Separating runoff change by the improved Budyko complementary relationship considering effects of both climate change and human activities on basin characteristics

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ABSTRACT

Numerous efforts have been made to separate effects of climate change and human activities on long-term runoff change, including a commonly used method based on the Budyko complementary relationship (BCR) to deal with the non-closure problems often encountered in separating the observed runoff change into its contributed components. The BCR was derived by assuming the change of the Budyko parameter reflecting basin characteristics is related to human activities alone. However, some studies show that basin characteristics are related to both climate change and human activities in certain basins, where applying the BCR method could lead to wrong results. In the study, a more flexible form of the BCR, the improved Budyko complementary relationship (IBCR), is developed under the situation that basin characteristics may relate to climate change. A separation method based on the IBCR is also developed. In this IBCR method, the relationship of the basin characteristics parameter to climate and/or human factors is estimated by using a multi-year moving window. To identify the flexibility of the IBCR method relative to the BCR method, both methods were applied to the Weihe basin of China, whose basin characteristics have been found to be affected by both climate change and human activities. Compared with the IBCR method, the BCR method overestimates the climate effect, while underestimates the human effect on the runoff change in the Weihe basin. It is found that whether or not to incorporate the climate effect into the basin characteristics parameter has a significant impact on the runoff change separation results in Weihe basin. Overall, the IBCR method is more reasonable and flexible for separating the long-term runoff change into different components.

Key Words: Improved Budyko complementary relationship; climate change; human activities; runoff change separation

1 Introduction

Simulating and predicting the temporal variabilities of the basin-scale long-term runoff are urgent challenges in water resources planning and management (Milly, 1994). These temporal variabilities have been proven to be attributed to the effects of both climate change and human activities worldwide (Ahn et al., 2014; Van der Velde et al., 2014; Jiang et al., 2015; Zhou et al., 2016; Pathiraja et al., 2016; Dey and Mishra, 2017; Stephens et al., 2018; Deng et al. 2018; Xiong et al. 2018; Deng et al., 2019). To identify the different roles of climate change and human activities on the variability of long-term runoff, various separation methods have been developed, including the decomposition method proposed by Wang and Hejazi (2011) and various sensitivity methods, among which, methods based on the runoff sensitivity concept have gained extensive attention (Roderick and Farquhar, 2011; Xu et al., 2014; Liang et al., 2015; Zhang et al., 2016; Xin et al., 2019).

In the methods based on the runoff sensitivity concept, sensitivity coefficients of runoff to the influential factors are represented by corresponding partial derivatives (Ma et al., 2008; Roderick and Farquhar, 2011; Jiang et al., 2015). In practice, these partial derivatives are simulated based on models that can simulate hydrological processes. The Budyko hypothesis, which considers both water and energy constraints on the actual evapotranspiration over a long period, is normally coupled with the long-term water balance equation to represent hydrological processes in the long-term runoff change separation (Budyko, 1974). Originally, the contribution of climate change to runoff change is estimated by summing up the change related to climate change, and the contribution of human activities to runoff change is estimated as the difference between observed runoff change and the estimated contribution of climate change (Koster and Suarez, 1999). Later, Roderick and Farquhar (2011) applied the total differential of runoff to separate long-term runoff change. In this total differential method, runoff is affected by precipitation, potential evapotranspiration and the basin characteristics parameter over a long period according to one-parameter Budyko equations, such as Turc-Pike, Fu and Mezentsev-Choudhury-Yang equations, and the water balance equation (Pike, 1964; Fu, 1981; Choudhury, 1999; Yang et al., 2008). In this method, the contribution of human activities to runoff change is estimated by the change of the parameter, since it is commonly assumed that basin characteristics are only related to human activities (Liang et al., 2015; Wu et al., 2017). For both sensitivity methods mentioned above, the differential form of runoff needs to be transformed into the difference form to estimate the contributions to runoff change in practice. The actual calculation of partial derivatives in the difference equations is essentially the first-order Taylor approximation, not an algebraic identity. It leads to the non-closure problems in separating the observed runoff change into the change components. Yang et al. (2014) has simulated the difference of the climatic effect on runoff change between the first-order Taylor approximation and the complete Taylor expansion, and results indicate that the non-closure problems lead to the underestimation of the climate effect on the runoff change when precipitation increases or potential evapotranspiration decreases, and overestimation otherwise. The error caused by the non-closure problems ranges from -118% to 174% in 207 basins in China. Thus, the non-closure problems in these conventional sensitivity methods cannot be ignored.

In addition to the aforementioned sensitivity methods to separate long-term runoff change, Zhou et al. (2016) has developed a separation method based on a Budyko complementary relationship (BCR) (Zhou et al., 2015). In this method, the approximate calculations in the difference equations are avoided, and algebraic identities have ensured that there is no non-closure problem in the separation of runoff change. The Budyko complementary relationship is derived from the partial derivatives of the general form for the Budyko hypothesis coupled with the long-term water balance equation, among which, the partial derivatives are derived based on the common assumption that the Budyko parameter reflecting basin characteristics is related to human activities alone. This derivation formula states that runoff is linearly related to input precipitation and potential evapotranspiration, among which the partial derivatives (sensitivity coefficients) are corresponding weights (Zhou et al., 2015). The BCR method remains the same as the total differential method in the way to estimate the effect of climate change on runoff, but differs in estimating the effect of human activities. In the BCR method, the effect of human activities on runoff is estimated based on the change in the partial derivatives of runoff to precipitation and potential evapotranspiration, rather than based on the change of the Budyko parameter as in the total differential method.

The BCR method has the ability to deal with the non-closure problems caused by the approximate calculations of the difference equation in the conventional sensitivity method, however, it is not true to assume that the Budyko parameter reflecting basin characteristics is related to human activities alone in certain areas, as some studies indicate that the Budyko parameter may relate to both climate change and human activities (Jiang et al., 2015). For example, Jiang et al. (2017) has used covariate analysis of the Budyko parameter to identify the influential factors, and results show that in some areas of China, the basin characteristics parameter is also related to climate change. In these specific areas, climate change affects runoff in two ways, one is the direct effect by input climate data, and the other is the indirect effect by altering the basin characteristics parameter. Thus, the neglecting climate effect on basin characteristics may lead to overestimate or underestimate the contribution of climate effect to runoff change.

In this study, a more flexible form of the BCR, the improved Budyko complementary relationship (IBCR) is developed considering that the Budyko parameter reflecting basin characteristics may be related to both climate change and human activities. Then, the separation method based on IBCR is developed. To carry out this IBCR method, the relationship of the basin characteristics parameter to factors of climate change and human activities (such as precipitation, potential evapotranspiration and irrigated area) is estimated by using a multi-year moving window, among which, the proper covariates and the function form of the parameter is selected through the model selection criteria. This IBCR method inherits the advantages of the BCR method that the non-closure problems in the separation of runoff change have been solved, and can be applied to more areas than the BCR method. A specific basin, the Weihe basin of China, whose basin characteristics have been identified to be affected by both climate change and human activities, is chosen as the study area. Both the BCR method and the IBCR method are applied to the basin in order to justify the necessity of developing the IBCR method.

The reminder of this paper is organized as follows. In the first place, the methods used in this paper are described, followed by the study area and datasets. And then, results and discussions of the study are presented. The main conclusions for the study are summarized finally.

2 Methods

To apply the concept of the Budyko complementary relationship (BCR) proposed by Zhou et al. (2015) in separating runoff change in basins whose physical characteristics may be affected by both climate change and human activities, a method based on the improved Budyko complementary relationship (IBCR) is developed. In this section, the general Budyko hypothesis formula is introduced first. Based on the Budyko hypothesis, the IBCR developed in this study is presented, followed by the detailed derivation of the runoff change separation method based on the IBCR, including the mathematical expression and the attribution components of total runoff change. Finally, experiment is conducted to compare the BCR method and the IBCR method in separating runoff change.

2.1 Budyko hypothesis

The original Budyko hypothesis states that actual evapotranspiration E is mainly controlled by available water and energy. Evapotranspiration ratio $\frac{E}{P}$ can be expressed as

$$\frac{E}{P}=\mathrm{G}\left(\phi\right) \tag{1}$$

where $\mathrm{G}\left(\cdot\right)$ indicates a function, and ϕ is climatic aridity index, $\phi=\frac{Ep}{P}$, among which, precipitation P reflects available water, potential evapotranspiration Ep reflects available energy (Budyko, 1974; Arora, 2002). In the original Budyko hypothesis, if $\phi \ll 1$, the actual evapotranspiration is limited by energy, and if $\phi \gg 1$, the actual evapotranspiration is limited by water. This hypothesis assumes that $\frac{E}{P}$ is only related to climate factors. In some previous studies, $\frac{E}{P}$ has been proven to be also constrained by the effect of basin characteristics (Fu, 1981; Milly and Dunne, 2002; Zhang et al., 2001), a more general expression of Budyko hypothesis is shown as

$$\frac{E}{P}=\mathrm{F}\left(\phi,w\right) \tag{2}$$

where $\mathrm{F}\left(\cdot\right)$ indicates a function, the parameter w represents different Budyko curves, and in practice is used to reflect basin characteristics.

2.2 Improved Budyko complementary relationship (IBCR)

The BCR proposed by Zhou et al. (2015) is derived from the general Budyko equation, i.e. the equation (2), under the common assumption that the Budyko parameter w that reflects catchment characteristics is related to human activities alone (specifically speaking, w, P and Ep are assumed to be independent of each other). The BCR is expressed as

$$Q = P\frac{\partial Q}{\partial P} + Ep\frac{\partial Q}{\partial Ep} \tag{3}$$

The detailed derivation of the BCR is well documented in Zhou et al. (2015).

The assumption that w is related to human activities alone in the BCR is not completely true since other studies indicate that there are basins whose physical characteristics are also related to climate change (Jiang et al., 2015; Jiang et al., 2017). Thus, the BCR is not universally valid, and a more flexible form of the BCR should be considered, which is called the improved Budyko complementary relationship (IBCR). Relative to the BCR, the basin characteristics parameter w in the IBCR is also allowed to be related to climate factor P and Ep. Transforming the equation (2) to $E{=}P\cdot \mathrm{F}(\phi,w)$, the partial differentials of E to P, Ep and w are expressed as

$$\begin{aligned}\frac{\partial E}{\partial P} &= \mathrm{F}(\phi,w) + P\cdot\left[\frac{\partial \mathrm{F}(\phi,w)}{\partial \phi}\cdot\frac{\partial \phi}{\partial P} + \frac{\partial \mathrm{F}(\phi,w)}{\partial w}\cdot\frac{\partial w}{\partial P}\right] \\ &= \mathrm{F}(\phi,w) - \phi\cdot\frac{\partial \mathrm{F}(\phi,w)}{\partial \phi} + P\cdot\frac{\partial \mathrm{F}(\phi,w)}{\partial w}\cdot\frac{\partial w}{\partial P}\end{aligned} \tag{4}$$

$$\begin{aligned}\frac{\partial E}{\partial Ep} &= P\cdot\left[\frac{\partial \mathrm{F}(\phi,w)}{\partial \phi}\cdot\frac{\partial \phi}{\partial Ep} + \frac{\partial \mathrm{F}(\phi,w)}{\partial w}\cdot\frac{\partial w}{\partial Ep}\right] \\ &= \frac{\partial \mathrm{F}(\phi,w)}{\partial \phi} + P\cdot\frac{\partial \mathrm{F}(\phi,w)}{\partial w}\cdot\frac{\partial w}{\partial Ep}\end{aligned} \tag{5}$$

$$\frac{\partial E}{\partial w} = P\cdot\frac{\partial \mathrm{F}(\phi,w)}{\partial w} \tag{6}$$

By substituting the equations (2), (5) and (6) into the equation (4) to eliminate

$\mathrm{F}(\phi,w)$, $\dfrac{\partial \mathrm{F}(\phi,w)}{\partial \phi}$ and $\dfrac{\partial \mathrm{F}(\phi,w)}{\partial w}$, the equation (4) can be transformed into

$$\frac{\partial E}{\partial P}=\frac{E}{P}-\frac{Ep}{P}\left(\frac{\partial E}{\partial Ep}-\frac{\partial E}{\partial w}\cdot\frac{\partial w}{\partial Ep}\right)+\frac{\partial E}{\partial w}\cdot\frac{\partial w}{\partial P} \tag{7}$$

Based on the long-term water balance equation $P=E+Q$, substituting E=$P-Q$ into the equation (7) yields,

$$Q=P\cdot\frac{\partial Q}{\partial P}+Ep\cdot\frac{\partial Q}{\partial Ep}-P\cdot\frac{\partial Q}{\partial w}\cdot\frac{\partial w}{\partial P}-Ep\cdot\frac{\partial Q}{\partial w}\cdot\frac{\partial w}{\partial Ep} \tag{8}$$

The equation (8) derived above is just the improved Budyko complementary relationship (IBCR). It can be noted that the BCR proposed by Zhou et al. (2015) is the specific case of the equation (8) when $\dfrac{\partial w}{\partial P}$=0 and $\dfrac{\partial w}{\partial Ep}$=0.

2.3 Expression of runoff change based on the IBCR

Based on the IBCR, from the pre-change state (represented by the subscript 0) to the post-change state (represented by the subscript 1), the total runoff change ΔQ can be expressed as:

$$\begin{aligned}\Delta Q=Q_1-Q_0=P_1\cdot\left[\left(\frac{\partial Q}{\partial P}\right)_1-\left(\frac{\partial Q}{\partial w}\right)_1\cdot\left(\frac{\partial w}{\partial P}\right)_1\right]-P_0\cdot\left[\left(\frac{\partial Q}{\partial P}\right)_0-\left(\frac{\partial Q}{\partial w}\right)_0\cdot\left(\frac{\partial w}{\partial P}\right)_0\right]+\\ Ep_1\cdot\left[\left(\frac{\partial Q}{\partial Ep}\right)_1-\left(\frac{\partial Q}{\partial w}\right)_1\cdot\left(\frac{\partial w}{\partial Ep}\right)_1\right]-Ep_0\cdot\left[\left(\frac{\partial Q}{\partial Ep}\right)_0-\left(\frac{\partial Q}{\partial w}\right)_0\cdot\left(\frac{\partial w}{\partial Ep}\right)_0\right]\end{aligned} \tag{9}$$

where the difference operator Δ refers to the change of a variable from the pre-change state to the post-change state. By adding and taking away $P_1\cdot\left[\left(\dfrac{\partial Q}{\partial P}\right)_0-\left(\dfrac{\partial Q}{\partial w}\right)_0\cdot\left(\dfrac{\partial w}{\partial P}\right)_0\right]$, the first two terms

$P_1\cdot\left[\left(\frac{\partial Q}{\partial P}\right)_1-\left(\frac{\partial Q}{\partial w}\right)_1\cdot\left(\frac{\partial w}{\partial P}\right)_1\right]-P_0\cdot\left[\left(\frac{\partial Q}{\partial P}\right)_0-\left(\frac{\partial Q}{\partial w}\right)_0\cdot\left(\frac{\partial w}{\partial P}\right)_0\right]$ in the equation (9) can be transformed identically into

$$\begin{aligned}
&P_1\cdot\left[\left(\frac{\partial Q}{\partial P}\right)_1-\left(\frac{\partial Q}{\partial w}\right)_1\cdot\left(\frac{\partial w}{\partial P}\right)_1\right]-P_0\cdot\left[\left(\frac{\partial Q}{\partial P}\right)_0-\left(\frac{\partial Q}{\partial w}\right)_0\cdot\left(\frac{\partial w}{\partial P}\right)_0\right]=\\
&P_1\cdot\left[\left(\frac{\partial Q}{\partial P}\right)_1-\left(\frac{\partial Q}{\partial w}\right)_1\cdot\left(\frac{\partial w}{\partial P}\right)_1\right]-P_1\cdot\left[\left(\frac{\partial Q}{\partial P}\right)_0-\left(\frac{\partial Q}{\partial w}\right)_0\cdot\left(\frac{\partial w}{\partial P}\right)_0\right]+P_1\cdot\left[\left(\frac{\partial Q}{\partial P}\right)_0-\left(\frac{\partial Q}{\partial w}\right)_0\cdot\left(\frac{\partial w}{\partial P}\right)_0\right]-\\
&P_0\cdot\left[\left(\frac{\partial Q}{\partial P}\right)_0-\left(\frac{\partial Q}{\partial w}\right)_0\cdot\left(\frac{\partial w}{\partial P}\right)_0\right]=P_1\cdot\Delta\left(\frac{\partial Q}{\partial P}-\frac{\partial Q}{\partial w}\cdot\frac{\partial w}{\partial P}\right)+\left[\left(\frac{\partial Q}{\partial P}\right)_0-\left(\frac{\partial Q}{\partial w}\right)_0\cdot\left(\frac{\partial w}{\partial P}\right)_0\right]\cdot\Delta P
\end{aligned}\tag{10}$$

Similarly, $P_0\cdot\left[\left(\frac{\partial Q}{\partial P}\right)_1-\left(\frac{\partial Q}{\partial w}\right)_1\cdot\left(\frac{\partial w}{\partial P}\right)_1\right]$ can also be added and taken away for the term $P_1\cdot\left[\left(\frac{\partial Q}{\partial P}\right)_1-\left(\frac{\partial Q}{\partial w}\right)_1\cdot\left(\frac{\partial w}{\partial P}\right)_1\right]-P_0\cdot\left[\left(\frac{\partial Q}{\partial P}\right)_0-\left(\frac{\partial Q}{\partial w}\right)_0\cdot\left(\frac{\partial w}{\partial P}\right)_0\right]$, and the last two terms in the equation (9) can be transformed likewise. Thus, the equation (9) can be finally expressed as

$$\begin{aligned}
\Delta Q=&\left(\frac{\partial Q}{\partial P}\right)_0\cdot\Delta P+\left(\frac{\partial Q}{\partial Ep}\right)_0\cdot\Delta Ep-\left[\left(\frac{\partial Q}{\partial w}\right)_0\left(\frac{\partial w}{\partial P}\right)_0\cdot\Delta P+\left(\frac{\partial Q}{\partial w}\right)_0\left(\frac{\partial w}{\partial Ep}\right)_0\cdot\Delta Ep\right]+\\
&P_1\cdot\Delta\left(\frac{\partial Q}{\partial P}-\frac{\partial Q}{\partial w}\cdot\frac{\partial w}{\partial P}\right)+Ep_1\cdot\Delta\left(\frac{\partial Q}{\partial Ep}-\frac{\partial Q}{\partial w}\cdot\frac{\partial w}{\partial Ep}\right)
\end{aligned}\tag{11}$$

or

$$\begin{aligned}
\Delta Q=&\left(\frac{\partial Q}{\partial P}\right)_1\cdot\Delta P+\left(\frac{\partial Q}{\partial Ep}\right)_1\cdot\Delta Ep-\left[\left(\frac{\partial Q}{\partial w}\right)_1\left(\frac{\partial w}{\partial P}\right)_1\cdot\Delta P+\left(\frac{\partial Q}{\partial w}\right)_1\left(\frac{\partial w}{\partial Ep}\right)_1\cdot\Delta Ep\right]+\\
&P_0\cdot\Delta\left(\frac{\partial Q}{\partial P}-\frac{\partial Q}{\partial w}\cdot\frac{\partial w}{\partial P}\right)+Ep_0\cdot\Delta\left(\frac{\partial Q}{\partial Ep}-\frac{\partial Q}{\partial w}\cdot\frac{\partial w}{\partial Ep}\right)
\end{aligned}\tag{12}$$

2.4 Attribution of runoff change based on the IBCR

The total runoff change can be attributed to two sources: (1) the direct climate effect on runoff, i.e. the impact of changes in P and Ep on Q, denoted by ΔQ^{c-d}; (2) the effect of changes in w, which represents the physical characteristics of the basin, on Q, which is denoted by ΔQ^{w}. Thus, we have

$$\Delta Q = \Delta Q^{c-d} + \Delta Q^{w} \tag{13}$$

Considering that climate change can have impacts on runoff through both direct and indirect ways, we have

$$\Delta Q^{c-d} = \Delta Q^{c} - \Delta Q^{c-i} \tag{14}$$

where ΔQ^{c} is the total effect of climate change on runoff, ΔQ^{c-i} is the indirect climate effect on runoff change, i.e. the impact on Q of changes in w that are caused by changes in P and Ep. By associating the equation (11) with equations (13) and (14), we have the following definitions of different runoff change components

$$\Delta Q^{c} = \left(\frac{\partial Q}{\partial P}\right)_0 \cdot \Delta P + \left(\frac{\partial Q}{\partial Ep}\right)_0 \cdot \Delta Ep \tag{15}$$

$$\Delta Q^{c-i} = \left(\frac{\partial Q}{\partial w}\right)_0 \left(\frac{\partial w}{\partial P}\right)_0 \cdot \Delta P + \left(\frac{\partial Q}{\partial w}\right)_0 \left(\frac{\partial w}{\partial Ep}\right)_0 \cdot \Delta Ep \tag{16}$$

$$\Delta Q^{w} = P_1 \cdot \Delta\left(\frac{\partial Q}{\partial P} - \frac{\partial Q}{\partial w}\cdot\frac{\partial w}{\partial P}\right) + Ep_1 \cdot \Delta\left(\frac{\partial Q}{\partial Ep} - \frac{\partial Q}{\partial w}\cdot\frac{\partial w}{\partial Ep}\right) \tag{17}$$

$$\Delta Q^{c-d} = \left(\frac{\partial Q}{\partial P}\right)_0 \cdot \Delta P + \left(\frac{\partial Q}{\partial Ep}\right)_0 \cdot \Delta Ep - \left[\left(\frac{\partial Q}{\partial w}\right)_0 \left(\frac{\partial w}{\partial P}\right)_0 \cdot \Delta P + \left(\frac{\partial Q}{\partial w}\right)_0 \left(\frac{\partial w}{\partial Ep}\right)_0 \cdot \Delta Ep\right] \tag{18}$$

Then, the effect of human activities on runoff change (ΔQ^{h}) can be calculated as,

$$\Delta Q^{h} = \Delta Q^{w} - \Delta Q^{c-i} \tag{19}$$

We can also prove that

$$\Delta Q = \Delta Q^{c} + \Delta Q^{h} \tag{20}$$

which means that the total runoff change can also be separated into two components, one caused directly or indirectly by climate change, and the other caused by human activities.

To reduce the influence of the different numerical schemes for approximating the partial differentials in the above equations on runoff change attribution results, the averages of the partial differentials in the pre-change period and the post-change period are used in practice (Jiang et al., 2015; Zhou et al., 2016). Thus,

$$\Delta Q^{c} = \frac{1}{2}\left[\left(\frac{\partial Q}{\partial P}\right)_0 + \left(\frac{\partial Q}{\partial P}\right)_1\right]\Delta P + \frac{1}{2}\left[\left(\frac{\partial Q}{\partial Ep}\right)_0 + \left(\frac{\partial Q}{\partial Ep}\right)_1\right]\Delta Ep \tag{21}$$

$$\begin{aligned}\Delta Q^{c\_i} = {} & \frac{1}{2}\left[\left(\frac{\partial Q}{\partial w}\right)_0\left(\frac{\partial w}{\partial P}\right)_0 + \left(\frac{\partial Q}{\partial w}\right)_1\left(\frac{\partial w}{\partial P}\right)_1\right]\Delta P + \\ & \frac{1}{2}\left[\left(\frac{\partial Q}{\partial w}\right)_0\left(\frac{\partial w}{\partial Ep}\right)_0 + \left(\frac{\partial Q}{\partial w}\right)_1\left(\frac{\partial w}{\partial Ep}\right)_1\right]\Delta Ep\end{aligned} \tag{22}$$

$$\Delta Q^{c\_d} = \frac{1}{2}\left[\left(\frac{\partial Q}{\partial P}\right)_0 + \left(\frac{\partial Q}{\partial P}\right)_1\right]\Delta P + \frac{1}{2}\left[\left(\frac{\partial Q}{\partial Ep}\right)_0 + \left(\frac{\partial Q}{\partial Ep}\right)_1\right]\Delta Ep - \Delta Q^{c\_i} \tag{23}$$

The contribution of human activities to runoff change ΔQ^{h} is expressed as

$$\begin{aligned}\Delta Q^{h} = {} & \frac{1}{2}\left(P_0 + P_1\right)\Delta\left(\frac{\partial Q}{\partial P} - \frac{\partial Q}{\partial w}\cdot\frac{\partial w}{\partial P}\right) + \\ & \frac{1}{2}\left(Ep_0 + Ep_1\right)\Delta\left(\frac{\partial Q}{\partial Ep} - \frac{\partial Q}{\partial w}\cdot\frac{\partial w}{\partial Ep}\right) - \Delta Q^{c\_i}\end{aligned} \tag{24}$$

The BCR is the special case of the IBCR when $\frac{\partial w}{\partial P}=0$ and $\frac{\partial w}{\partial Ep}=0$. For the BCR method, there is no indirect climate effect on runoff change by altering basin characteristics ($\Delta Q^{c\_i}=0$), thus in the BCR method, ΔQ^{c} and ΔQ^{h} are expressed as

$$\Delta Q^{c}=\frac{1}{2}\left[\left(\frac{\partial Q}{\partial P}\right)_{0}+\left(\frac{\partial Q}{\partial P}\right)_{1}\right]\Delta P+\frac{1}{2}\left[\left(\frac{\partial Q}{\partial Ep}\right)_{0}+\left(\frac{\partial Q}{\partial Ep}\right)_{1}\right]\Delta Ep \qquad (25)$$

$$\Delta Q^{h}=\frac{1}{2}\left(P_{0}+P_{1}\right)\Delta\left(\frac{\partial Q}{\partial P}\right)+\frac{1}{2}\left(Ep_{0}+Ep_{1}\right)\Delta\left(\frac{\partial Q}{\partial Ep}\right) \qquad (26)$$

2.5 Experimental setup

To identify the necessity to improve the original BCR method, both the BCR method and the IBCR method are applied to separate long-term runoff change in a specific basin whose basin characteristics relate to both climate change and human activities. Since the BCR and the IBCR methods are derived based on the one-parameter Budyko equation, Fu-Equation (Fu, 1981), which is widely used and has shown good results in many steady-state and unsteady-state basins across China, is chosen in the study (Jiang et al., 2015; Jiang et al., 2017). Fu-Equation is expressed as:

$$\frac{E}{P}=1+\frac{Ep}{P}-\left[1+\left(\frac{Ep}{P}\right)^{w}\right]^{1/w}, \quad w\in\left(1,\infty\right) \qquad (27)$$

In the IBCR method, an additional formula is needed to quantify the relationship of w to the influencing factors such as P and Ep and land use/land cover for runoff change separation. Here, a moving window is applied to smooth random variations of series of hydro-meteorological and human factors. The length and the shift of the moving window is chosen according to the length of data series. In the study, the 11-year moving window and one year shift are chosen for the moving window method. To indicate that the parameter w is obtained from factors of both climate change and human activities, the denotation w_t^{ch} is employed as the corresponding w value in the time window centered with year t, and its function can be expressed as

$$w_t^{ch} = \psi\left[\beta_0 + \sum_{i=1}^{m} \beta_i \varphi_i\left(X_{i,t}^{c}\right) + \sum_{i=m+1}^{n} \beta_i \varphi_i\left(X_{i,t}^{h}\right)\right] \tag{28}$$

where $\beta_i\left(i=0,1,\ldots,n\right)$ is the regression parameter, $X_{i,t}^{c}\left(i=1,2,...,m\right)$ and $X_{i,t}^{h}\left(i=m+1,m+2,...,n\right)$ are the mean annual value of the explanatory variable for climate change and human activities respectively. $\varphi_i\left(\cdot\right)\left(i=1,2,...,n\right)$ and $\psi\left(\cdot\right)$ represent transformation functions, whose forms may be identity, logarithmic and exponential.

Substituting the equation (28) into the equation (27), and introducing the long-term water balance equation, the mean annual Q in the time window centered with year t can be expressed as

$$Q_t = P_t\left[1 - B\left(\frac{Ep_t}{P_t}, w_t^{ch}\right)\right] = -Ep_t + P_t\left[1 + \left(\frac{Ep_t}{P_t}\right)^{w_t^{ch}}\right]^{1/w_t^{ch}} \tag{29}$$

where P_t and Ep_t are the mean annual P and Ep in the time window centered with year t. $\beta_i\left(i=0,1,\ldots,n\right)$ in the w_t^{ch} equation is estimated by the maximum likelihood estimation method (MLE). In practice, to determine the proper explanatory variables for the basin characteristics parameter as well as the type of transformation functions, a commonly used criterion, the Bayesian Information Criterion (BIC) is used (Schwarz, 1978). In the study, a relevant control case is also built by excluding all climate variables from the covariate analysis for the basin characteristics parameter, which is presumably equivalent to the BCR, and in this case, the parameter is denoted as w_t^h, with the superscript representing that the parameter w is a function of only human activities.

In the BCR method adopted in Zhou et al. (2016), there is no need to figure out the relationship of the basic characteristics parameter to its influential factors. The parameter is directly estimated by the MLE method, which is denoted by w_t for the time window centered with year t. It should be noted that in this study w_t is also directly estimated by the MLE method for the IBCR method, without resorting to the equation (28).

3 Study area and datasets

3.1 Weihe basin

The Weihe, which originates from the Gansu Province and flows through the southern Loess Plateau into the Yellow River of China in the Shaanxi Province, is the largest tributary of the Yellow River. The mean annual runoff at the outlet hydrological station of the river (Huaxian station) is 10.4 billion m^3, contributing about seventeen percent of the Yellow River’s total discharge. The basin drainage area is 134800 km^2, located within 104°00″E to 110°30″E and 33°50″N to 37°20″N with the elevation ranging from 318 to 3671 m a.s.l., increasing from east to west (Fig. 1). The basin is the transitional area of arid and semi-humid regions. The climate in the basin is characterized by the typical continental monsoon with annual precipitation ranging from 500 to 800 mm, most of which falls in summer, and annual mean temperature ranging from 7.8 to 13.5 °C.

The Weihe basin is a traditional agricultural area, but it has become an important commerce and industry area in Northwestern China due to rapid economic development. Extensive human activities have largely altered underlying surface of the basin, especially before the 2000s (Chang et al., 2015). For example, irrigation area has increased, and the measurements of soil and water conservation increase the area of bench terrace and afforestation. Human activities in the Weihe basin have significant influences on hydrological processes (Zhao et al., 2013). Over the past several decades, runoff in the Weihe has exhibited a decreasing trend. Since the Weihe is the primary water supply for 76 major cities with a total population of 22 million, it is of great significance to analyze the contributions of climate change and human activities to its long-term runoff change.

<Fig. 1>

3.2 Data

To perform the case study, the annual runoff (Q), precipitation (P) and potential evapotranspiration (Ep) are needed for the Budyko hypothesis. Annual Q from the Huaxian station are gathered from 1979 to 2015. The corresponding P and Ep are calculated from daily observed data that are acquired from 21 meteorological stations within and around the basin (as shown in Fig. 1) by the Inverse Distance Weighted method. All meteorological stations cover the period from 1979 to 2015.

In order to quantify the effects of climate change and human activities on basin characteristics, the climate factors P and Ep are used to reflect climate change, since both the direct and indirect climate effects on runoff change in the IBCR method have to be calculated based on these two climate factors. Irrigation area (IA), soil water storage capacity (SC) and land use/land cover ($LULC$) are considered as the factors related to human activities. This is because these variables directly affect the underlying surface, but population and gross domestic product, which are usually used to quantify the impact of human activities in previous papers, are not directly related to basin characteristics. For SC, different from soil moisture that varies with P and Ep, it is not influenced by water cycle, it is only related to the underlying surface, and remains unchanged in a stable-state basin. As for $LULC$, although it may change due to climate change in a long period (e.g., hundreds of years), in a 35-year period it is more susceptible to human activities, such as ecological restoration and urban construction. Thus, the change of $LULC$ is used to represent human activities in the study.

Since the majority of agricultural regions of the Weihe basin is distributed in the Shaanxi Province, the annual data of IA are represented by the data of this province, and are acquired from the book of China Compendium of Statistics 1949-2008 (Department of Comprehensive Statistics of National Bureau of Statistics, 2010) and the website of the National Bureau of Statistics of the People’s Republic of China (http://www.stats.gov.cn/tjsj/ndsj/). The annual data of SC are calculated based on the gridded soil moisture in the Weihe basin, which are acquired from the European Space Agency Climate Change Initiative (ESA CCI) Soil Moisture dataset (version 04.4) (https://www.esa-soilmoisture-cci.org/). In this study, it is assumed that there is at least one day in each year that the soil is fully saturated/dried in each grid of the soil moisture dataset, thus the maximum soil moisture value can be regarded as the soil porosity value. SC in each year is calculated as

$$SC = SM^{\max} - SM^{\min} \tag{30}$$

where $SM^{\max}$ and $SM^{\min}$ are the maximum and minimum soil moisture values in each year. The annual data of $LULC$ are calculated based on interpolation for $LULC$ data of seven years, 1980, 1990, 1995, 2000, 2005, 2010 and 2015, which are derived from the Geographical Information Monitoring Cloud Platform (http://www.dsac.cn/). $LULC$ can be classified into six categories, including cultivated land ($LULC_C$), forest ($LULC_F$), grassland ($LULC_G$), water bodies ($LULC_W$), built-up land ($LULC_B$) and unused land ($LULC_U$). Areas for these categories are used as candidate factors.

4 Results

4.1 Trend analysis for data of hydro-meteorology and human activities

In the study, the modified Mann-Kendall trend test is used to detect the variations of the generated moving average points that may have inherent autocorrelation (Hamed and Rao, 1998). As shown in Table 1, the moving averages of Q and $LULC_W$ fail to pass the modified Mann-Kendall trend test at the 0.05 significance level, but can pass the original Mann-Kendall trend test. For other variables, the inherent autocorrelation has limited effects on the calculated significance of trend slopes. According to the test, P, Q and $LULC_C$ have decreasing trends, and other variables show some degree of increasing trends, among which, P, IA and $LULC_U$ cannot pass both the modified and original Mann-Kendall trend test at the 0.05 significance level.

<Table 1>

Annual time series and the 11-year moving averages of hydro-meteorology and human activities are presented in Fig. 2. It can be seen that Q has an obvious decreasing trend before the 2000s, and then increases slightly. The climate factor precipitation P decreases before 2000, and then slightly increase, while potential evapotranspiration Ep shows a consistently increasing trend. As for human activities, it can be seen that most variables for human activities indicate two stages. IA increases before the 2000s, and then decreases slightly. SC increases over the period, but in different rates before and after 2000. Areas of cultivated land $LULC_C$ and unused land $LULC_U$ shows a decreasing trend nearly after 2000. Areas of forest $LULC_F$ and built-up land $LULC_B$ increase over the period. Overall, human activities increase before 2000, but then slow down.

<Fig. 2>

4.2 Estimation of the basin characteristics parameter

In the estimation of w_t^{ch} and w_t^h, to eliminate the influence of physical dimensions of different explanatory variables, all explanatory variables are normalized by their averages, among which, $\overline{P}$, $\overline{Ep}$, $\overline{IA}$, $\overline{SC}$, $\overline{LULC_C}$, $\overline{LULC_F}$, $\overline{LULC_G}$, $\overline{LULC_W}$, $\overline{LULC_B}$ and $\overline{LULC_U}$ are the averages of P, Ep, IA, SC,

$LULC_C$, $LULC_F$, $LULC_G$, $LULC_W$, $LULC_B$ and $LULC_U$ respectively. The suitable explanatory variables and corresponding function forms for w_t^{ch} and w_t^h are determined according to the BIC values, which are shown in Table 2. The estimated w_t^{ch} and w_t^h for the Weihe basin is given as:

$$w_t^{ch} = -6.761 + 0.809\exp(P/\overline{P}) + 2.711\exp(IA/\overline{IA}) + 0.126\exp(LULC_U/\overline{LULC_U}) \tag{31}$$

$$\begin{gathered} w_t^h = -0.594 + 1.378\exp(IA/\overline{IA}) - \\ 13.307\ln\left(LULC_C/\overline{LULC_C}\right) - 5.092\ln\left(LULC_F/\overline{LULC_F}\right) \end{gathered} \tag{32}$$

<Table 2>

Fig. 3 shows the w_t over the period and the comparison between w_t, w_t^{ch} and w_t^h. Fig. 3(a) indicates that the Budyko parameter estimated in the Weihe basin are unstable over the period, showing an increasing trend. As the result, when climate input data (precipitation and potential evapotranspiration) remain constant, the increasing Budyko parameter will lead to the increase of the evapotranspiration ratio and the decrease of runoff. This result is similar with previous studies in Weihe basin (Jiang et al, 2015). From Fig. 3(b) and (c), it is obvious that w_t^{ch} fits w_t better than w_t^h.

<Fig. 3>

Fig. 4 shows the comparison between the observed mean annual runoff and the simulated mean annual runoff with w_t, w_t^{ch} and w_t^h. It shows runoff estimated with w_t fits quite well with the observed runoff. There are only minor differences between runoff estimated with w_t and w_t^{ch}, and the differences are obvious between runoff estimated with w_t and w_t^h. Nash-Sutcliffe efficiency coefficient (NSE), root-mean-square error (RMSE) and relative error (RE) between the observed mean annual runoff and the simulated mean annual runoff with w_t^{ch} and w_t^h are shown in the Table 2 (Nash and Sutcliffe, 1970). It indicates that although both w_t^{ch} and w_t^h can explain the change of the parameter to some extent, w_t^{ch} performs obviously better than w_t^h. Specifically, RE between observed and simulated runoff is -0.04% when w_t^{ch} is applied, and reaches to -1.35% when w_t^h is applied. Overall, w_t^{ch} performs better than w_t^h. Thus, it is necessary to introduce climate factors to explain the change of the Budyko parameter reflecting basin characteristics in the Weihe basin.

<Fig. 4>

In the Fig. 4(a), it can be seen that runoff estimated with w_t^{ch} fits relatively worse with runoff estimated with w_t nearly after the middle of the 1990s. It indicates that the difference between w_t and w_t^{ch} may have a slight effect on the runoff change separation after the middle of the 1990s in the IBCR method. To quantify the impact that both w_t and w_t^{ch} are used in the IBCR method, the comparisons of the partial differentials ($\frac{\partial Q}{\partial P}$, $\frac{\partial Q}{\partial Ep}$ and $\frac{\partial Q}{\partial w}$) calculated based on w_t and w_t^{ch} in the IBCR method are shown in Fig. (5). It shows that the deviations of the partial differentials using w_t and w_t^{ch} are very small. Thus, the impact of simultaneously using w_t and w_t^{ch} in the IBCR method on the separation of runoff change is negligible.

<Fig. 5>

4.3 Comparison of separation results of the BCR method and the IBCR method

The change of mean annual runoff in each time window is quantified relative to mean annual runoff in the first time window 1979-1989 centered at 1984. Fig. 6 indicates the contributions of climate change and human activities to long-term runoff change estimated by both the BCR method and IBCR method. It shows that both climate change and human activities lead to the decline of long-term runoff. There is an obvious difference between separation results of the two methods. The BCR method indicates that the main driving factor to the decline of long-term runoff is related to climate change, while the IBCR method shows that the main driver is related to human activities.

<Fig. 6>

Fig. 7 demonstrates two components of ΔQ^{c} estimated by the IBCR method in the Weihe basin of China, where the direct climate effect on runoff change ΔQ^{c-d} is driven by both precipitation P and potential evapotranspiration Ep, and the indirect climate effect on runoff change ΔQ^{c-i} is only related to P. According to the equation (31), the decreasing P will lead to the decrease of the basin characteristics parameter w, and thus lead to the increase of runoff. In this case, P may alter basin characteristics through affecting the Normalized Difference Vegetation Index (NDVI) or scouring the soil surface. From the Fig. 7, the absolute values of ΔQ^{c-i} are almost the half of the absolute values of ΔQ^{c-d}. ΔQ^{c-d} is attributed to the decline of runoff, but ΔQ^{c-i} leads to the rise of runoff in the Weihe basin. Overall, the indirect climate effect on runoff change cannot be ignored in the

Weihe basin according to the IBCR method.

<Fig. 7>

To further analyze the dynamic change of the contributions to long-term runoff change in the BCR method and the IBCR method, ΔQ^c and ΔQ^h in three time windows that can approximately represent 1980s, 1990s, and 2000s are summarized in Fig. 8. From this figure, the effects of climate change and human activities vary over the whole period. For both methods, climate change poses a positive effect on the rise of runoff in 1980s, and on the decline of runoff in 1990s and 2010s. It can be seen that in the 1980s, the ratio of ΔQ^c to ΔQ is 192%, and the ration of ΔQ^h to ΔQ is -92% in the BCR method. It is unreasonable that both the climate and human activities experience such a great change, since the 1980s is only one year shift from the first time window centered at 1984. The results of the IBCR method are more reasonable. The climate effect on the runoff in the IBCR method is nearly half of that in the BCR method in the 1980s and 1990s, and more than half in the 2000s. This may due to that P, which determines the indirect climate effect according to the equation (31), experiences a slight increase in 2000s after a continuous decrease. From 1980s to 2000s, the ratio of ΔQ^h to ΔQ increase from -92% to 25%, and to 38% in the BCR method, and increase from 2% to 62%, and decrease to 59% in the IBCR method. The change of ΔQ^h in the IBCR method is more reasonable than that in the BCR method, since human activities increase due to the rapid development in 1980s and 1990s, but slow down in the 2000s. Overall, the separation results of the IBCR method is more reasonable than those of the BCR method.

<Fig. 8>

5 Discussion

5.1 Effectiveness and advantages of the IBCR method

In the study, the newly developed IBCR method has adopted the novel concept of the BCR method proposed by Zhou et al. (2016). Thus, it has the advantage of the BCR method that algebraic identities during the derivation have ensured that there is no non-closure problem in separating the observed runoff change into a number of the change components. In theory, the IBCR method developed in the study is a more comprehensive one with the BCR method as a special case of the IBCR method. This is because the derivation of the IBCR is based on the assumption that the Budyko parameter reflecting basin characteristics may relate to climate change and/or human activities, and the BCR is assumed that the basin characteristics parameter is only related to human activities. Overall, the IBCR method can be applied to more areas than the BCR method. In practice, to identify the necessity of developing the IBCR method, both the BCR method and the IBCR method are applies in a basin whose basin characteristics are related to both climate change and human activities, and results indicate the proposed improvement of the BCR method is necessary.

Apart from most studies that assume w, P and Ep are independent with each other, Jiang et al. (2015) has considered climate and human effects on the basin characteristics parameter in the Budyko-type equation during the runoff change separation, called “Jiang method”. In the Jiang method, the effect of the basin characteristics parameter on runoff change is estimated by the total differential method, and is furtherly separated by the ratios of climate change and human activities to the parameter. Compared with the IBCR method, there are non-closure problems in the Jiang method. Fig. 9 has depicted comparisons of the estimated runoff change attributed to human activities ΔQ^h and total runoff changes ΔQ between the IBCR method and the Jiang method. The figure shows that estimated ΔQ^h in the two methods are similar, and there is difference between simulated total runoff changes between the two methods. Thus, the IBCR method is effective, and is superior to the Jiang method.

<Fig. 9>

In this study, w_t simulated by statistical fitting is used in the IBCR method, and w_t^{ch} is only used to calculate the relationship of the basin characteristics parameter to its influential factors, enabling a direct comparison between the BCR method and the IBCR method. However, in further study, only w_t^{ch} is needed for runoff separation in the IBCR method. Since w_t^{ch} can be predicted through future climate and human factors, the IBCR method can also predict runoff change in the future using w_t^{ch}, while the BCR method cannot.

5.2 Limitations of the IBCR method

One issue should be noted that in practice the robustness of the IBCR method depends on how well the basin is characterized. This is because the separation results are highly affected by the relationship of the basin characteristics parameter in the

Budyko-type equation to its influential factors in the IBCR method. In the study, the relationship is estimated by using an 11-year moving window, and as many variables and function forms as possible have been used to find a set of explanatory variables and function forms providing the strongest explanatory power. According to the results, the estimated parameter w_t^{ch} performs better than the control case w_t^h, and the estimated runoff with w_t^{ch} fits quite well with the observed runoff, thus the relationship of the parameter to its influential factors in the w_t^{ch} is regarded to be effective in the study. However, available explanatory variables and suitable function forms are limited, and the underlying mechanisms of how the explanatory variables affect the basin characteristics parameter are unknown, thus there is still uncertainty in the results of this covariate analysis. Further studies remain required to estimate the relationship of the basin characteristics parameter to its explanatory variables.

In addition, climate change mentioned in the study only refer to the change of precipitation and potential evapotranspiration. The IBCR method cannot separate the impacts of other climate factors, such as temperature or wind speed, on runoff change. This is because both the direct effect and the indirect effect of the climate change on runoff change needed to be estimated based on precipitation and potential evapotranspiration in the IBCR method. However, according to Jiang et al. (2015), temperature change has the potential to affect the Budyko parameter in some basins, thus the newly developed method may be subject to some uncertainties in estimating the effects of climate change on runoff in some basins.

In this study, the general one-parameter Budyko hypothesis is used to separate runoff change, but there are also some multi-parameter Budyko equations proposed to account for the non-stationarity (Greve et al., 2016). It is obvious that the separation of runoff change based on the multi-parameter Budyko hypothesis is far more complicate than that on general one-parameter Budyko hypothesis, since its derivation of partial differentials needs to account for both the relationship between climate change and multiple parameters, and the relationship between different parameters. The IBCR method in this study can only be applied to the one-parameter Budyko hypothesis. Further studies can focus on improving the IBCR method to suit multi-parameter Budyko hypothesis.

6 Conclusions

In this study, the runoff change separation method based on an improved Budyko complementary relationship (IBCR) is developed considering that the basin characteristics parameter w in the Budyko equation may be affected by both climate change and human activities. The advantage of the IBCR method includes (i) algebraic identities have ensured that the non-closure problems often encountered in separating the observed runoff change into the change components are solved; (ii) relative to previous studies that assume the basin characteristics parameter is only related to human activities, the effect of climate change on basin characteristics can also be considered.

In the study, the separation method based on the IBCR, with the one-parameter Fu Equation as one concrete Budyko-type equation, is applied to attribute runoff change causes in the Weihe basin. The relationship of the Fu-Equation parameter w to factors of climate change and human activities is established and estimated by using an 11-year moving window. To identify the necessity of considering both the climate and human effects on the basin characteristics parameter in the Weihe basin, the separation method based on the Budyko complementary relationship (BCR) proposed by Zhou et al. (2016) is also applied. Results indicate that there are obvious differences in separation results between the BCR method and the IBCR method, which means whether considering the climate effect on the Budyko parameter w will have an impact on how to explain the causes of runoff change in the Weihe basin. By considering the Budyko parameter w to be function of not only climate change but also human activities, the IBCR method is regarded to be more flexible than the BCR for the separation of long-term runoff change, and is recommended to be used in investigating runoff change attribution in practice.

Acknowledgements

This research is financially supported jointly by the National Natural Science Foundation of China (NSFC Grants 51525902 and 41890822), the Research Council of Norway (FRINATEK Project 274310), and the Ministry of Education “Plan 111” Fund of China (B18037), all of which are greatly appreciated.

Declaration of interest

None.

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***Credit Author Statement**

Credit Author Statement

Han Yang: Conceptualization, Methodology, Software, Formal analysis, Writing - Original Draft. **Lihua Xiong:** Conceptualization, Resources, Writing - Review & Editing, Project administration, Funding acquisition. **Bin Xiong:** Methodology, Writing - Review & Editing. **Quan Zhang:** Writing - Review & Editing. **Chong-Yu Xu:** Writing - Review & Editing.

***Declaration of Interest Statement**

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:

Cover letter for Editors

Dear Editor:

Thanks to you all for your evaluation of our work and for your constructive comments and suggestions concerning our manuscript entitled "Separating runoff change by the improved Budyko complementary relationship considering effects of both climate change and human activities on basin characteristics" (HYDROL36652R1). These comments are all valuable and very helpful for significantly improving the quality of the manuscript.

The manuscript has been carefully revised according to the comments from the reviewers. Revised parts have been highlighted as red in the new version of the paper. The point-by-point responses to comments and the corresponding correction in the manuscript are presented in Revision Notes. Please note that the line number in reviewer's comments refers to the original manuscript, while in our reply refers to the revised version. We hope that the modifications will meet your satisfaction.

We hope that the modifications will meet your satisfaction. Looking forward to your consideration and further advices.

Yours sincerely,
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Tables

Table 1. Results of trend analysis for moving average points of hydro-meteorology and human activities using the modified Mann–Kendall trend test. Corrected Z_{MK} means Z statistic after variance correction considering the inherent autocorrelation, and original Z_{MK} is the original Mann-Kendall Z statistic. The symbol '*' indicates that the corresponding p value is below 0.05.

Variables	Corrected Z_{MK}	Trend	Original Z_{MK}	Trend
Q	-1.09	↓	-2.00*	↓
P	-0.03	↓	-0.09	↓
Ep	3.12*	↑	4.67*	↑
IA	1.03	↑	1.88	↑
SC	2.49*	↑	3.88*	↑
$LULC_C$	-3.80*	↓	-6.92*	↓
$LULC_F$	3.66*	↑	6.50*	↑
$LULC_G$	2.77*	↑	4.98*	↑
$LULC_W$	1.52	↑	2.79*	↑
$LULC_B$	2.77*	↑	4.98*	↑
$LULC_U$	1.03	↑	1.71	↑

Table 2. Results of covariate analysis for the Budyko parameter. w_t^{ch} indicates the usage of explanatory variables of both climate change and human activities, and w_t^{h} indicates the usage of only human activities explanatory variables. NSE, RMSE and RE represent Nash-Sutcliffe efficiency coefficient, root-mean-square error, and relative error between observed runoff and simulated runoff with corresponding parameter, respectively.

Parameter	Covariates for the parameter	BIC	NSE	RMSE	RE (%)
w_t^{ch}	$\exp\left(P/\overline{P}\right)$, $\exp\left(IA/\overline{IA}\right)$, $\exp\left(LULC_U/\overline{LULC_U}\right)$	98.50	0.99	1.19	-0.40
w_t^{h}	$\exp\left(IA/\overline{IA}\right)$, $\ln\left(LULC_C/\overline{LULC_C}\right)$, $\ln\left(LULC_F/\overline{LULC_F}\right)$	107.28	0.96	1.69	-1.35

Figure1

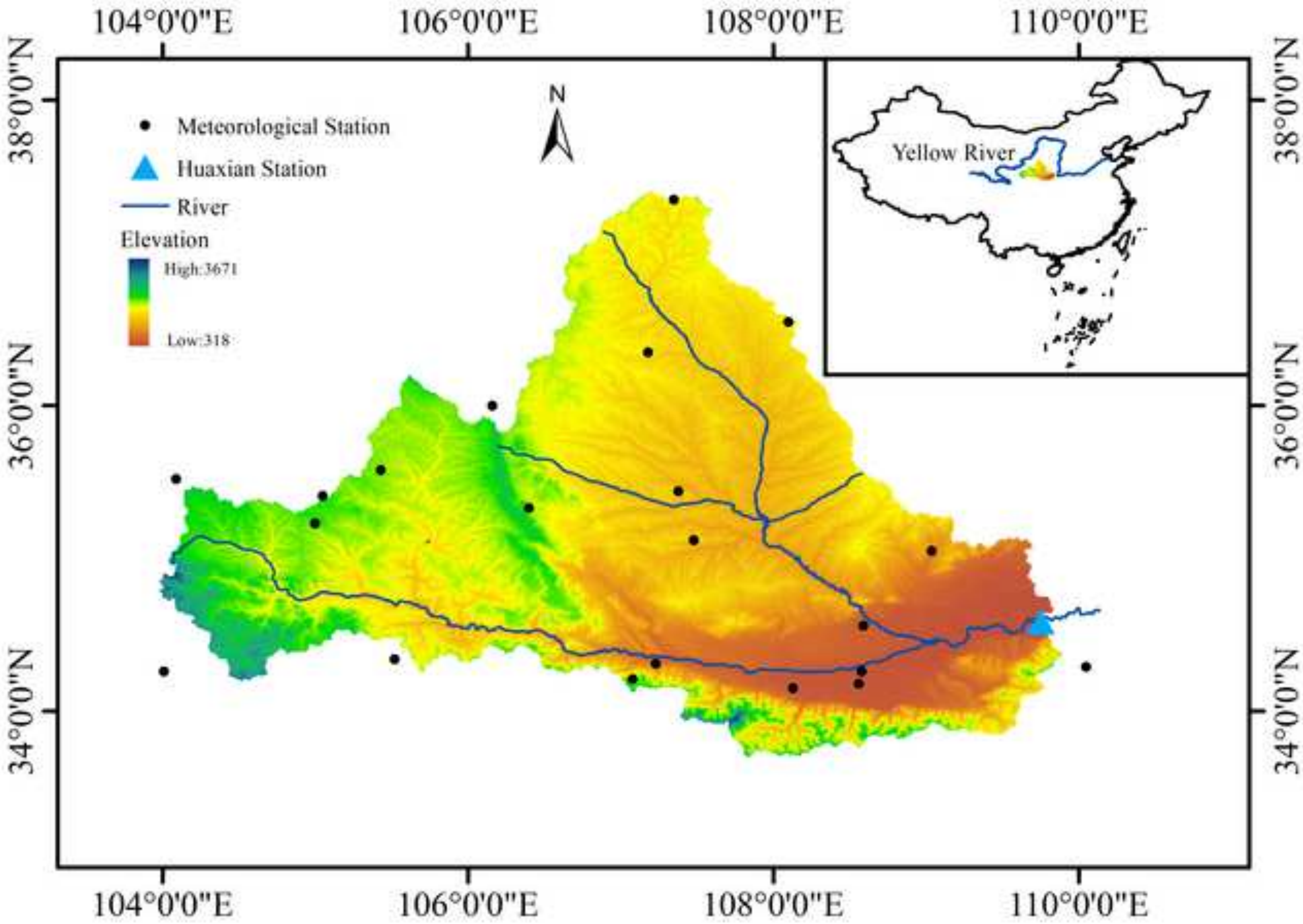
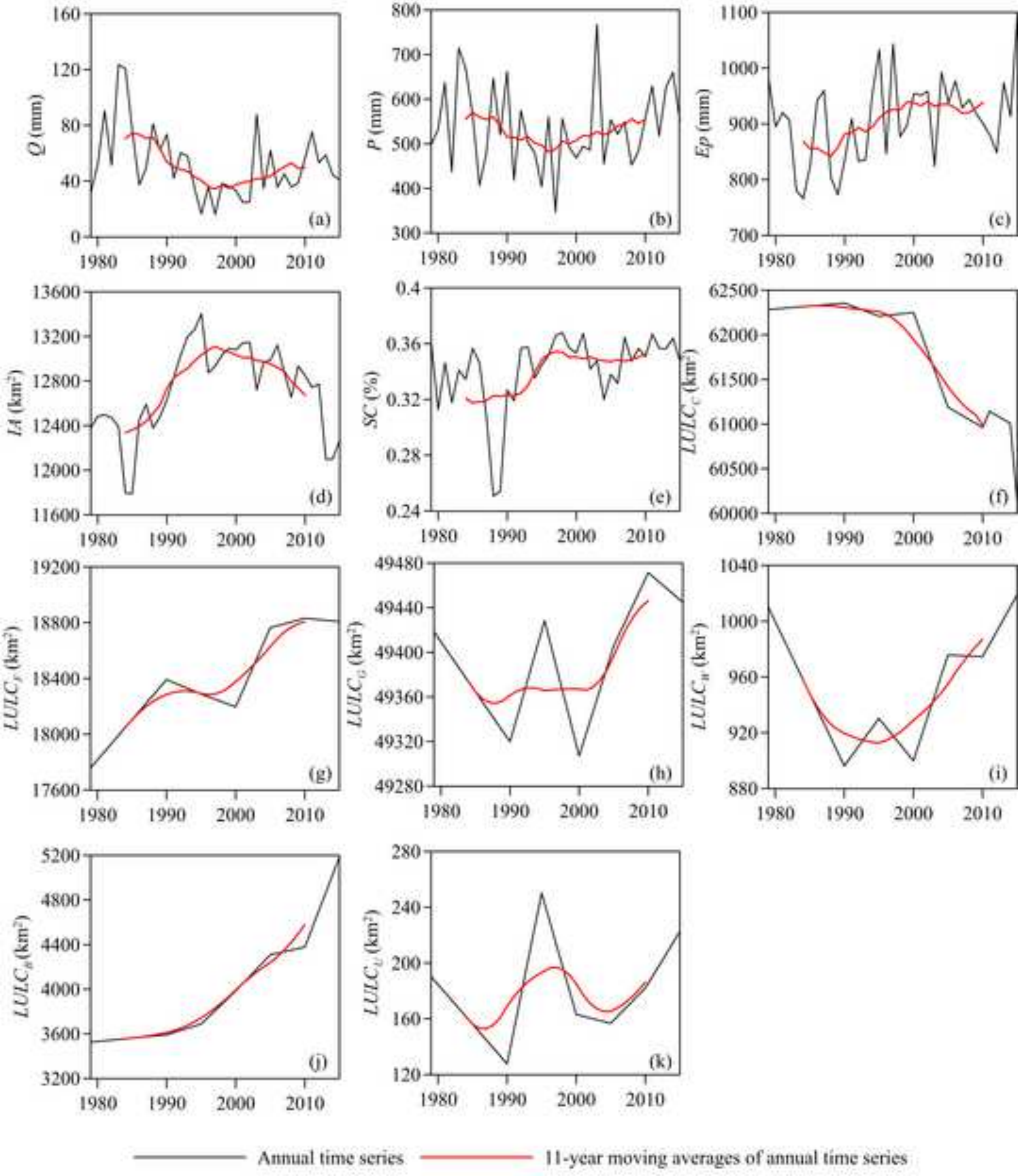

104°0'0"E
106°0'0"E
108°0'0"E
110°0'0"E
38°0'0"N
36°0'0"N
34°0'0"N
N
● Meteorological Station
▲ Huaxian Station
River
Elevation
High:3671
Low:318
Yellow River

Figure2


Q (mm)
0
40
80
120
160
(a)
P (mm)
300
400
500
600
700
800
(b)
Ep (mm)
700
800
900
1000
1100
(c)
IA (km²)
11600
12000
12400
12800
13200
13600
(d)
SC (%)
0.24
0.28
0.32
0.36
0.4
(e)
LULC_C (km²)
60000
60500
61000
61500
62000
62500
(f)
LULC_F (km²)
17600
18000
18400
18800
19200
(g)
LULC_G (km²)
49280
49320
49360
49400
49440
49480
(h)
LULC_W (km²)
880
920
960
1000
1040
(i)
LULC_B (km²)
3200
3600
4000
4400
4800
5200
(j)
LULC_U (km²)
120
160
200
240
280
(k)
1980
1990
2000
2010
Annual time series
11-year moving averages of annual time series

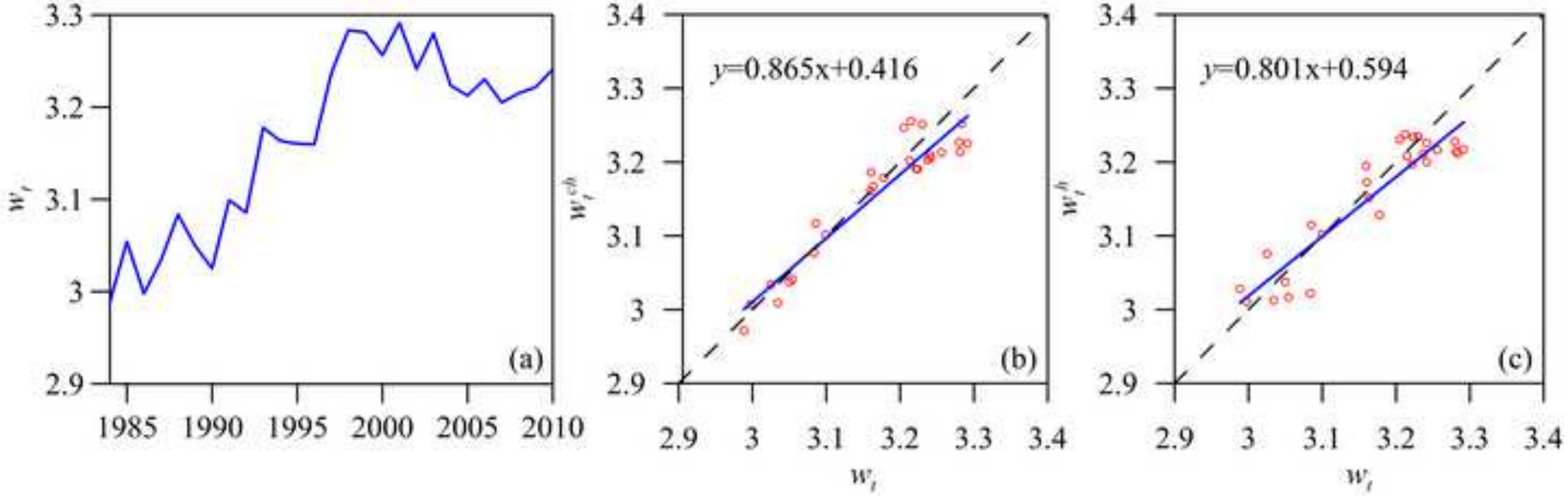

3.3
3.2
3.1
3
2.9
w_t
1985
1990
1995
2000
2005
2010
(a)
3.4
3.3
3.2
3.1
3
2.9
w_t^{ch}
y=0.865x+0.416
2.9
3
3.1
3.2
3.3
3.4
w_t
(b)
3.4
3.3
3.2
3.1
3
2.9
w_t^{h}
y=0.801x+0.594
2.9
3
3.1
3.2
3.3
3.4
w_t
(c)

Figure4

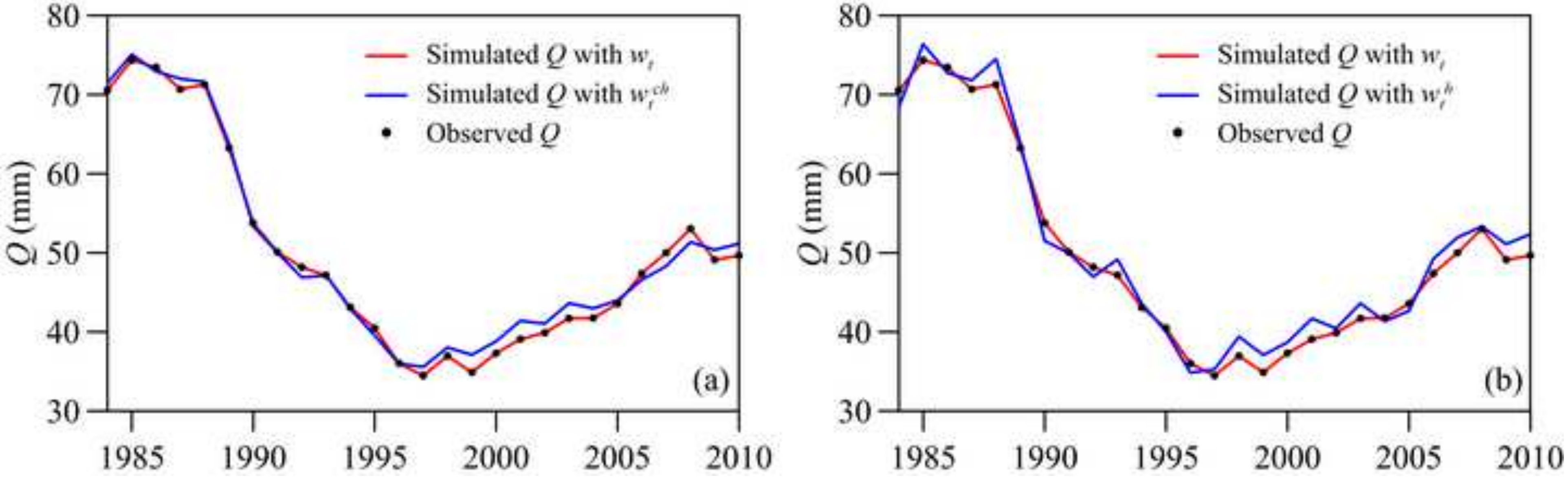

80
70
60
50
40
30
Q (mm)
1985
1990
1995
2000
2005
2010
Simulated Q with w_t
Simulated Q with w_t^{ch}
Observed Q
(a)
80
70
60
50
40
30
Q (mm)
1985
1990
1995
2000
2005
2010
Simulated Q with w_t
Simulated Q with w_t^{h}
Observed Q
(b)

Figure5

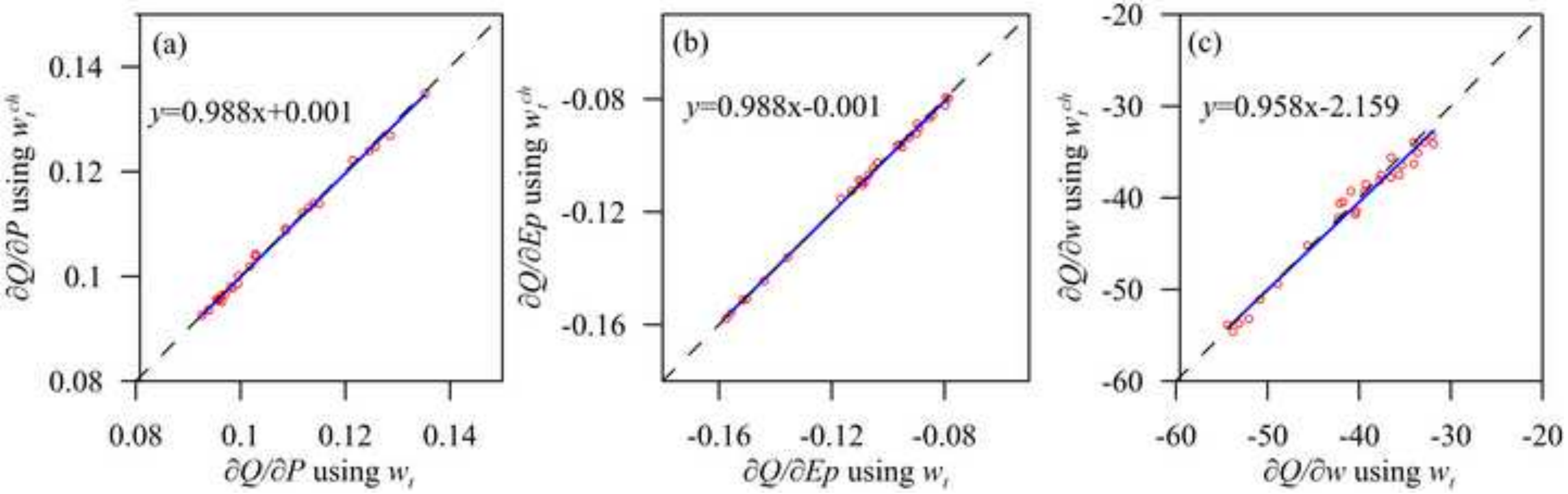

(a)
y=0.988x+0.001
0.08
0.1
0.12
0.14
∂Q/∂P using w_t^ch
∂Q/∂P using w_t
(b)
y=0.988x-0.001
-0.16
-0.12
-0.08
∂Q/∂Ep using w_t^ch
∂Q/∂Ep using w_t
(c)
y=0.958x-2.159
-60
-50
-40
-30
-20
∂Q/∂w using w_t^ch
∂Q/∂w using w_t

Figure6

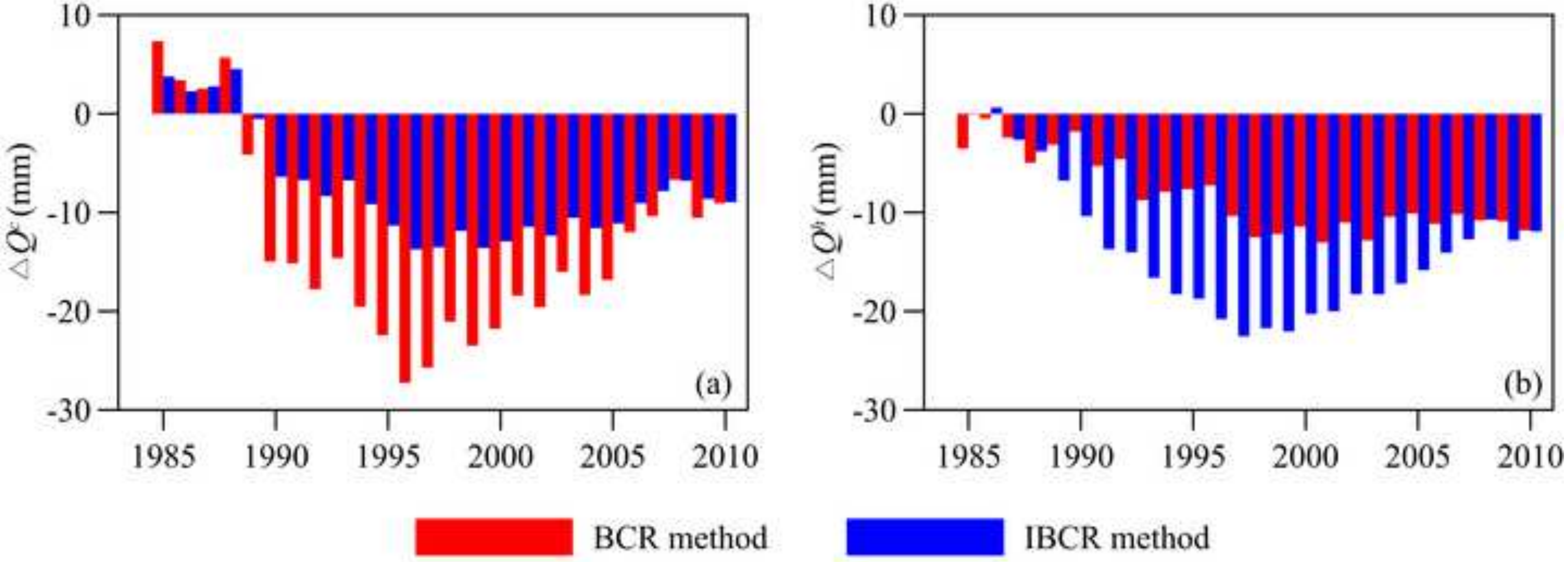

10
0
-10
-20
-30
△Q^c (mm)
1985
1990
1995
2000
2005
2010
(a)
10
0
-10
-20
-30
△Q^h (mm)
1985
1990
1995
2000
2005
2010
(b)
🟥 BCR method
🟦 IBCR method

Figure7

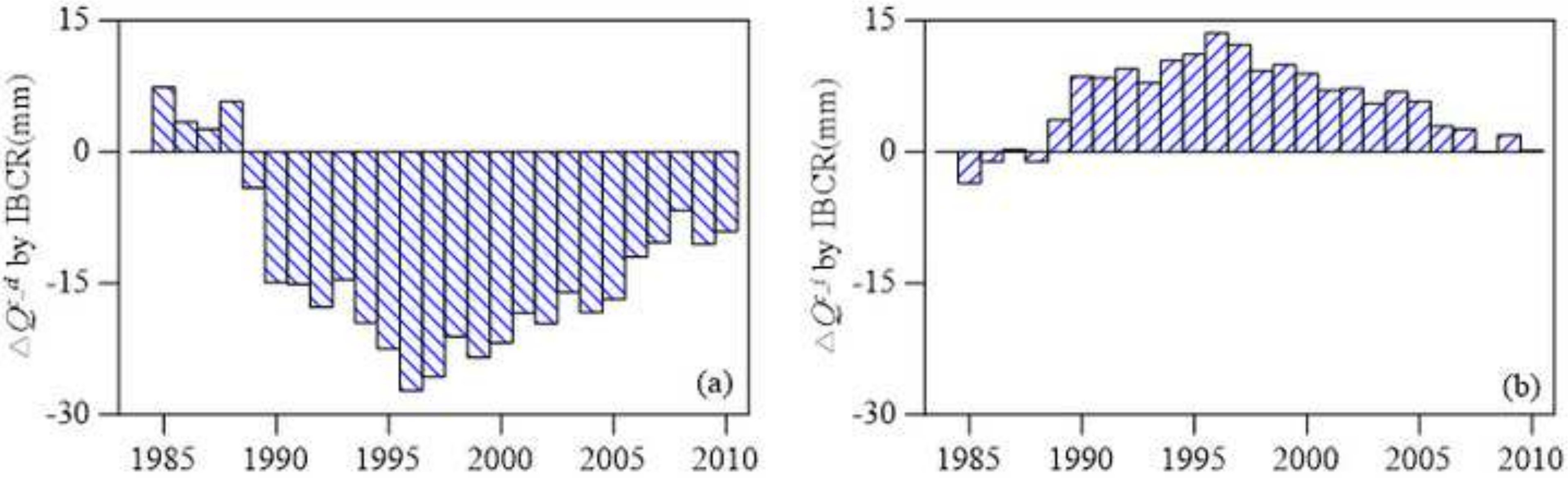

15
0
-15
-30
$\triangle Q^{-d}$ by IBCR(mm)
1985
1990
1995
2000
2005
2010
(a)
15
0
-15
-30
$\triangle Q^{-l}$ by IBCR(mm)
1985
1990
1995
2000
2005
2010
(b)

Figure8

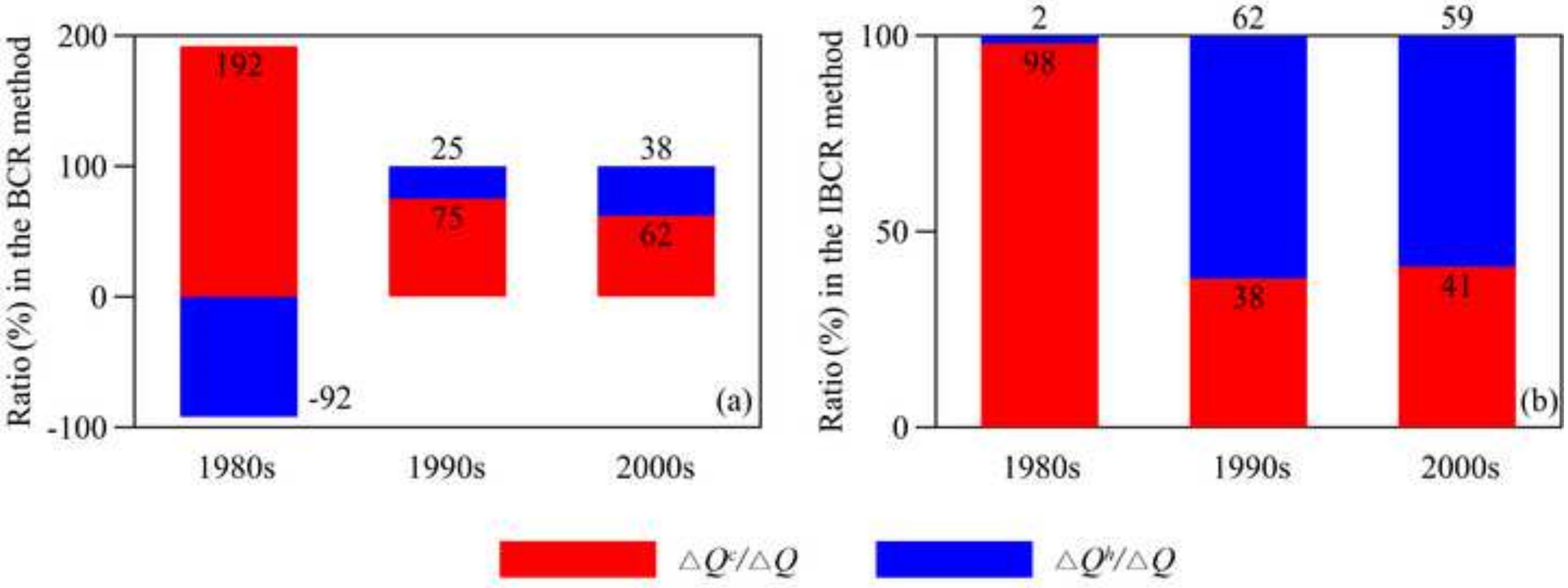

Ratio (%) in the BCR method
200
100
0
-100
192
-92
25
75
38
62
(a)
1980s
1990s
2000s
Ratio (%) in the IBCR method
100
50
0
2
98
62
38
59
41
(b)
1980s
1990s
2000s
$\triangle Q^c/\triangle Q$
$\triangle Q^h/\triangle Q$

Figure9

Click here to download high resolution image

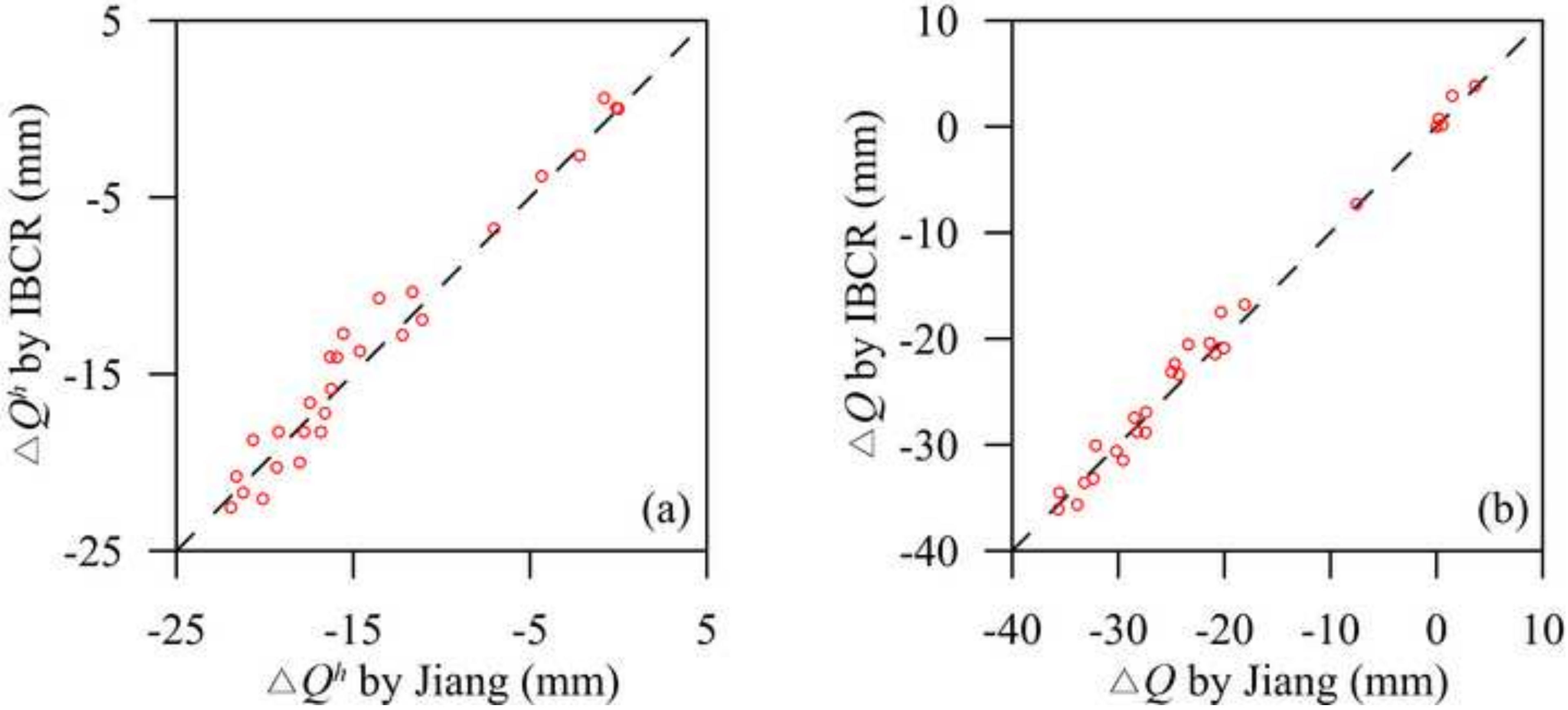


Fig. 1. Topography, river networks, meteorological stations and the Huaxian hydrological station in the Weihe basin.

Fig. 2. Evolutions of hydrological variables, including runoff Q (a), precipitation P (b), potential evapotranspiration Ep (c), and explanatory variables of human activities, including irrigated area IA (d), soil water storage capacity SC (e), cultivated land $LULC_C$ (f), forest $LULC_F$ (g), grassland $LULC_G$ (h), water bodies $LULC_W$ (i), built-up land $LULC_B$ (j) and unused land $LULC_U$ (k), in the Weihe basin.

Fig. 3. (a) The basin characteristics parameter w_t estimated directly by the maximum likelihood estimation method (MLE) (no covariate analysis); (b) Comparison between w_t and w_t^{ch} calculated by the equation (31); (c) Comparison between w_t and w_t^h calculated by the equation (32).

Fig. 4. The comparison of the simulated mean annual runoff Q with w_t and w_t^{ch} (a), and with w_t and w_t^h (b) to corresponding observed mean annual runoff.

Fig. 5. The comparison between the partial differentials calculated with w_t and w_t^{ch} in the IBCR method. (a), (b) and (c) are for $\partial Q/\partial P$, $\partial Q/\partial Ep$ and $\partial Q/\partial w$, respectively.

Fig. 6. (a) The contribution of climate change to long-term runoff change ΔQ^c and (b) the contribution of human activities to long-term runoff change ΔQ^h estimated by the Budyko complementary relationship (BCR) method and the improved Budyko complementary relationship (IBCR) method. ΔQ^c and ΔQ^h are quantified relative to the mean annual runoff in the first time window 1979-1989, which is centered at 1984.

Fig. 7. Two components of ΔQ^c estimated by the improved Budyko complementary relationship (IBCR) method, including (a) ΔQ^{c-d} that is attributed to the direct climate effect, i.e. the impact

of changes in P and Ep on Q, and (b) ΔQ^{c-i} that is attributed to the indirect climate effect, i.e. the impact on Q of changes in Budyko parameter w that are caused by changes in P and Ep. ΔQ^{c-d} and ΔQ^{c-i} are quantified relative to the mean annual runoff in the first time window 1979-1989, which is centered at 1984.

Fig. 8. The relative contributions of climate change ΔQ^{c} and human activities ΔQ^{h} to runoff change ΔQ in three time windows that approximately represent 1980s, 1990s, and 2000s estimated by the Budyko complementary relationship (BCR) method (a) and the improved Budyko complementary relationship (IBCR) method (b). ΔQ, ΔQ^{c}, and ΔQ^{h} are quantified relative to the mean annual runoff in the first time window 1979-1989, which is centered at 1984.

Fig. 9. Comparison of the (a) estimated ΔQ^{h} attributed to human activities and (b) estimated total runoff ΔQ in the improved Budyko complementary relationship (IBCR) method with the corresponding ΔQ^{h} and ΔQ calculated by the separation method proposed by Jiang et al. (2015) (Jiang method). ΔQ^{h} and ΔQ are quantified relative to the mean annual runoff in the first time window 1979-1989, which is centered at 1984.