Contributions of Climate Change and Human Activities to Changes in Base Flow and Direct Runoff in the Huai River Basin, China

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Abstract: Neglecting the changes in runoff components, i.e., base flow (Q_b) and direct runoff (Q_d), may lead to inaccurate estimations of the relative influence of climate change and human activities on total runoff (Q). To evaluate this impact, the base-flow Budyko function was used to quantify the contributions of climate change and human activities to the changes in Q_b and Q_d in the Upper and Middle Reach of the Huai River, China. More than five decades (1950s–2018) of continuous daily streamflow observation data from nine subcatchments were analyzed. Results show that the change points of total runoff generally occurred in the 1980s–1990s. Compared to the prechange period, the climate change-induced Q_b and Q_d changes were $-11.6-18.4\ \mathrm{mm\cdot yr^{-1}}$ and $48-78.4\ \mathrm{mm\cdot yr^{-1}}$, respectively, in the postchange period; the human activities-induced Q_b and Q_d changes were $-133.3-65.7\ \mathrm{mm\cdot yr^{-1}}$ and $-127.1-43.1\ \mathrm{mm\cdot yr^{-1}}$, respectively. The contributions of human activities to Q changes at Dapoling, Huangchuan, and Huangweihe increased from 26.2%, 24.4%, and 94.3% (when ignoring changes in runoff components) to 50.5%, 85.5%, and 94.4% (when considering changes in runoff components), respectively. Our results demonstrated that ignoring the runoff component change could result in underestimating the relative contribution of human activities and overestimating that of climate change. This implies that the impact of human activities on total runoff change may be more intensive than currently recognized. This study emphasizes the importance of investigating runoff component changes when conducting runoff change attribution analysis. **DOI: 10.1061/JHYEFF.HEENG-6212.** *© 2024 American Society of Civil Engineers.*

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Introduction

In recent years, climate change and human activities have led to considerable runoff changes (Gudmundsson et al. 2021; Wang et al. 2020; Zhang and Wei 2021) that are expected to have major impacts on human societies (Khan et al. 2017) and ecosystems (Barron et al. 2012). Separating the impacts of climate change and human activities on total runoff has garnered significant attention in hydrological research (Wang et al. 2020; Dai et al. 2023; Liu et al. 2023). However, limited emphasis has been placed on the changes in runoff components (Wang et al. 2020).

Catchment runoff is mainly composed of base flow and direct runoff. Base flow is defined as the portion of streamflow originating from groundwater storage and other delayed sources (Hall 1968) and is crucial for environmental flow regulation (de Graaf et al. 2019; Ebrahim and Villholth 2016), water supply (Hellwig and Stahl 2018; Miller et al. 2021), and contaminant transport (Chen and Ruan 2021; He et al. 2020). Direct runoff stems from overland flow and shallow subsurface flow and is often associated with floods (Blöschl et al. 2019) and soil erosion (Williams 1995). Responses of base flow and direct runoff to environmental changes can often diverge, with one increasing while the other decreases (Price 2011). For instance, land management practices such as conservation tillage, farm ponds, and soil drainage improvement in the Upper Mississippi and Ohio regions of the United States were found to enhance water infiltration into soil, resulting in reduced surface runoff but increased base flow (Kochendorfer and Hubbart 2010; Potter 1991; Xu et al. 2013). Conversely, urbanization, characterized by impervious surface coverage, soil compaction, channelization, and the development of subsurface storm drainage networks, tends to reduce the hydraulic resistance of land surfaces, diminishing infiltration and subsurface recharge, and subsequently increasing surface runoff while decreasing base flow (Chang 2007; Price 2011; Rose and Peters 2001). These findings suggest that changes in base flow and direct runoff may often exhibit opposing trends, partially offsetting each other. Consequently, when changes in runoff components are overlooked, the impacts of climate change and human activities on total runoff may be underestimated. However, the extent to which neglecting changes in runoff components affects the separation of the impacts of climate change and human activities on total runoff has not been thoroughly investigated. To gain a betterer understanding of the relative role of climate change and human activities on water resources, it is essential to distinguish the individual responses of base flow and direct runoff (Bhaskar et al. 2016; Blöschl et al. 2007; Wang et al. 2020).

Various methods have been applied to separate the impacts of climate change and human activities on runoff. These include empirical

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statistics (Liu et al. 2023; Sankarasubramanian et al. 2001; Zheng et al. 2009), hydrological modeling (Dong et al. 2014; Liu et al. 2013), paired catchment analysis (Brown et al. 2005; Xu et al. 2022), and the Budyko framework (Dai et al. 2023; Wang et al. 2020; Yang et al. 2020). The statistical methods require less data and have a straightforward calculation process, but they lack a robust physical basis (Dai et al. 2023). Hydrological models are process-based, but their accuracy and reliability are challenged by heavy reliance on the availability of high-quality data, sensitivity to model parameters, and uncertainties in complex environmental conditions (Zeng et al. 2020). Paired catchment experiments offer a valuable method for a controlled comparison of human impacts on runoff by contrasting disturbed and undisturbed catchments. However, their practicality is constrained by the requirement for highly similar catchments, resource-intensive maintenance, and potential ethical concerns associated with introducing disturbances (Brown et al. 2005). The Budyko framework (Budyko 1974) examines the balance between water supply and demand in a catchment, offering a clear physical concept, concise mechanism, and simple structure (Zeng et al. 2020). It has been widely applied to assess the impacts of climate change and human activities on runoff changes globally, including in the Haihe River Basin (Wang et al. 2013), the Yellow River Basin (Dai et al. 2023; Yang et al. 2020; Zheng et al. 2009), the Loess Plateau (Zhang et al. 2008), South Australia (Zhou et al. 2016), and the continuous United States (Wang and Hejazi 2011). Under the Budyko framework, the mean annual total runoff is a function of mean annual precipitation, evapotranspiration, and a shape parameter that represents the impact of catchment attributes, such as elevation, slope, soil texture, vegetation cover, and subsurface hydraulic conductivity (Chen and Ruan 2023; Yang et al. 2008). Climate change-induced and human activities-induced changes in total runoff can be quantified through differentiation of the Budyko functions (Dey and Mishra 2017). Traditional Budyko functions apply only to total runoff and not to base flow or direct runoff (Xu et al. 2013). Fortunately, in recent years, the Budyko framework has been extended to include base flow and different types of base-flow Budyko functions have been developed, for example, by Meira-Neto et al. (2020), Cheng et al. (2021), and Chen and Ruan (2023). These base-flow Budyko functions provide practicable methods for quantifying the contributions of climate change and human activities to base-flow change and direct runoff change. In this study, the base-flow Budyko function was selected to differentiate between the impacts of climate change and human activities on runoff components.

Over the past five decades, both climate change and human activities have led to significant changes in total runoff in the Huai River Basin, China (An and Hao 2017; Zhu et al 2015). Extreme floods are more frequent during the wet season (Gao and Ruan 2018) and ecological flows are threatened during the base-flow period (Pan 2014). However, the contributions of climate change and human activities to changes in base flow and direct runoff are still unclear. Therefore, the aims of this study are to: (1) quantify the individual responses of base flow and direct runoff to climate change and human activities in the Huai River Basin, and (2) assess the extent to which neglecting changes in runoff components affects the relative role of climate change and human activities on total runoff. This study provides valuable insights into the detailed hydrological responses to environmental changes and offers useful reference information for effective water resources management. The paper is organized as follows: the study area and data sources are introduced in the "Study Area and Data" section. The "Methods" section presents the methods used to separate base flow from total runoff, detect trends and change points, and quantify runoff component changes induced by climate change and human activities. "Results," "Discussion," and "Conclusions" are presented in following sections.

Study Area and Data

Study Area

Our study area is the Upper and Middle Reach of the Huai River (UMRHR) in China [Fig. 1(a)], which has a surface area of about 120,000 km^2. Plains cover two-thirds of the study area and are surrounded by hills and mountains to the northwest, west, and southwest. Groundwater is mainly found in pore aquifers in the plains at a depth of 2–4 m (Gong et al. 2021). The mean annual precipitation varies across the study area and is 400–800 $mm \cdot yr^{-1}$ to the north of the Huai River and 800–1,600 $mm \cdot yr^{-1}$ to the south of the Huai River (Pan 2014). The UMRHR is an important agricultural region in eastern China. Rice, wheat, and maize are the main crops. In 2020, agricultural land accounted for 68% of the total watershed area [Fig. 1(c)] and agricultural irrigation accounted for 62% of the total water usage (The Huai River Commission of the Ministry of Water Resources, P.R.C. 2021). Southern UMRHR is humid and has abundant surface water resources for irrigation, while northern UMRHR is arid and groundwater is the main water source for irrigation. Climate change and human activities have considerably altered the hydrological cycle of the UMRHR in recent years, threatening the safety of water supply and food production (An and Hao 2017).

Data

More than five decades of continuous daily streamflow observation data from nine subcatchments were analyzed [Fig. 1(b)]. The data series that were used started at various times between 1956 and 1965, and our analyses included all data up to 2018 (Table 1). Daily streamflow data were provided by the Bureau of Hydrology of the Huai River Commission of the Ministry of Water Resources. We used annual precipitation data and potential evapotranspiration data from the 1-km monthly precipitation data set for China (1901–2021) (Peng 2020) and the 1-km monthly potential evapotranspiration data set in China (1901–2022) (Peng 2022), respectively.

The spatial distributions of mean annual precipitation, potential evapotranspiration, and aridity index of the UMRHR are shown in Fig. S1. The mean annual precipitation is lower in the north and higher in the south, while the mean annual potential evapotranspiration and aridity index are higher in the north and lower in the south. The annual total runoff time series of the nine subcatchments are shown in Fig. 2, and the annual precipitation and annual potential evapotranspiration time series are shown in Fig. S2, respectively. Table 1 shows the different hydrological conditions in the nine subcatchments. The mean annual precipitation, potential evapotranspiration, and total runoff were 652.2–1,499.7, 1,011.3–1,170.2, and 88.5–1,053.5 $mm \cdot yr^{-1}$, respectively. The aridity index ranged from 0.67 to 1.78.

Methods

Base Flow Separation

Because no direct approach exists for continuously measuring the base flow, five base-flow separation methods were applied to the daily total runoff time series—the revised United Kingdom Institute of Hydrology (UKIH) method (Piggott et al. 2005), three HYdrograph SEParation (HYSEP) methods (fixed-interval, sliding-interval, and local-minimum) (Sloto and Crouse 1996), and the Lyne-Hollick (L–H) digital filter method (Lyne and Hollick 1979). The digital filter with a filter parameter of 0.925 was applied forward, backward, and forward again as recommended by

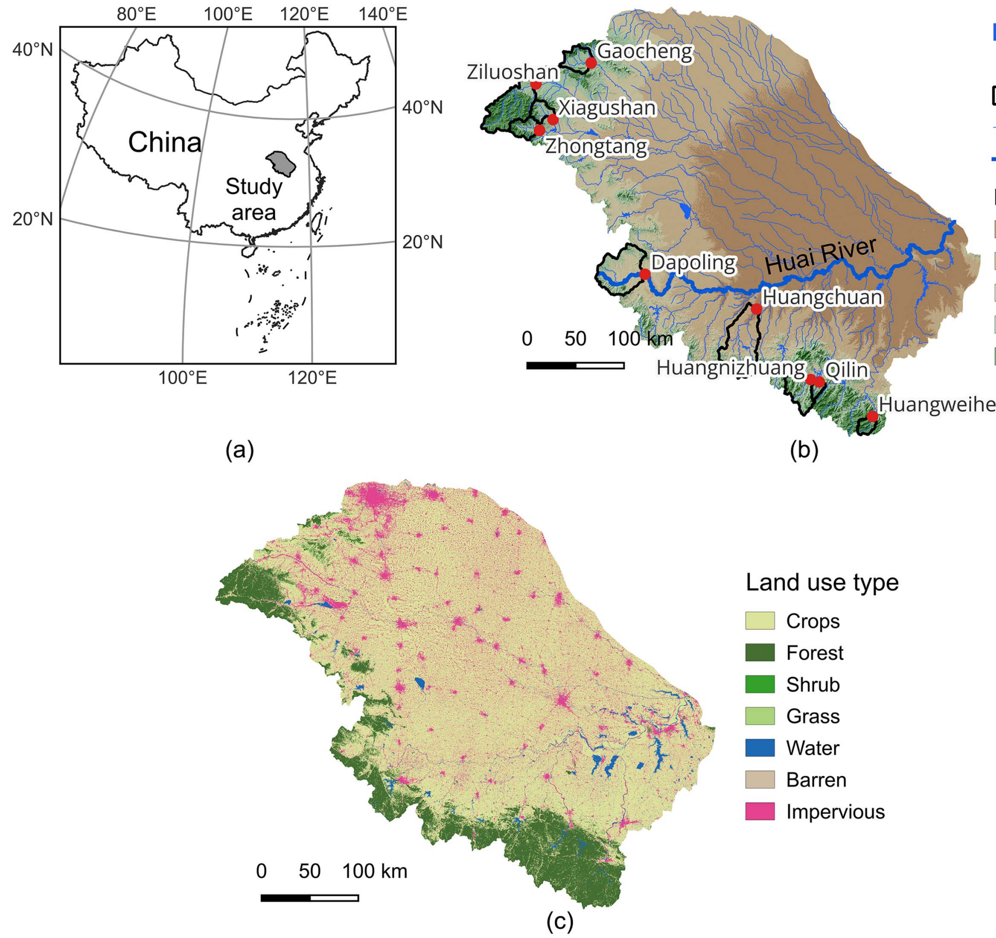

Fig. 1. (a) Location of the study area; (b) distribution of the selected subcatchments [base map courtesy of Caltech/JPL (ASTER GDEMV3)]; and (c) land use type (data from Yang and Huang 2021).

Table 1. Hydrological conditions and analysis periods of the study subcatchments

ID	Station	Area (km^2)	Mean annual precipitation ($mm \cdot yr^{-1}$)	Mean annual potential evapotranspiration ($mm \cdot yr^{-1}$)	Mean annual runoff ($mm \cdot yr^{-1}$)	Aridity index	Start year	End year	Length
1	Gaocheng	627	652.2	1,160.7	88.5	1.78	1965	2018	54
2	Ziluoshan	1,880	664.6	1,098.5	228.5	1.65	1956	2018	63
3	Xiagushan	354	788.2	1,168.6	272.6	1.48	1962	2018	57
4	Zhongtang	485	928.1	1,108.4	388.2	1.19	1961	2018	58
5	Dapoling	1,640	984.6	1,170.2	355.9	1.19	1956	2018	63
6	Huangchuan	2,050	1,013.9	1,152.7	436.5	1.14	1956	2018	63
7	Huangnizhuang	805	1,390.6	1,064.7	642.5	0.77	1958	2018	61
8	Qilin	185	1,386.1	1,091.5	773.8	0.79	1964	2018	55
9	Huangweihe	270	1,499.7	1,011.3	1,053.5	0.67	1958	2018	61

Nathan and McMahon (1990). As suggested by Zhang et al. (2020), we used the average of the outputs from the five methods and considered it as the referenced daily base flow to minimize uncertainties that could be introduced by using different methods (Fig. 3). The daily direct runoff was then computed as the difference between the total runoff and the referenced daily base flow. The daily base flow and direct runoff were then aggregated to annual values.

Trend Analysis and Change Point Detection

In studying the effects of climate change and human activities on runoff, the first challenge is to distinguish the reference period (when these impacts are negligible) from the interference period (when these impacts are significant). In this study, the nonparametric Mann–Kendall test was used to detect monotonic trends in the time series of annual total runoff, base flow, and direct runoff. Trend magnitude was quantified using Sen's slope, which indicates

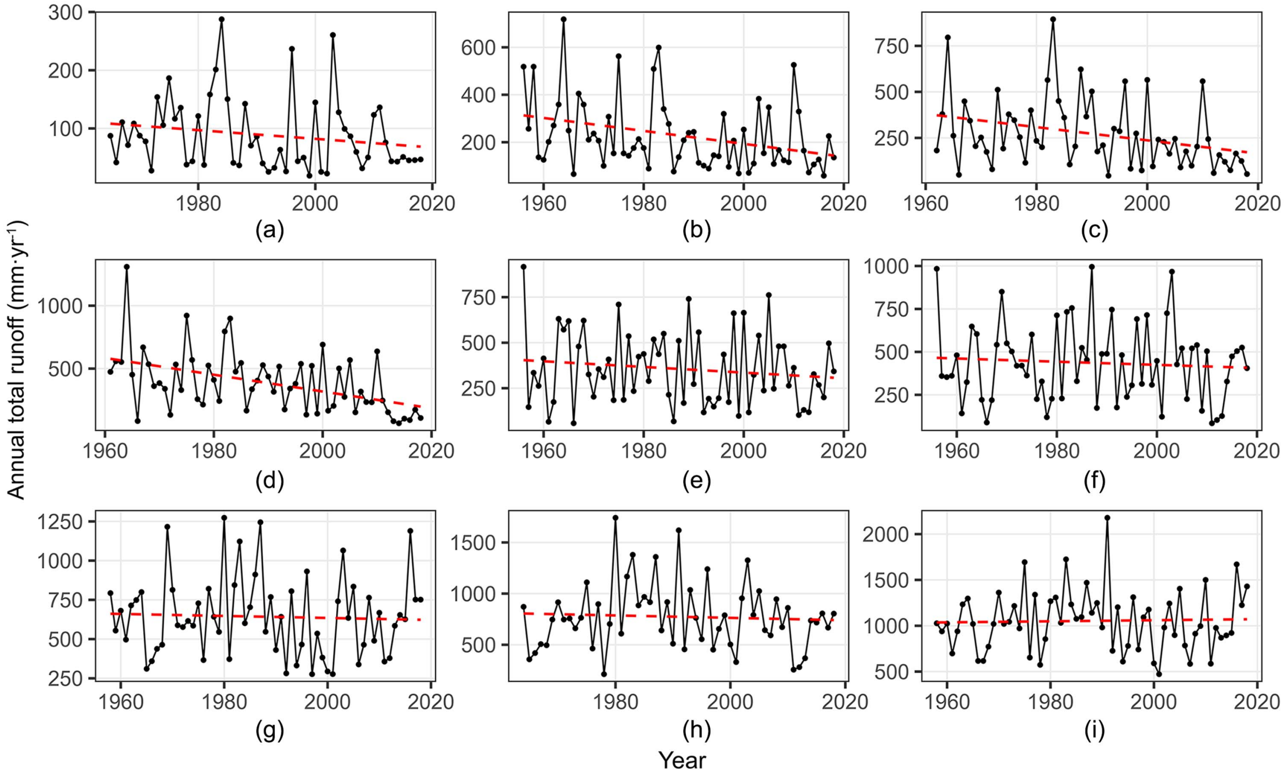

Fig. 2. Annual total runoff time series in (a) Gaocheng; (b) Ziluoshan; (c) Xiagushan; (d) Zhongtang; (e) Dapoling; (f) Huangchuan; (g) Huangnizhuang; (h) Qilin; and (i) Huangweihe. The dashed lines represent the linear trend of the annual total runoff time series.

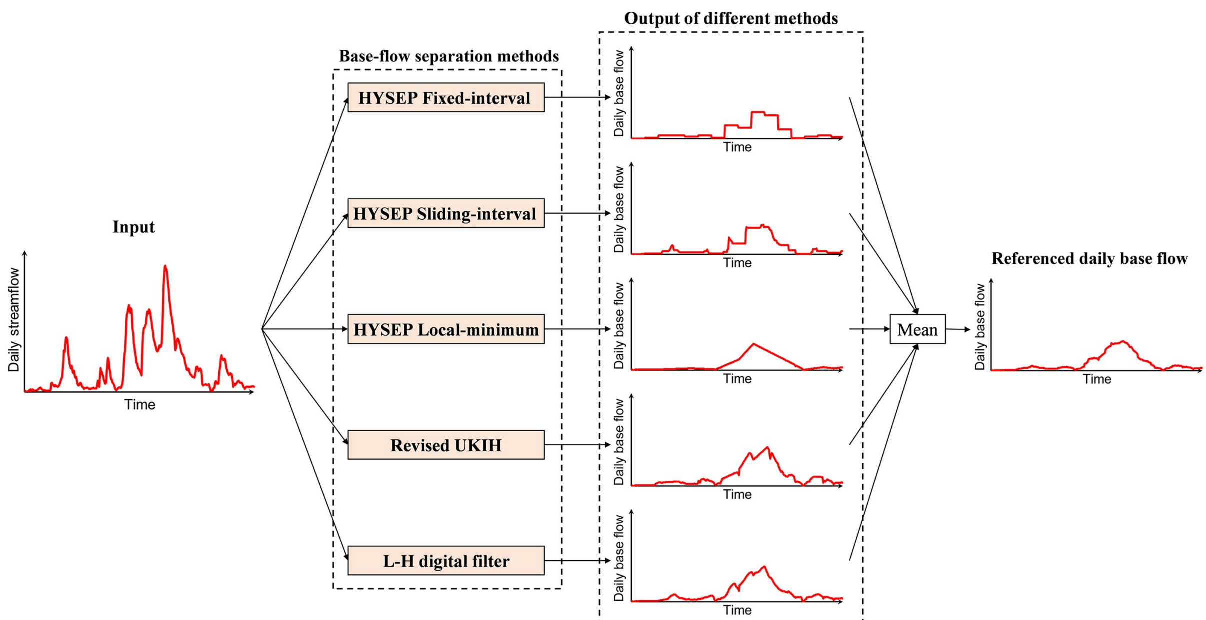

Fig. 3. Flowchart for calculation of the referenced base flow.

the linear rate of change (Helsel et al. 2020). Pettitt's test (Pettitt 1979) was used to detect the change point in the time series of annual total runoff, base flow, and direct runoff. Results were used to divide the analysis periods into prechange and postchange periods. The Mann–Kendall test and Pettitt's test were conducted using the trend package (Pohlert 2023) in R software (R Core Team 2022).

Quantifying Changes in Runoff Components Induced by Climate Change and Human Activities

Under the Budyko (1974) framework and the assumption of negligible mean annual changes in catchment storage, the runoff coefficient (ratio of total runoff to precipitation, Q/P) can be expressed as a function of the aridity index (ratio of potential evapotranspiration to precipitation; E_P/P); Fu's equation (Fu 1981) is one example

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

where ω (≥ 1) = shape parameter that accounts for the influence of catchment characteristics (Zhou et al. 2015); and φ = aridity index

$$\varphi = E_P/P \tag{2}$$

Assuming that base flow (Q_b) is proportional to subsurface water storage and direct runoff (Q_d) is proportional to P and the relative subsurface water storage, Chen and Ruan (2023) proposed that the base-flow index (BFI), i.e., the ratio of Q_b to Q, can be expressed as a function of P and a conceptual parameter α at the mean annual scale

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

where α = catchment storage capacity. Combining Eqs. (1) and (3), the base-flow coefficient (BFC), i.e., the ratio of Q_b to P, can be written as

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

Following Eqs. (1) and (4), the mean annual Q_b and Q_d can be expressed as functions of mean annual P, E_P, ω, and α as follows:

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

$$Q_d = P \cdot \left(\left(1+\left(\frac{E_P}{P}\right)^{\omega}\right)^{\frac{1}{\omega}} - \frac{E_P}{P}\right) \cdot \frac{P}{P+\alpha} \tag{6}$$

The changes in Q_b and Q_d resulting from climate change (i.e., changes in P and E_P) can be estimated through the first-order differentiation of Eqs. (5) and (6)

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

$$\Delta Q_d^C = Q_d \cdot \left(\varepsilon_{Q_d,P} \cdot \frac{\Delta P}{P} + \varepsilon_{Q_d,E_P} \cdot \frac{\Delta E_P}{E_P}\right) \tag{8}$$

where Δ = change in a variable between the prechange and postchange periods; ΔQ_b^C and ΔQ_d^C = changes in Q_b and Q_d induced by climate change, respectively; ΔP and ΔE_P = changes in P and E_P, respectively; ε = elasticities of Q_b or Q_d to changes in P or E_P, indicating the percent change in Q_b or Q_d due to a 1% change in P or E_P (Berghuijs et al. 2017). Assuming that P is independent of E_P and that both P and E_P are independent of ω and α (Zhou et al. 2016), $\varepsilon_{Q_b,P}$, $\varepsilon_{Q_d,P}$, ε_{Q_b,E_P}, and ε_{Q_d,E_P} can be derived from Eqs. (5) and (6)

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

$$\varepsilon_{Q_d,P} = \frac{\partial Q_d/Q_d}{\partial P/P} = f(\varphi,\omega) + \frac{\alpha}{P+\alpha} \tag{10}$$

$$\varepsilon_{Q_b,E_P} = \varepsilon_{Q_d,E_P} = \frac{\partial Q_b/Q_b}{\partial E_P/E_P} = \frac{\partial Q_d/Q_d}{\partial E_P/E_P} = g(\varphi,\omega) \tag{11}$$

where

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

$$g(\varphi,\omega) = \frac{\varphi^{\omega} \cdot (1+\varphi^{\omega})^{\frac{1}{\omega}-1} - \varphi}{(1+\varphi^{\omega})^{\frac{1}{\omega}} - \varphi} \tag{13}$$

Because elasticities vary with P, E_P, ω, and α, the following equations were used to calculate ΔQ_b^C and ΔQ_d^C (Zhou et al. 2016):

$$\begin{aligned}\Delta Q_b^C = {} & \gamma \cdot Q_{b,1} \cdot \left((\varepsilon_{Q_b,P})_1 \cdot \frac{\Delta P}{P_1} + (\varepsilon_{Q_b,E_P})_1 \cdot \frac{\Delta E_P}{E_{P,1}}\right) \\ & + (1-\gamma) \cdot Q_{b,2} \cdot \left((\varepsilon_{Q_b,P})_2 \cdot \frac{\Delta P}{P_2} + (\varepsilon_{Q_b,E_P})_2 \cdot \frac{\Delta E_P}{E_{P,2}}\right)\end{aligned} \tag{14}$$

$$\begin{aligned}\Delta Q_d^C = {} & \gamma \cdot Q_{d,1} \cdot \left((\varepsilon_{Q_d,P})_1 \cdot \frac{\Delta P}{P_1} + (\varepsilon_{Q_d,E_P})_1 \cdot \frac{\Delta E_P}{E_{P,1}}\right) \\ & + (1-\gamma) \cdot Q_{d,2} \cdot \left((\varepsilon_{Q_d,P})_2 \cdot \frac{\Delta P}{P_2} + (\varepsilon_{Q_d,E_P})_2 \cdot \frac{\Delta E_P}{E_{P,2}}\right)\end{aligned} \tag{15}$$

where γ = coefficient ranging from 0 to 1, variables with subscripts 1 and 2 refer to the variables in the prechange and postchange periods, respectively. The value of γ was set to 0.5, as recommended by Zhou et al. (2016). After calculating ΔQ_b^C and ΔQ_d^C using Eqs. (14) and (15), the changes in Q_b and Q_d resulting from human activities can be estimated by

$$\Delta Q_b^H = \Delta Q_b - \Delta Q_b^C \tag{16}$$

$$\Delta Q_d^H = \Delta Q_d - \Delta Q_d^C \tag{17}$$

where ΔQ_b^H and ΔQ_d^H = changes in Q_b and Q_d induced by human activities, respectively; ΔQ_b and ΔQ_d = observed changes in Q_b and Q_d, respectively.

The parameters ω and α need to be estimated before using Eqs. (14) and (15) to calculate ΔQ_b^C and ΔQ_d^C. In this study, ω and α in the prechange and postchange periods were inversely calculated by using Eqs. (1) and (3), respectively.

Assessing the Relative Contributions of Climate Change and Human Activities

The following equation was used to calculate the relative contributions of climate change and human activities to Q changes on the basis of the changes in the runoff components of base flow and direct runoff

$$\theta^X = \frac{|\Delta Q_b^X| + |\Delta Q_d^X|}{|\Delta Q_b^C| + |\Delta Q_d^C| + |\Delta Q_b^H| + |\Delta Q_d^H|} \times 100\% \tag{18}$$

where θ^X = contribution of X (climate change or human activities) to runoff changes. The following equation was used when only total runoff was considered and the runoff components of base flow and direct runoff were ignored

$$\theta^X = \frac{|\Delta Q^X|}{|\Delta Q^C| + |\Delta Q^H|} \times 100\% \tag{19}$$

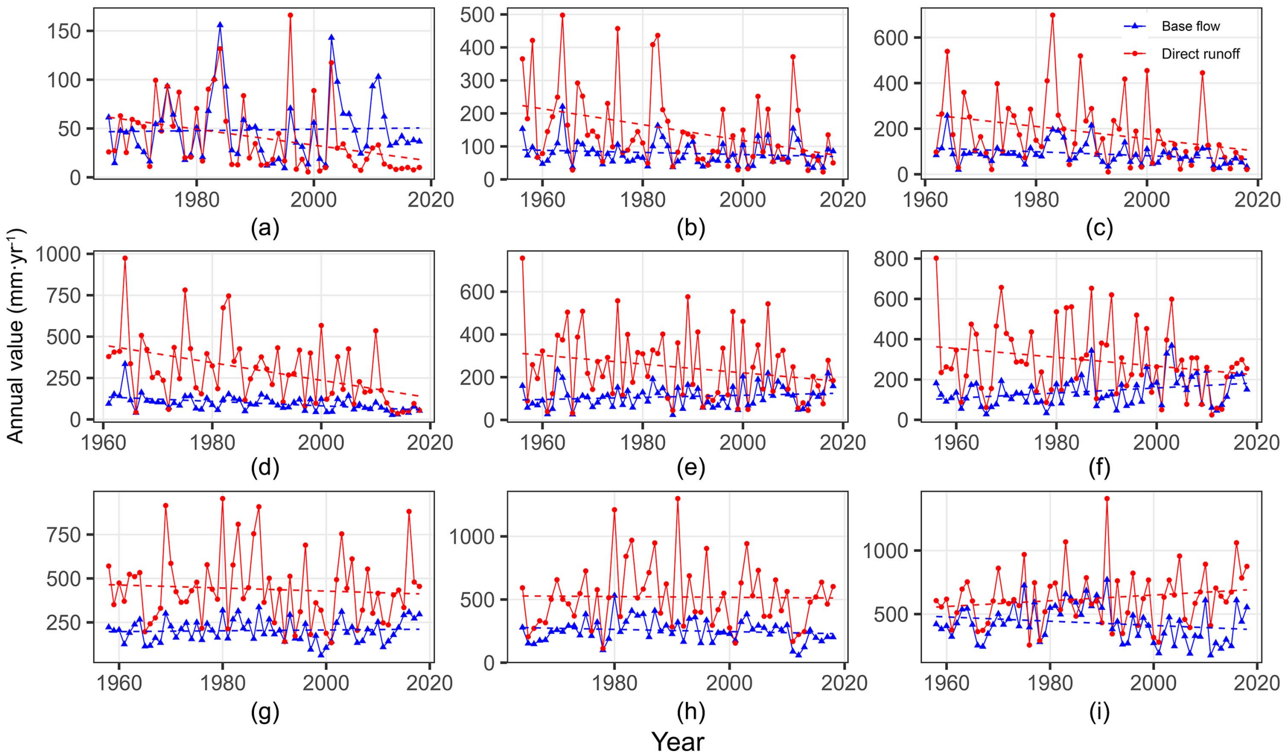

Fig. 4. Annual base-flow and direct runoff time series at (a) Gaocheng; (b) Ziluoshan; (c) Xiagushan; (d) Zhongtang; (e) Dapoling; (f) Huangchuan; (g) Huangnizhuang; (h) Qilin; and (i) Huangweihe.

Results

Base Flow and Direct Runoff

Fig. 4 and Table 2 show the results of base-flow separation. The mean annual Q_b and Q_d varied from 48.6 and 39.9 $\mathrm{mm \cdot yr^{-1}}$, respectively, at Gaocheng to 430.7 and 622.8 $\mathrm{mm \cdot yr^{-1}}$, respectively, at Huangweihe. The BFI was the lowest at Zhongtang with a value of 0.25, which is in the south, and the highest at Gaocheng with a value of 0.55, which is in the north. The average BFI value of the nine subcatchments was 0.35, which generally agrees with the findings of Pan (2014) and Chen and Ruan (2021). They reported mean annual BFI values ranging from 0.26 to 0.38 in the UMRHR. The BFC was the lowest at Gaocheng with a value of 0.07 in the north and the highest at Huangweihe with a value of 0.29 in the south.

Table 2. Mean annual base flow, direct runoff, BFI, and BFC for the nine study subcatchments

ID	Station	Mean annual base flow ($\mathrm{mm \cdot yr^{-1}}$)	Mean annual direct runoff ($\mathrm{mm \cdot yr^{-1}}$)	Base-flow index	Base-flow coefficient
1	Gaocheng	48.6	39.9	0.55	0.07
2	Ziluoshan	79.5	149.1	0.35	0.12
3	Xiagushan	90.1	182.6	0.33	0.11
4	Zhongtang	96.2	292.0	0.25	0.10
5	Dapoling	108.9	247.0	0.31	0.11
6	Huangchuan	141.7	294.8	0.32	0.14
7	Huangnizhuang	204.1	438.5	0.32	0.14
8	Qilin	253.8	520.0	0.33	0.18
9	Huangweihe	430.7	622.8	0.41	0.29

Temporal Changes of Runoff Components

The trend in annual Q was negative at all stations except Huangweihe (Fig. 2); trends ranged from −6.29 to −0.49 $\mathrm{mm \cdot yr^{-2}}$ (Table 3). The trends at Ziluoshan, Xiagushan, and Zhongtang were statistically significant ($p < 0.01$), and trend magnitudes were large. The trend of annual Q at Huangweihe was 0.21 $\mathrm{mm \cdot yr^{-2}}$. The change points of the annual Q time series generally occurred in the 1980s and 1990s and were used to define the prechange and postchange periods. The trends of annual Q_b varied from −1.82 to 1.16 $\mathrm{mm \cdot yr^{-2}}$; they were negative at Ziluoshan, Xiagushan, Zhongtang, Qilin, and Huangweihe and positive at Gaocheng, Dapoling, Huangchuan, and Huangnizhuang (Fig. 4; Table 3). The change points of the annual Q_b time series generally occurred in the 1990s at most stations and occurred in the 1980s, 2000s, and 2010s at the remaining stations. The trends in annual Q_d at Qilin and Huangweihe were 0.42 and 1.95 $\mathrm{mm \cdot yr^{-2}}$, respectively. The trends at all other stations were negative and varied from −5.26 to −0.59 $\mathrm{mm \cdot yr^{-2}}$ (Fig. 4; Table 3). The trends at Gaocheng, Ziluoshan, Xiagushan, and Zhongtang were statistically significant. The change points of the annual Q_d time series generally occurred in the 1980s and 1990s. Table 3 shows that although the trends in annual Q at Gaocheng, Dapoling, Huangchuan, and Huangweihe are not statistically significant, the trends in annual base flow (e.g., Huangchuan, and Huangweihe) or direct runoff (e.g., Gaocheng, Dapoling, and Huangweihe) are statistically significant. This demonstrates that no statistically significant trend in Q does not mean there is no statistically significant trend in runoff components.

Table 4 shows the mean annual values of Q, Q_b, Q_d, P, E_P, ω, and α for the periods before and after the change points and the amount of change between the two periods; ΔQ ranged from −200.4 to 154.7 $\mathrm{mm \cdot yr^{-1}}$; ΔQ_b ranged from −132 to

Table 3. Results of Mann–Kendall trend test and Pettitt's test for change point detection

ID	Station	Total runoff		Base flow		Direct runoff		Selected change point
		Slope ($mm \cdot yr^{-2}$)	Change point	Slope ($mm \cdot yr^{-2}$)	Change point	Slope ($mm \cdot yr^{-2}$)	Change point	
1	Gaocheng	−0.69	1985	0.07	2002	-0.59^{***}	1985^{***}	1985
2	Ziluoshan	-2.22^{***}	1985^{**}	−0.27	1985	-1.95^{***}	1985^{***}	1985
3	Xiagushan	-3.33^{***}	1996^{**}	-0.78^{**}	1990^{**}	-2.54^{***}	1996^{***}	1996
4	Zhongtang	-6.29^{***}	1996^{***}	-1.19^{***}	1991^{***}	-5.26^{***}	1996^{***}	1996
5	Dapoling	−1.49	1991^{*}	0.50	1999	-1.66^{*}	1984	1991
6	Huangchuan	−0.65	1997^{*}	1.16^{**}	1997	−1.92	1991	1997
7	Huangnizhuang	−0.50	1989	0.26	2013	−0.80	1989^{*}	1989
8	Qilin	−0.49	1979^{*}	−0.70	2010	0.42	1978	1979
9	Huangweihe	0.21	1991	-1.82^{*}	1991^{***}	1.95^{*}	2001	1991

Note: ***, **, and * indicate statistical significance with $p < 0.01$, $p < 0.05$, and $p < 0.1$, respectively.

60.4 $mm \cdot yr^{-1}$; and ΔQ_d ranged from −161.7 to 121.5 $mm \cdot yr^{-1}$; ΔP ranged from −85.6 to 115.6 $mm \cdot yr^{-1}$; and ΔE_P ranged from −11.0 to 9.3 $mm \cdot yr^{-1}$; $\Delta\omega$ ranged from −0.2 to 0.6; and $\Delta\alpha$ ranged from −322.9 to 390.2 mm. The largest absolute changes in Q, Q_b, Q_d, P, E_P, ω, and α were found at Zhongtang, Huangweihe, Zhongtang, Qilin, Qilin, Zhongtang, and Huangchuan, respectively.

Effects of Climate Change and Human Activities on Runoff Components

The elasticities of Q_b and Q_d to climate change in the prechange and postchange periods were estimated using Eqs. (9)–(13), respectively (Table 5). In the prechange period, the ranges of $\varepsilon_{Q_b,P}$ and $\varepsilon_{Q_d,P}$ were 0.64–1.78 and 1.64–2.78, respectively; ε_{Q_b,E_P} ranged from −1.30 to −0.20, and ε_{Q_d,E_P} ranged from −1.30 to −0.20. In the postchange period, the ranges of $\varepsilon_{Q_b,P}$ and $\varepsilon_{Q_d,P}$ were 0.67–2.28 and 1.67–3.28, respectively; ε_{Q_b,E_P} ranged from −1.67 to −0.31; and ε_{Q_d,E_P} ranged from −1.67 to −0.31.

The climate change-induced and human activities-induced changes in runoff components were calculated using Eqs. (14) and (15), respectively, with a γ of 0.5 (Table 6). At all stations except Qilin and Huangweihe, climate change resulted in decreases in Q_b (2.9–11.6 $mm \cdot yr^{-1}$) and Q_d (3.8–48.0 $mm \cdot yr^{-1}$). At Qilin, climate change resulted in Q_b and Q_d increasing by 18.4 and 78.4 $mm \cdot yr^{-1}$, respectively. At Huangweihe, climate change resulted in Q_b and Q_d increasing by 1.3 and 6.7 $mm \cdot yr^{-1}$, respectively. For a particular station, it was observed that ΔQ_b^C and ΔQ_d^C had the same sign, indicating that changes in Q_b and Q_d in response to climate change were in the same direction for a given catchment. Human activities resulted in Q_b decreasing by 4.3–133.3 $mm \cdot yr^{-1}$ at all the stations except Dapoling, Huangchuan, and Qilin, where ΔQ_b^H was 17.9, 65.7, and 14.8 $mm \cdot yr^{-1}$, respectively; human activities resulted in Q_d decreasing by 25.0–127.1 $mm \cdot yr^{-1}$ at all the stations except Qilin and Huangweihe, where ΔQ_d^H was 43.1 and 1.3 $mm \cdot yr^{-1}$, respectively. At Dapoling, Huangchuan, and Huangweihe, the sign of ΔQ_b^H was different from that of ΔQ_d^H, indicating that human activities had an opposite impact on Q_b and Q_d.

Fig. 5 shows the relative contributions of climate change and human activities to Q changes in the study subcatchments by considering only total runoff change and ignoring changes in the runoff components of base flow and direct runoff [Fig. 5(a)] and by considering changes in the runoff components [Fig. 5(b)]. When ignoring changes in runoff components, climate change was the main contributor to Q changes at Dapoling, Huangchuan, Huangnizhuang, and Qilin, where climate change contributed to 73.8%, 75.6%, 53.7%, and 62.6% of Q changes, respectively [Fig. 5(a)]. Human activities were the main contributor to Q changes for the other subcatchments, where climate change only contributed to 5.7%–22.1% of Q changes. Compared to Fig. 5(a), Fig. 5(b) shows that when considering changes in runoff components, the contributions of human activities to Q changes at Dapoling, Huangchuan, and Huangweihe increased from 26.2%, 24.4%, and 94.3% to 50.5%, 85.5%, and 94.4%, respectively. Human activities became the main contributor to Q changes at Dapoling and Huangchuan, where climate change was the main contributor if ignoring changes in runoff components. Our results demonstrated that ignoring the runoff component change might result in underestimating the relative contribution of human activities and overestimating that of climate change. This is because human activities could have opposite impacts on Q_b and Q_d (Table 6).

Discussion

Factors Driving Runoff Change

Our study showed that human activities were the main contributor to runoff change in the UMRHR, where human activities accounted for 50.5%–94.4% of total runoff change in 7 out of 9 subcatchments. The contribution of human activities to runoff change was found to be greater than that of climate change in many other regions, such as the upper and middle reaches of the Yellow River (Dai et al. 2023; Liu et al. 2023; Yang et al. 2020), the Haihe River Basin (Wang et al. 2013), and Central Poland (Senbeta and Romanowicz 2021). Wang et al. (2020) performed a metaanalysis based on 1,321 global catchment cases and found that total runoff changes due to climate change and human activities were 3.6 ± 48.1 $mm \cdot yr^{-1}$ and -15.5 ± 44.4 $mm \cdot yr^{-1}$, respectively, indicating that human activities were the main driver of total runoff change over the past decades. Wang and Hejazi (2011) found that among 431 watersheds in the contiguous United States, there are 146 (33.9%) watersheds where human activities were the main contributor. However, these studies did not inspect the changes in base flow and direct runoff, which could lead to an underestimation of the relative contribution of human activities according to our findings. Therefore, the impact of human activities on total runoff change may be more intensive than currently recognized.

Compared to the absolute values of ΔE_P (Table 4), ε_{Q_b,E_P}, and ε_{Q_d,E_P} (Table 5), the relatively large absolute values of ΔP, $\varepsilon_{Q_b,P}$, and $\varepsilon_{Q_d,P}$ indicate that P is the main climate factor that drives Q_b and Q_d change in the UMRHR. The impacts of human activities on Q_b and Q_d change are more complex. In the northern region of UMRHR, including Gaocheng, Ziluoshan, Xiagushan, and

Table 4. Mean annual values of the hydrological, climate, and landscape variables for the periods before (prechange) and after (postchange) the change points, and the amount of change

ID	Prechange period							Postchange period							Amount of change						
	Q_1	$Q_{b,1}$	$Q_{d,1}$	P_1	$E_{P,1}$	ω_1	α_1	Q_2	$Q_{b,2}$	$Q_{d,2}$	P_2	$E_{P,2}$	ω_2	α_2	ΔQ	ΔQ_b	ΔQ_d	ΔP	ΔE_P	$\Delta\omega$	$\Delta\alpha$
1	111.8	54.3	57.5	664.9	1,166.7	2.5	628.7	73.7	45.0	28.7	644.1	1,161.5	2.8	1,010.0	−38.1	−9.3	−28.8	−20.8	−5.2	0.4	381.3
2	287.8	87.5	200.4	683.1	1,098.0	1.6	298.1	174.6	72.2	102.4	647.8	1,099.2	2.0	456.5	−113.2	−15.3	−97.9	−35.3	1.2	0.4	158.4
3	327.1	103.1	224.0	809.6	1,173.5	1.7	372.5	186.1	69.4	116.6	754.3	1,171.5	2.2	449.1	−141.0	−33.6	−107.4	−55.3	−2.1	0.5	76.5
4	464.2	110.9	353.3	951.7	1,114.0	1.6	298.7	263.8	72.2	191.7	889.4	1,111.9	2.2	334.9	−200.4	−38.7	−161.7	−62.3	−2.2	0.6	36.2
5	387.1	105.7	281.4	1,021.2	1,173.8	2.0	383.5	314.3	113.2	201.1	935.6	1,170.6	2.1	526.6	−72.8	7.5	−80.3	−85.6	−3.2	0.1	143.1
6	446.9	121.6	325.3	1,024.2	1,150.4	1.8	383.0	415.7	182.0	233.8	993.2	1,159.7	1.8	773.1	−31.1	60.4	−91.5	−31.0	9.3	0.0	390.2
7	695.2	211.6	483.6	1,426.1	1,093.3	2.0	623.9	584.3	195.7	388.6	1,351.4	1,097.0	2.2	680.7	−110.9	−15.9	−95.0	−74.7	3.7	0.2	56.7
8	664.1	230.3	433.8	1,304.2	1,063.3	1.9	692.2	818.8	263.5	555.4	1,419.8	1,052.3	1.7	673.6	154.7	33.2	121.5	115.6	−11.0	−0.2	−18.7
9	1,108.4	489.1	619.3	1,494.5	1,012.0	1.3	1,180.4	984.3	357.1	627.2	1,506.2	1,020.6	1.5	857.5	−124.0	−132.0	8.0	11.7	8.6	0.2	−322.9

Note: Q, Q_b, Q_d, P, and E_P denote the mean annual total runoff ($\mathrm{mm \cdot yr^{-1}}$), base flow ($\mathrm{mm \cdot yr^{-1}}$), direct runoff ($\mathrm{mm \cdot yr^{-1}}$), precipitation ($\mathrm{mm \cdot yr^{-1}}$), and potential evapotranspiration ($\mathrm{mm \cdot yr^{-1}}$), respectively; ω and α denote the shape parameters of the base-flow Budyko function, respectively; the subscripts of 1 and 2 represent the prechange and postchange periods, respectively; and Δ denotes the difference of a variable between the prechange and postchange periods.

Zhongtang, groundwater is the main source of irrigation. The decline in Q_b and Q_d (Table 6) caused by human activities is probably related to excessive groundwater extraction and land use change. As shown in Fig. S3, the amount of annual groundwater extraction in the Huai River Basin has increased from about 8 billion $\mathrm{m^3}$ in the 1970s to about 140 billion $\mathrm{m^3}$ in the 2000s and remained within the range of $120-160$ billion $\mathrm{m^3}$ afterward (Gong et al. 2021). In addition, according to the annual land cover data set in China (Yang and Huang 2021), an increasing trend of impervious land area was detected in the north of UMRHR (0.09–2.10 $\mathrm{km^2 \cdot yr^{-1}}$) between 1985 and 2015 (Table S1), especially at Gaocheng (2.10 $\mathrm{km^2 \cdot yr^{-1}}$), which may also be responsible for the decreased Q_b. This reminded urban planners of the necessity of sponge city practice (Yin et al. 2021) in the north of UMRHR. The increase in forest area (0.75–1.75 $\mathrm{km^2 \cdot yr^{-1}}$) probably resulted in the decrease of Q_d (Table 6). This is because the increase in forest cover could result in increased vegetation interception and evapotranspiration rates, thereby reducing Q_d (Brown et al. 2005; Zhang et al. 2017). In the southern region of UMRHR, including Dapoling, Huangchuan, Huangnizhuang, Qilin, and Huangweihe, it was difficult to explain the human activities-induced Q_b and Q_d changes merely according to land use change (i.e., Table S1). Other factors, such as intensified artificial drainage (Schottler et al. 2014), increased population density (Tan and Gan 2015), dam construction (Miao et al. 2011), and soil and water conservation practices (Ye et al. 2013), may contribute to the changes in Q_b and Q_d that require further investigation.

Sensitivity of Runoff Components to Climate Change

Fig. 6 shows the theoretical lines of $f(\varphi,\omega)$ and $g(\varphi,\omega)$ for different values of $\omega\,(\geq 1)$; $f(\varphi,\omega) \geq 1$, $g(\varphi,\omega) \leq 0$, and both $\alpha/(P+\alpha)$ and $P/(P+\alpha)$ lie between 0 and 1. Therefore, according to Eqs. (9)–(13), $\varepsilon_{Q_b,P}$ and $\varepsilon_{Q_d,P}$ are positive and ε_{Q_b,E_P} and ε_{Q_d,E_P} are negative. This suggests that increasing mean annual P will result in increases in both mean annual Q_b and Q_d and that increasing mean annual E_P will result in decreases in both mean annual Q_b and Q_d. Accordingly, the following equations can be derived from Eqs. (9)–(13)

$$\varepsilon_{Q_d,P} - \varepsilon_{Q_b,P} = 1 \tag{20}$$

$$|\varepsilon_{Q_d,P}| - |\varepsilon_{Q_b,E_P}| = |\varepsilon_{Q_d,P}| - |\varepsilon_{Q_d,E_P}| = 1 + \frac{\alpha}{P+\alpha} \tag{21}$$

$$|\varepsilon_{Q_b,P}| - |\varepsilon_{Q_b,E_P}| = |\varepsilon_{Q_b,P}| - |\varepsilon_{Q_d,E_P}| = 1 - \frac{P}{P+\alpha} \tag{22}$$

Eq. (20) shows that $\varepsilon_{Q_d,P}$ exceeds $\varepsilon_{Q_b,P}$ by 1, which is also evident in Table 4. This suggests that at the mean annual scale, Q_d is more sensitive to P than Q_b and that a 1% change in mean annual P results in a 1% more change in mean annual Q_d than in Q_b. For example, if $\varepsilon_{Q_b,P}$ is 1.5, $\varepsilon_{Q_d,P}$ will be 2.5, meaning that a 1% change in mean annual P will result in a 1.5% change in mean annual Q_d and a 2.5% change in mean annual Q_b. Our analysis confirms the results of Harman et al. (2011) and Xu et al. (2012), which reported higher precipitation elasticity in surface runoff and lower precipitation elasticity in subsurface flow. Eq. (11) and Table 5 show that ε_{Q_b,E_P} is equal to ε_{Q_d,E_P}, suggesting that the mean annal Q_b change and Q_d change in response to the mean annual E_P change were the same. Mean annual total runoff Q is more sensitive to P than to E_P in many catchments, including the Yarkand River source area of the Tarim Basin (Wang et al. 2016), the Yellow River Basin (Zheng et al. 2009), and Australia catchments (Xu et al. 2012). This is also

Table 5. Estimated elasticities (ε) of base flow (Q_b) and direct runoff (Q_d) to changes in precipitation (P) and potential evapotranspiration (E_P) in the prechange and postchange periods

ID	Station	Prechange period				Postchange period			
		$\varepsilon_{Q_b,P}$	$\varepsilon_{Q_d,P}$	ε_{Q_b,E_P}	ε_{Q_d,E_P}	$\varepsilon_{Q_b,P}$	$\varepsilon_{Q_d,P}$	ε_{Q_b,E_P}	ε_{Q_d,E_P}
1	Gaocheng	1.78	2.78	−1.30	−1.30	2.28	3.28	−1.67	−1.67
2	Ziluoshan	0.82	1.82	−0.52	−0.52	1.28	2.28	−0.87	−0.87
3	Xiagushan	0.91	1.91	−0.59	−0.59	1.39	2.39	−1.01	−1.01
4	Zhongtang	0.72	1.72	−0.48	−0.48	1.24	2.24	−0.97	−0.97
5	Dapoling	1.01	2.01	−0.74	−0.74	1.19	2.19	−0.83	−0.83
6	Huangchuan	0.87	1.87	−0.60	−0.60	1.06	2.06	−0.63	−0.63
7	Huangnizhuang	0.93	1.93	−0.63	−0.63	1.10	2.10	−0.77	−0.77
8	Qilin	0.89	1.89	−0.55	−0.55	0.75	1.75	−0.43	−0.43
9	Huangweihe	0.64	1.64	−0.20	−0.20	0.67	1.67	−0.31	−0.31

Table 6. Estimated changes in base flow, direct runoff, and total runoff induced by climate change and human activities

ID	Station	ΔQ_b^C (mm · yr^{-1})	ΔQ_d^C (mm · yr^{-1})	ΔQ_b^H (mm · yr^{-1})	ΔQ_d^H (mm · yr^{-1})	ΔQ^C (mm · yr^{-1})	ΔQ^H (mm · yr^{-1})
1	Gaocheng	−2.9	−3.8	−6.5	−25.0	−6.7	−31.5
2	Ziluoshan	−4.4	−15.9	−10.8	−82.0	−20.3	−92.8
3	Xiagushan	−6.6	−24.6	−27.0	−82.8	−31.2	−109.8
4	Zhongtang	−5.6	−34.6	−33.1	−127.1	−40.2	−160.2
5	Dapoling	−10.4	−43.4	17.9	−37.0	−53.8	−19.1
6	Huangchuan	−5.4	−18.1	65.7	−73.3	−23.5	−7.6
7	Huangnizhuang	−11.6	−48.0	−4.3	−47.0	−59.6	−51.3
8	Qilin	18.4	78.4	14.8	43.1	96.8	57.9
9	Huangweihe	1.3	6.7	−133.3	1.3	8.0	−132.0

Note: ΔQ_b^C and ΔQ_d^C represent the climate change-induced base-flow change and direct runoff change, respectively; ΔQ_b^H and ΔQ_d^H represent the human activities-induced base-flow change and direct runoff change, respectively; and ΔQ^C and ΔQ^H represent the climate change-induced and human activities-induced total runoff changes, respectively.

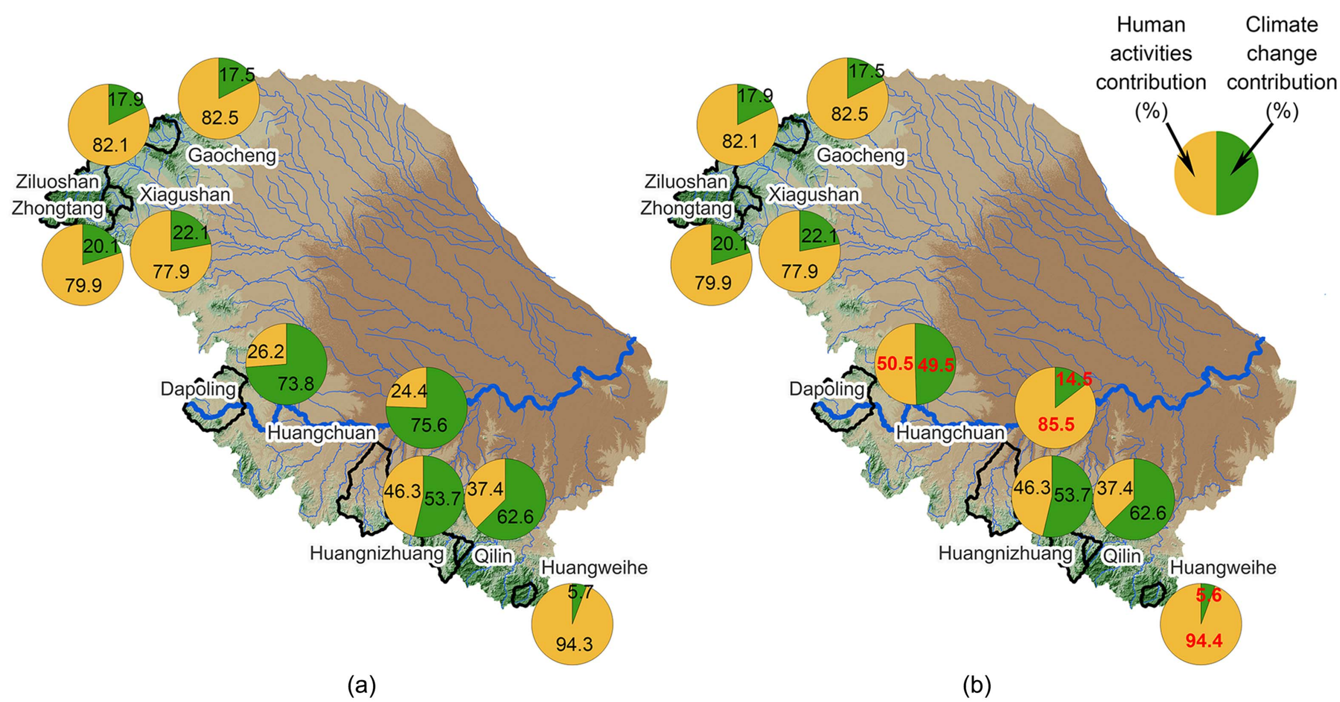

Fig. 5. Relative contributions of climate change and human activities to runoff changes in the study subcatchments by considering (a) only total runoff change; and (b) changes in runoff components. [Base maps courtesy of Caltech/JPL (ASTER GDEMV3).]

true for mean annual Q_b and Q_d. We can infer from Eqs. (20)–(22) that $\varepsilon_{Q_d,P} > \varepsilon_{Q_b,P} \geq |\varepsilon_{Q_b,E_P}| = |\varepsilon_{Q_d,E_P}| > 0$. This suggests that both mean annual Q_b and Q_d are more sensitive to mean annual P than to mean annual E_P.

According to Eqs. (9)–(13) and Fig. 6 the absolute values of $\varepsilon_{Q_b,P}$, $\varepsilon_{Q_d,P}$, ε_{Q_b,E_P}, and ε_{Q_d,E_P} increase with φ when all other parameters are kept constant. Furthermore, Fig. 7 shows that the absolute values of $\varepsilon_{Q_b,P}$, $\varepsilon_{Q_d,P}$, ε_{Q_b,E_P}, and ε_{Q_d,E_P} appear to be

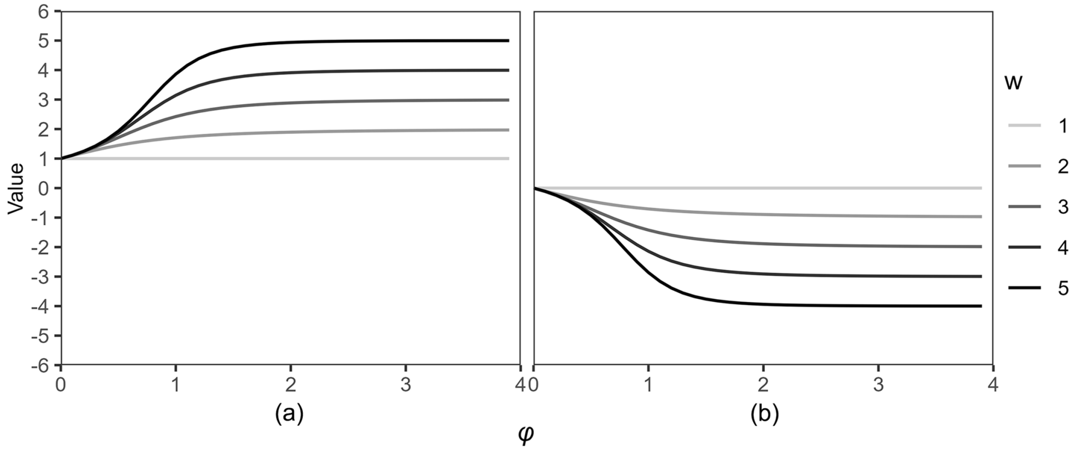

Fig. 6. Theoretical lines for different values of ω: (a) $f(\varphi,\omega)$; and (b) $g(\varphi,\omega)$.

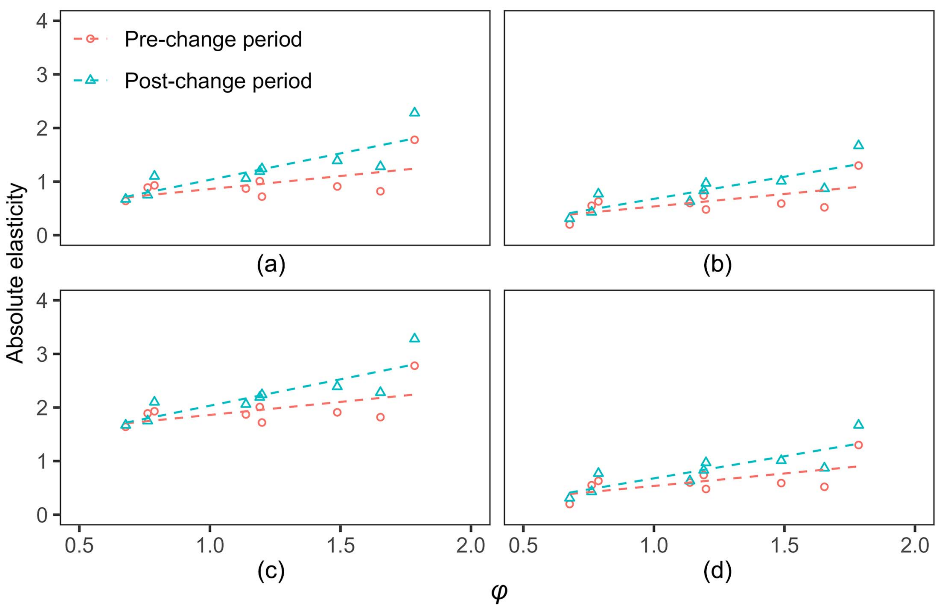

Fig. 7. Relationships between aridity index (φ) and the absolute values of (a) elasticities of base flow to precipitation change ($\varepsilon_{Q_b,P}$); (b) elasticities of base flow to potential evapotranspiration change (ε_{Q_b,E_P}); (c) elasticities of direct runoff to precipitation change ($\varepsilon_{Q_d,P}$); and (d) elasticities of direct runoff to potential evapotranspiration change (ε_{Q_d,E_P}) for the study subcatchments in the prechange and postchange periods.

positively correlated to φ in the study subcatchments. As a result, we infer that dry catchments are associated with high Q_b and Q_d sensitivity to P and E_P change. This conclusion is similar to the conclusions of Zheng et al. (2009) and Berghuijs et al. (2017); they found that dry regions generally display high sensitivities of Q to changes in P. At all stations except Qilin, the absolute values of $\varepsilon_{Q_b,P}$, $\varepsilon_{Q_d,P}$, ε_{Q_b,E_P}, and ε_{Q_d,E_P} in the postchange period all exceed those in the prechange period (Fig. 7), indicating that both Q_b and Q_d have become more sensitive to climate change in recent decades.

Model Applicability and Uncertainty Analysis

In this study, we utilized the base-flow Budyko formulation [Eq. (4)], as proposed by Chen and Ruan (2023), to assess the impacts of climate change and human activities on Q_b and Q_d. This method has a physical basis, simple structure, and low data requirements. However, it is mainly used for analysis on long-time scales (steady-state conditions) and does not reflect annual and seasonal changes in the flow process. It assumes that (1) the runoff coefficient can be expressed as a function of the aridity index when the mean annual change in catchment storage is negligible (Budyko assumption), (2) the mean annual Q_b is proportional to mean annual subsurface water storage, and (3) the mean annual Q_d is proportional to mean annual P and subsurface water storage. In addition, when calculating the elasticities of runoff components [Eqs. (9)–(13)], another assumption was proposed that (4) the mean annual P is independent of the mean annual E_P and that both mean annual P and E_P are independent of the shape parameters ω and α. Assumption 1 (i.e., the Budyko formulation) is broadly applicable under various conditions, such as arid regions (Dai et al. 2023; Zheng et al. 2009), humid regions (Reaver et al. 2022), irrigation districts (Chen et al. 2020), and permafrost regions (Wang et al. 2018). Assumption 2 describes the linear reservoir model, which is generally recognized as being applicable in most catchments (van Dijk 2010), except where the area is too small for natural averaging to occur, or where intensive anthropogenic activities affect the natural flow regime, or where the geological formations are relatively young and the self-organization of the natural environment has not yet fully developed (Fenicia et al. 2006). Several water balance models, such as the Vrije Universiteit, Brussels (VUB) model (Vandewiele and Xu 1992) and the water balance (WatBal) model (Wang et al. 2014), based on assumption 3 at the monthly scale, were found to have satisfactory performance in runoff simulation. However, the validity of assumption 3 at the mean annual scale needs to be further investigated. Many studies of runoff elasticity using the Budyko formulation have hypothesized that P is independent of E_P and that both P and E_P are independent of the shape parameter ω (Zhou et al. 2016; Berghuijs et al. 2017). In contrast, Kim and Chun (2021) suggest that P may not be independent of E_P at certain temporal (typically longer than one day) and spatial (larger than one km^2) scales. This suggests that the validity of assumption 4 also requires further justification. In general, the presented four assumptions should be carefully considered when applying the base-flow Budyko formulation to the attribution of changes in runoff components.

The uncertainties of our results probably stem from observation data, parameters, and model structure (Moges et al. 2021). In this study, the daily streamflow data were provided by the local bureau of hydrology, while the precipitation and evapotranspiration data were derived from reanalysis data. Using data from different sources may have introduced inconsistencies in our analysis. There were also some uncertainties in the referenced base flow caused by different base-flow separation methods. However, it is difficult to measure the magnitude of base-flow uncertainty because no direct approach exists for continuously measuring the base flow. The shape parameters ω and α of the base-flow Budyko formulation were inverted from climate data, observed streamflow, and referenced base flow. The effects of uncertainty in the shape parameters and model structures (i.e., the four assumptions listed above) require a large number of numerical experiments and quantitative analysis, which is beyond the scope of this study and should be thoroughly investigated in the future.

Conclusions

The novelties of this study include: (1) providing valuable insights into the detailed hydrological responses to environmental changes by quantifying the climate change-induced and human activities-induced changes in base flow and direct runoff; (2) suggesting that human activities may have a more significant impact on total runoff change than previously recognized due to their opposing effects on base flow and direct runoff; and (3) showing that both base flow and direct runoff are more sensitive to climate change in recent decades in the UMRHR. This study highlights the importance of examining changes in runoff components when conducting runoff change attribution analysis. However, to offer practical guidance for water resources management, further investigation is required on the impact of specific human activities, such as land use change, agricultural activity, urbanization, and dam construction. Additionally, it is important to carefully consider the underlying assumptions and possible uncertainties when applying the base-flow Budyko formulation to attribute changes in runoff components.

Data Availability Statement

Streamflow records are available from the corresponding author upon reasonable request.

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Notation

The following symbols are used in this paper:

A = catchment area;
E_P = potential evapotranspiration;
P = precipitation;
Q = total runoff;
Q_b = base flow;
Q_d = direct runoff;
α = parameter of the base-flow Budyko function;
γ = a coefficient ranging from 0 to 1;
ΔE_P = potential evapotranspiration change;
ΔP = precipitation change;
ΔQ^C = climate-induced runoff change;
ΔQ^H = human-induced runoff change;
ΔQ_b^C = climate-induced base-flow change;
ΔQ_b^H = human-induced base-flow change;
ΔQ_d^C = climate-induced direct runoff change;
ΔQ_d^H = human-induced direct runoff change;
ε = elasticity;
θ = contribution;
φ = aridity index; and
ω = shape parameter of the Budyko function.

Supplemental Materials

Figs. S1–S3 and Table S1 are available online in the ASCE Library (www.ascelibrary.org).

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