy	1.24	2.03	1.50	1.12	0.45	0.51
	Pre-Dry	1.63	1.75	2.02	1.18	0.91	0.77
	Post-Dry	1.70	2.04	2.04	1.34	0.80	0.77
ΔS	Pre-change	88.69	90.19	112.77	12.86	87.84	40.75

(mm)	Post- change	73.91	88.53	102.46	17.81	67.06	42.57

Note: α and ω represent the shape parameters of the baseflow Budyko function; Φ denotes the Aridity index; ΔS is soil storage.

Table 5 Comparison of the contributions of climate changes to runoff in this study and previous studies

Basins	Results in reference			Result in this study	
	Reference	Study period	η_c (%)	η_c (%)	η_c without (%)
Yellow	Zheng et al. (2009)	1960-2000	30.0	36.1	35.5
Jinghe	Yang et al. (2021)	1961-2018	24.5-41.5	65.3	64.1
Luanhe	Li and Zhou (2016)	1956-2011	15.0-40.0	17.2	10.3
Huaihe	Pan et al. (2018)	1956-2000	19.2-68.8	66.7	65.3
Ganjiang	Wang et al. (2018)	1961-2015	58.7-93.5	135.0	134.5
Dongjiang	Shen et al. (2017)	1960-2010	27.5-39.4	48.0	47.3

Note: The climatic contributions estimated considering the components are listed the fifth column, and without considering the components are listed in the last column.

Lists of Figure Captions

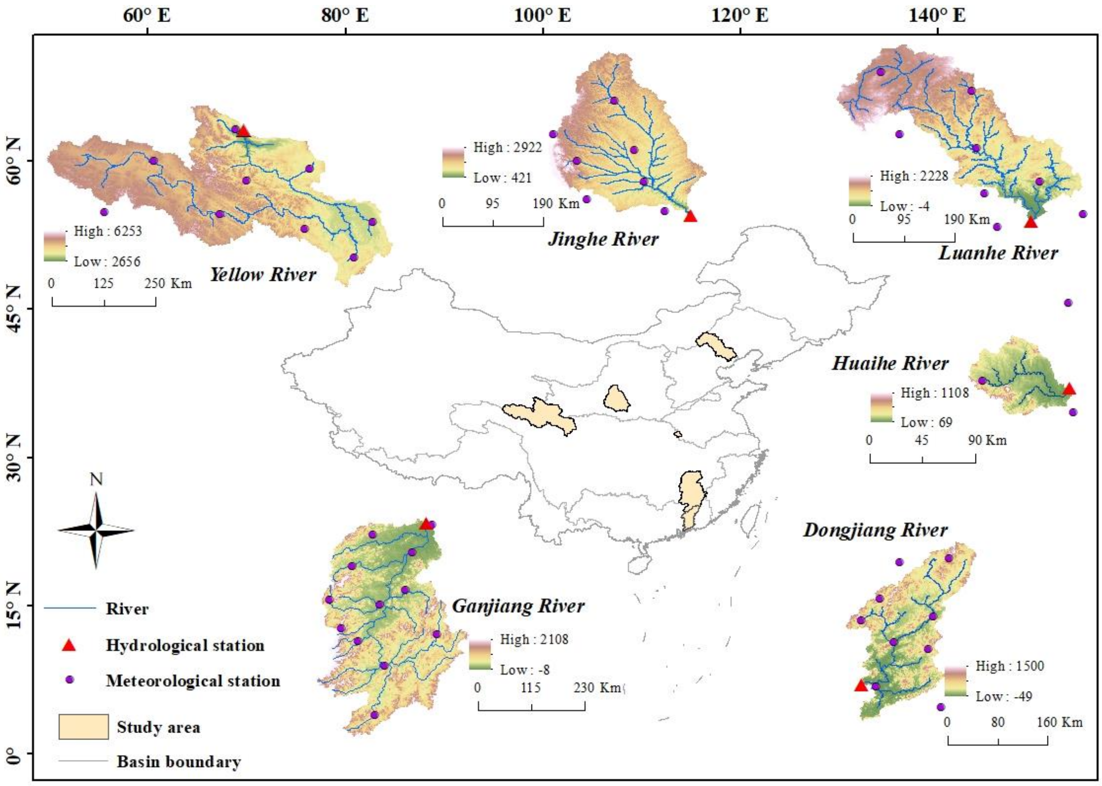

Fig. 1. Geographic locations of the six basins and associated hydro-meteorological stations used in this study.

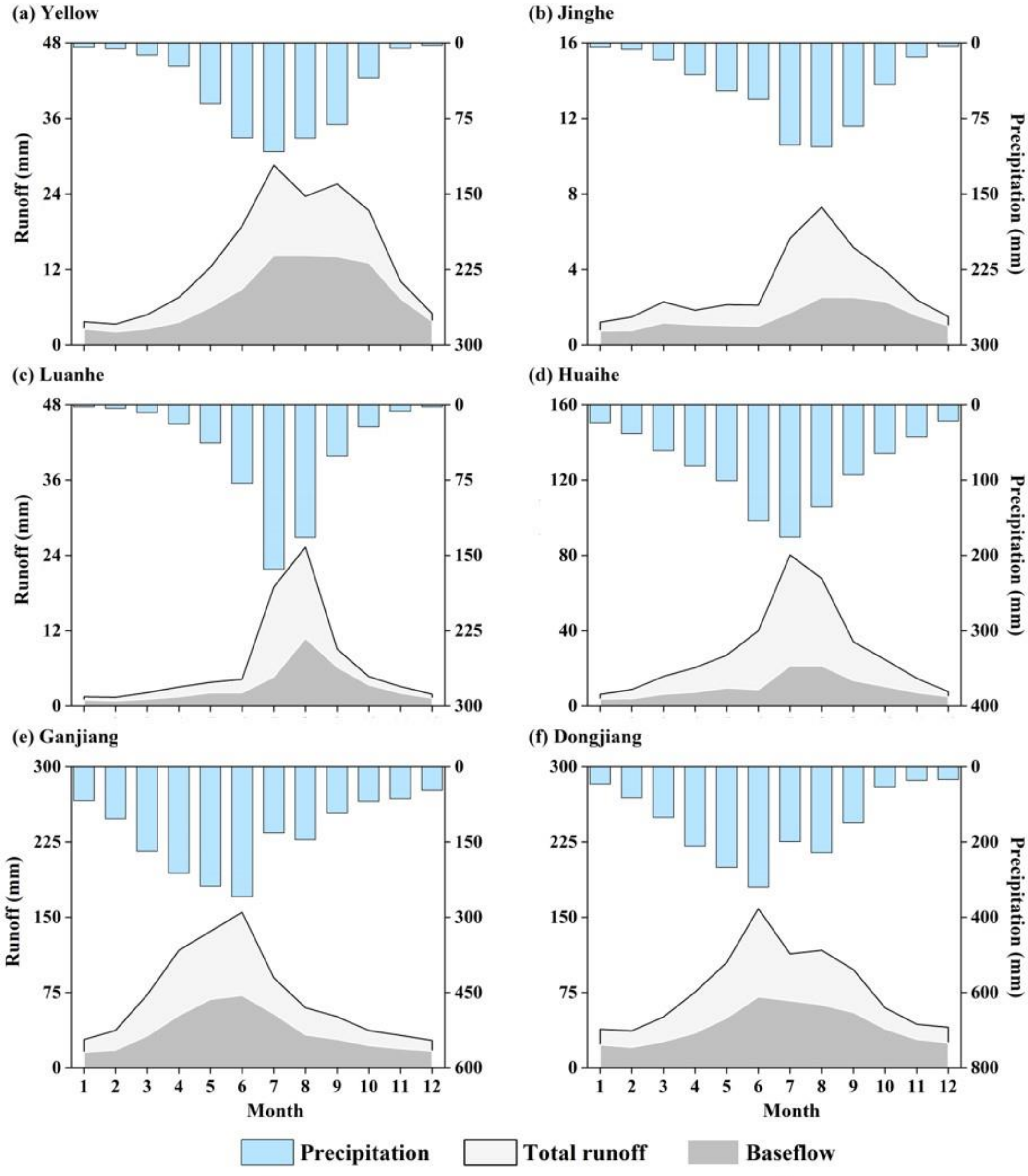

Fig. 2. Monthly precipitation, total runoff, and baseflow across the six basins.

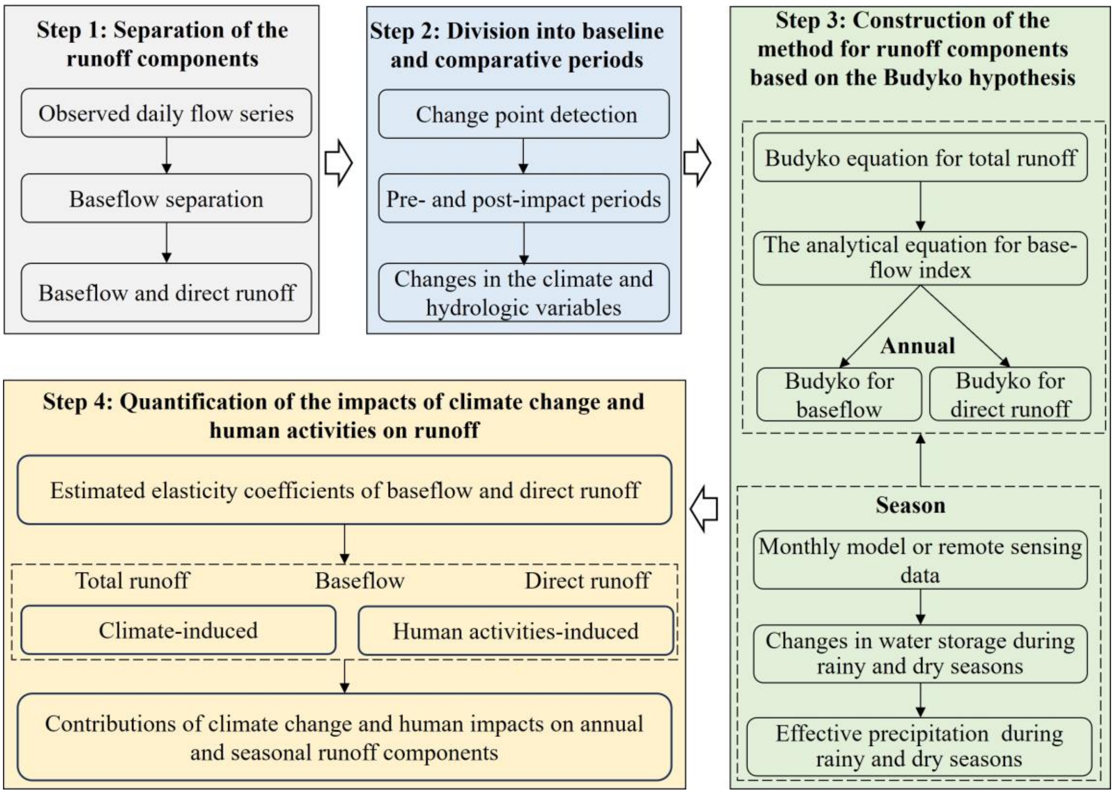

Fig. 3. Flowchart of the comprehensive assessment framework for quantifying the impacts of climate change and human activities on runoff components on annual and seasonal scales.

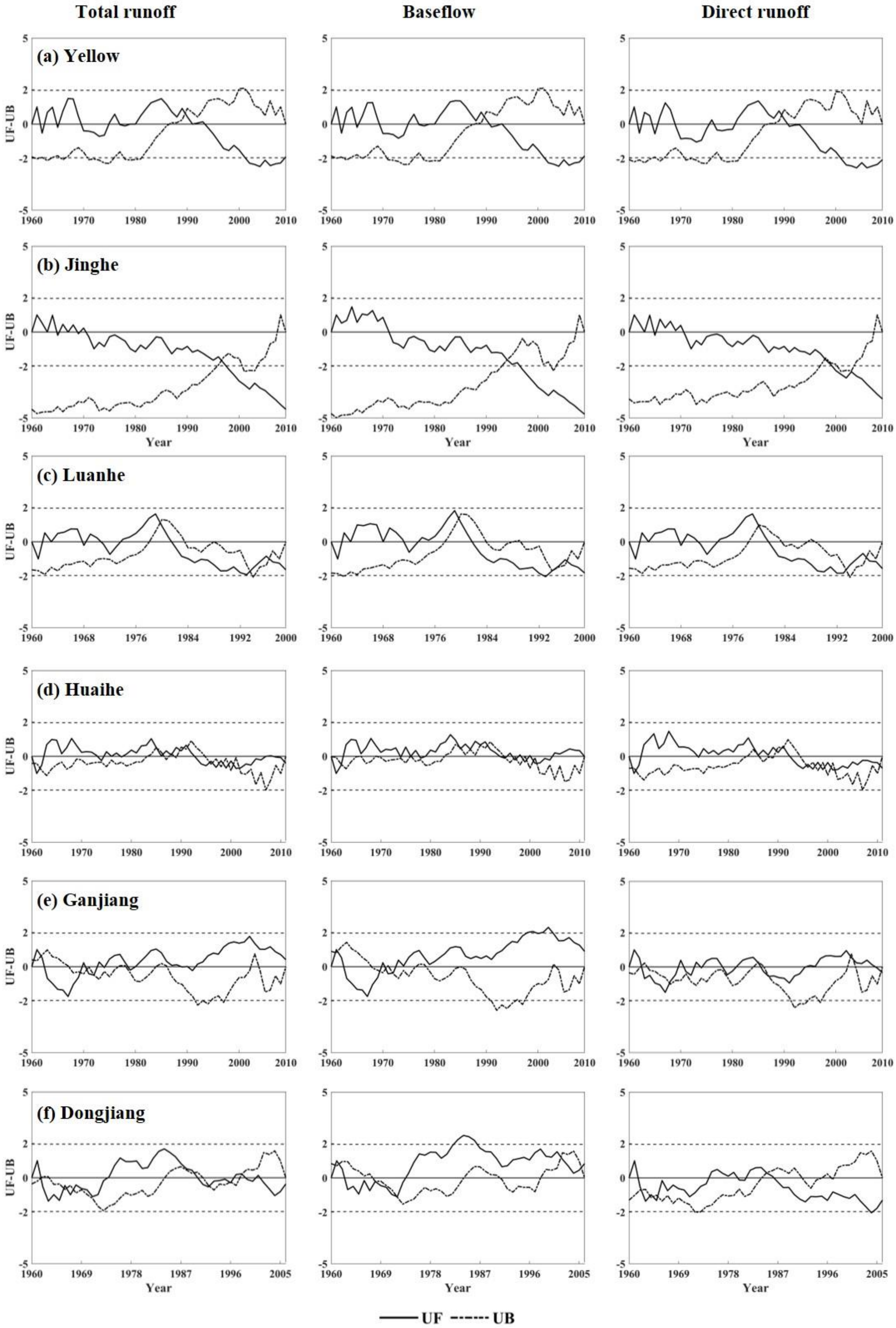

Fig. 4. Mann-Kendall test results for total runoff, baseflow, and direct runoff. The horizontal dashed lines indicate the critical value at the 0.05 significance level.

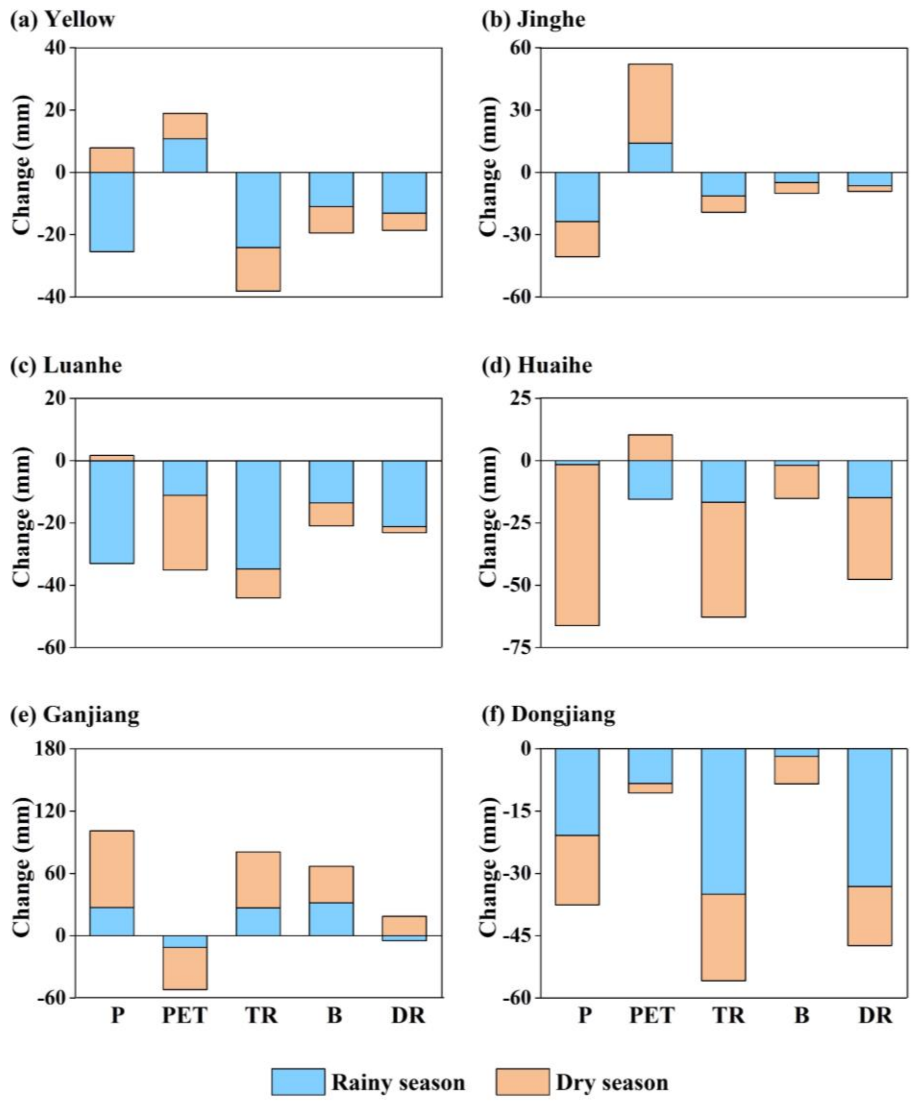

Fig. 5. Changes in precipitation (P), potential evapotranspiration (PET), total runoff (TR), baseflow (B), and direct runoff (DR) before (pre-impact) and after (post-impact).

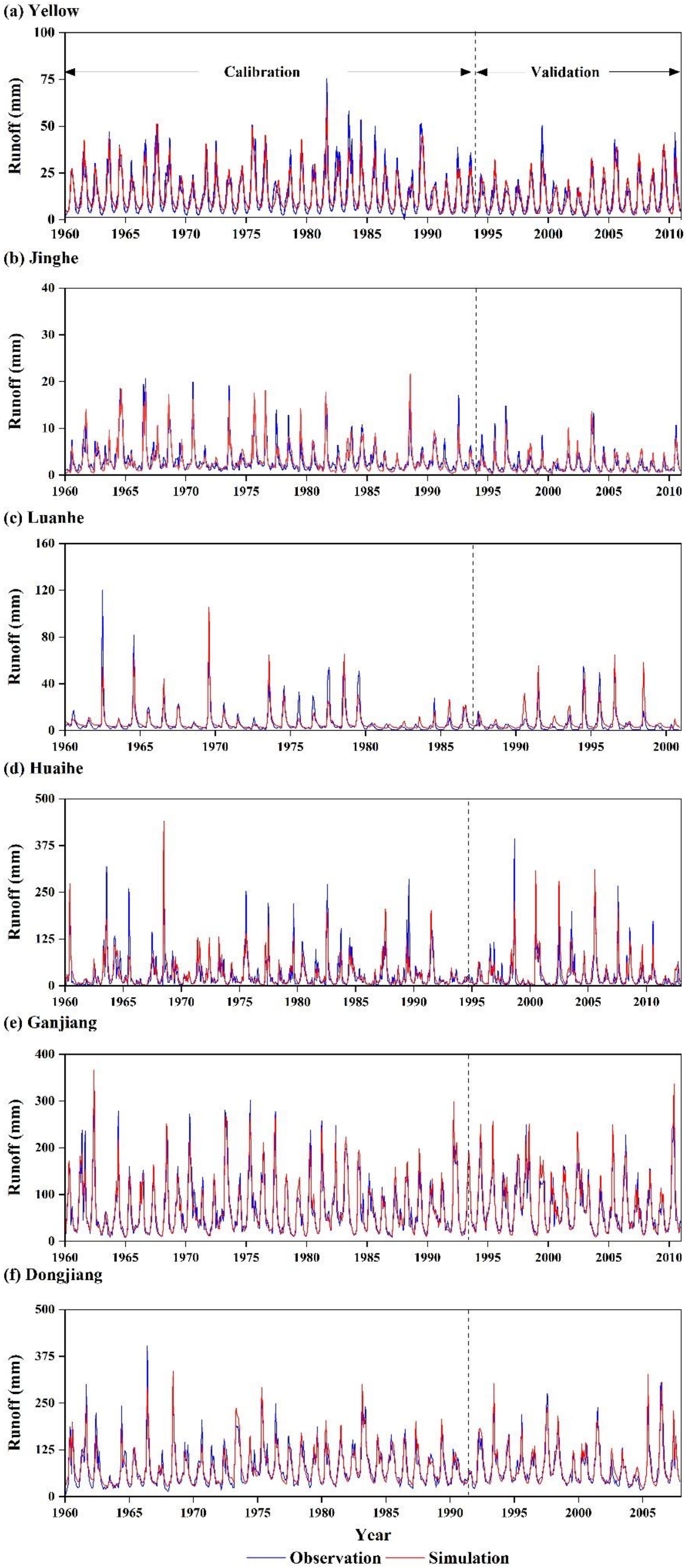
(a) Yellow
Calibration
Validation
Runoff (mm)
(b) Jinghe
Runoff (mm)
(c) Luanhe
Runoff (mm)
(d) Huaihe
Runoff (mm)
(e) Ganjiang
Runoff (mm)
(f) Dongjiang
Runoff (mm)
Year
Observation
Simulation

Fig. 6. Comparison of observed and simulated monthly runoff using the abcd model for the six basins.

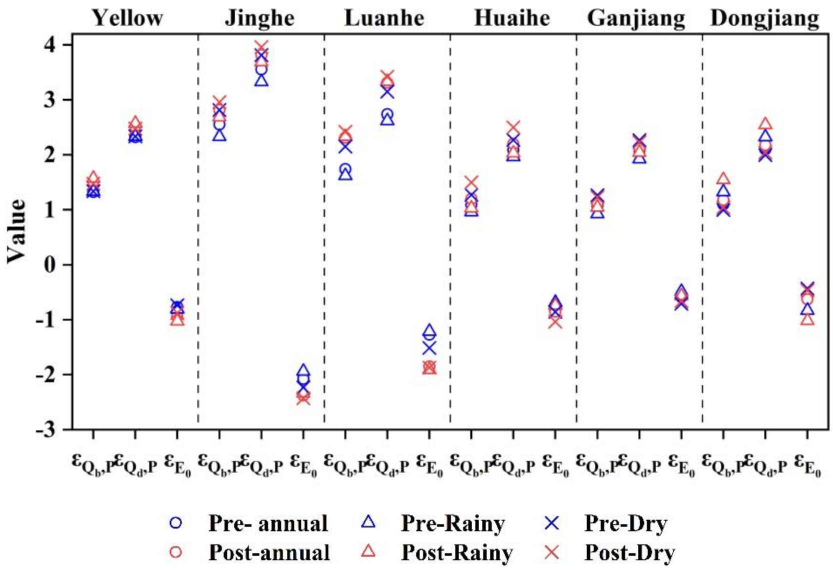

Fig. 7. Estimated elasticities of baseflow and direct runoff to precipitation and potential evapotranspiration in the pre-impact and post-impact periods.

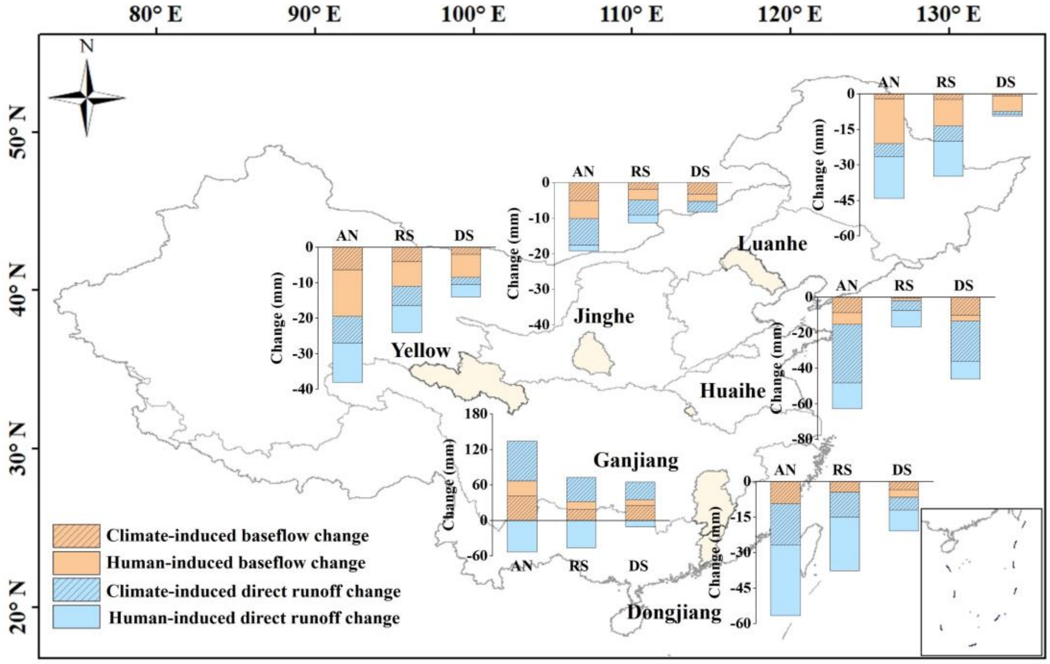

Fig. 8. Impacts of climate change and human activities on baseflow and direct runoff in annual (AN), rainy season (RS), and dry season (DS).

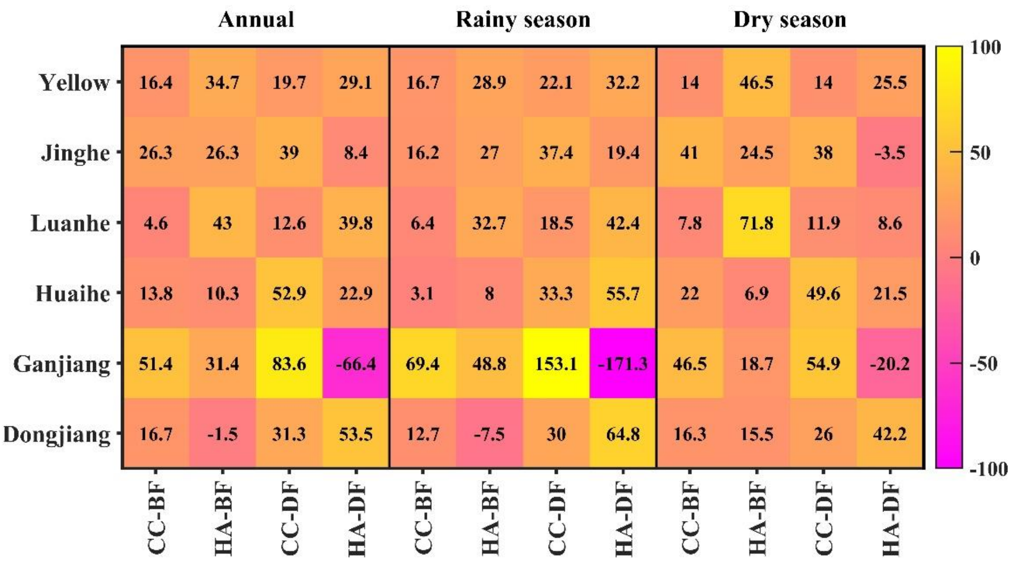

Fig. 9. Quantitative contributions (%) of climate change (CC) and human activities (HA) to baseflow (BF) and direct runoff (DF) in the annual, rainy season, and dry season.

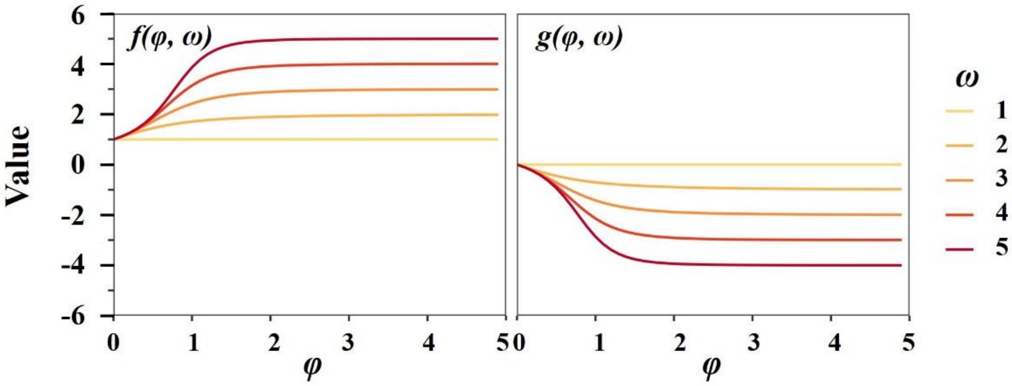

Fig. 10. Theoretical lines for different values of ω.

Declaration of interests

☒The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: