Quantifying the contribution of climate- and human-induced runoff decrease in the Luanhe river basin, China

Jianzhu Li and Shuhan Zhou

ABSTRACT

Climate variability and human activities are two main factors influencing hydrological processes. For more reasonable water management, understanding and quantifying the contributions of the two factors to runoff change is a prerequisite. In this paper, the Budyko decomposition hypothesis and the geometric approach were employed to quantify climate change and human activities on mean annual runoff (MAR) in six sub-basins of Luanhe river basin. We split a long-term period (1956–2011) into two sub-periods (pre-change and post-change periods) to quantify the change over time. Observations show that annual runoff has had a decreasing trend during the past 56 years in the Luanhe river basin. Based on a geometric approach, the climate impacts in these six sub-basins were 7–49%, and the contributions of human activities were 51–93%, approximately. According to the Budyko decomposition method, impacts of climate variation accounted for 15–40% of the runoff decrease, and the contribution of human activities was 60–85%. Both methods were simple to understand, and it is feasible to separate the climatic- and human-induced impacts on MAR. This study could provide significant information for water resources managers.

Key words | Budyko decomposition method, climate-caused runoff change, geometric approach, human-induced runoff change, Luanhe river basin, mean annual runoff

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INTRODUCTION

Quantifying climate variability and human activities on mean annual runoff (MAR) has received much attention, since climate change and human activities are known to affect hydrologic cycles and exert impacts on our environment on a global scale (Barnett *et al.* 2008; Zhang *et al.* 2008; Wang & Cai 2010). Human activities such as land use changes, water withdrawals, reservoir operations, and return flow can affect hydrological processes (Wang & Cai 2010; Schilling *et al.* 2010). Climate change and its impact on water resources is a problem that has to be coped with worldwide (Piao *et al.* 2010), because climate change can affect runoff by the redistribution of precipitation and temperature change (Karl *et al.* 1996). However, hydrological processes are subject to the combined effects of climate change and human activities (Berry *et al.* 2005; Rodriguez-lturbe & Porporato 2005; Donohue *et al.* 2007), resulting in basin-scale changes in runoff or the water balance (Sun 2007; Zhang *et al.* 2008). Therefore, quantification of the impacts of climate change and human activities on hydrology and water resources is of vital necessity (Lane *et al.* 2005; Siriwardena *et al.* 2006; Tuteja *et al.* 2007; Huo *et al.* 2008; Yang & Tian 2009; Wei & Zhang 2010; St. Jacques *et al.* 2010).

In order to quantify the climate- and human-induced impacts on MAR accurately, various methods have been proposed. One way was to adopt hydrological models such as SWAT (Liu *et al.* 2013a), HBV (Liu *et al.* 2013b) and SIMHYD (Bao *et al.* 2012), etc., by varying the meteorological inputs to obtain the quantitative assessment of human impacts. However, there were structural errors for hydrological models, suggesting that the estimated human impacts may be inaccurate or insensitive to climate change (Sankarasubramanian *et al.* 2001; Sun 2007; Zheng *et al.*

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2009; Xu *et al.* 2014). Another way was to use empirical approaches or conceptual models. Empirical approaches such as statistical regression methods have always been short of physical meaning (Ma *et al.* 2008; Schilling *et al.* 2010; Xu *et al.* 2014). Conceptual models built on the principle of water-energy balance have been useful for investigating the hydrological response (Renner *et al.* 2012b). Some conceptual models were developed based on the Budyko hypothesis (Budyko 1974). Wang & Hejazi (2011) quantified the climate- and human-induced impacts for 413 gauge stations by the Budyko decomposition method across the USA. Wang *et al.* (2013) used hydrological sensitivity analysis, the Budyko decomposition method and Zhang's curve (Zhang *et al.* 2001) to evaluate the effects of climate variability and human activities on runoff in the Haihe River basin, suggesting that the Budyko decomposition method was valid in the Haihe River basin. Li (2014) developed a stochastic soil moisture model within the Budyko framework (Fu's equation), and distinguished the impact of interannual variability of precipitation and potential evaporation on evapotranspiration in the USA.

Moreover, in a remarkable paper, Tomer & Schilling (2009) introduced a method to distinguish climate effects from land use change effects on runoff. They observed different soil conservation treatments, and the watershed showed different evaporation ratios. They found that the shift within this hydro-climatic state space was perpendicular to the observed shift over time, due to the conservation treatments. Renner *et al.* (2014) used this separation method to quantify the contributions of environmental factors to evaporation in 68 small–medium river basins, which cover the greatest part of the German Federal State of Saxony, and they confirmed the validity of this method. However, the geometric approach is rarely used in China.

Many studies in recent years have focused on quantification of climate change and human activities on MAR in the Luanhe river basin, China. The Luanhe River is a very significant water resource for Tianjin City, an important municipality city in China. Previous studies chose different models/methods to quantify the influence of climate change and human activities on MAR, and they achieved opposite results about whether climate variability or human activity was the main driving factor for the reduction of the MAR in the Luanhe river basin. Bao *et al.* (2012) used the Variable Infiltration Capacity (VIC) model to prove that climate variability was the major driving factor in the Luanhe river basin. Zeng *et al.* (2014) combined a hydrological model (Distributed Time Variant Gain Model) and a global terrestrial biogeochemical model (CASACNP) to estimate the effects of climate change, land use/land cover (LUCC) and increase in CO_2 concentration on runoff in the Luanhe river basin, and they reported that the effects of climate change and LUCC on runoff are stronger. Xu *et al.* (2013) made a statistical analysis and found a 79.5% decrease of annual inflow in the Panjiakou Reservoir caused by climate change and human activities. However, they did not separate the contributions of each factor. Wang *et al.* (2013) discovered that the impact of human activities was the main driving factor for the decline of annual runoff in the Luanhe river basin. Therefore, there is a need for a consistent understanding of the dominant cause for the reduction of runoff in the Luanhe river basin.

The main objectives of this study were to: (1) illustrate runoff decrease in the study regions by observing the annual rainfall-runoff relationships; and (2) quantify the contributions of climate change and human activities to MAR in the Luanhe river basin by the Budyko decomposition method and the geometric approach.

STUDY AREA

The Luanhe river basin is located at the northeast part of China (Figure 1). It extends from 115 °30′E to 119 °15′E longitude and 39 °10′N to 42 °30′N latitude with a total drainage area of 44,600 km^2. The elevation within the basin ranges from 2 to 2,205 m and averages 766 m. In the entire area, the topography significantly descends from northwest to southeast, and mountainous regions account for nearly 98% of the area while plains account for about 2%. The basin has a temperate, semi-arid continental monsoon climate, with an annual average temperature of –0.3–11 °C, and the annual average precipitation is 516.6 mm (ranging from 400 to 700 mm) per year in the Sandaohezi sub-basin. The potential evaporation (E_P), with original data obtained from DuoLun meteorological station in the Sandaohezi sub-basin, was calculated by the Penman–Monteith equation,

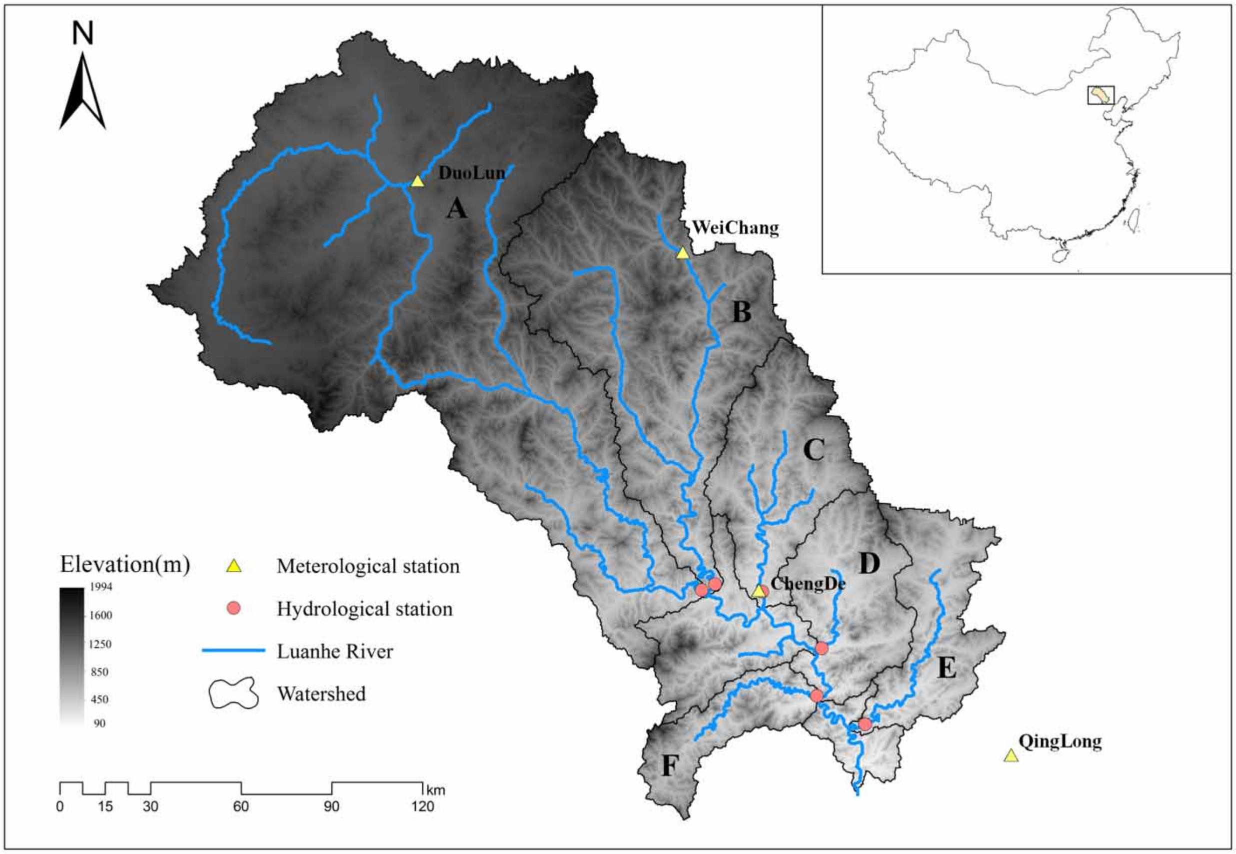

Figure 1 | Map showing the locations of the six sub-basins (A Sandaohezi sub-basin, B Yixunhe sub-basin, C Wuliehe sub-basin, D Laoniuhe sub-basin, E Baohe sub-basin, F Liuhe sub-basin) in the Luanhe river basin and the gauging stations used in this study.

and we found that the potential evaporation (E_P) (ranging from 620 to 1,416 mm) had a decreasing trend.

The spatial and temporal distribution of the precipitation within the Luanhe river basin is uneven, and about 70–80% of the annual precipitation falls in the rainy months of June to September. The region receives an average runoff of 4.69 billion cubic meters per year. Floods in the basin are often caused by rainstorms and occur in July and August, since the rainstorms with characteristics of short duration and high intensity are likely to result in floods of high peaks and large amounts.

The Luanhe river basin is well known for its water supply function for the Tianjin city, an important metropolis of China. It was planned to introduce a billion cubic meters of water to Tianjin per year from the basin. However, the actual amount of water transferred to Tianjin has been less than this for several years, especially in the last decade (Li *et al.* 2014). The deficient water supply to Tianjin is mainly due to the decrease of annual water storage in the Panjiakou reservoir in the 21st century. Due to rainfall reduction, land use change and construction of many small check dams for soil and water conservation, the average annual runoff decreased by about 30% after 1980 (Li & Feng 2007). The long-lasting water shortage aggravated the water crisis in Tianjin city (Yi *et al.* 2011; Liu & Wu 2012). In this study, six sub-watersheds were selected, Luanhe, Yixunhe, Wuliehe, Liuhe, Baohe and Laoniuhe, with areas of 17,100 km^2, 6,761 km^2, 2,460 km^2, 626 km^2, 1,661 km^2 and 1,615 km^2, respectively.

DATA AND METHODS

Data

The observed data of annual precipitation and runoff for each sub-basin during the period of 1956–2011 are presented in Figure 2. Monthly rainfall and runoff data for the period 1956–2011 were provided by the Hydrology and Water Resource Survey Bureau of Hebei Province. Daily meteorological data at four stations were downloaded from the China Administration of Meteorology. Monthly average maximum and minimum air, sunshine hours, wind speed and relative humidity data for the period 1956–2011 were used to calculate potential evapotranspiration (E_P) using the Penman–Monteith equation recommended by The United Nations Food and Agriculture Organization (FAO) (Allen *et al.* 1994).

Methods

In this study, the Budyko decomposition method and the geometric approach were used to quantify the contributions of climate-caused and human-induced impact on MAR. The procedures of both methods are listed in the following sections.

Budyko decomposition method

Budyko (1948) and Budyko & Zubenok (1961) postulated that the mean annual evaporation from a watershed could

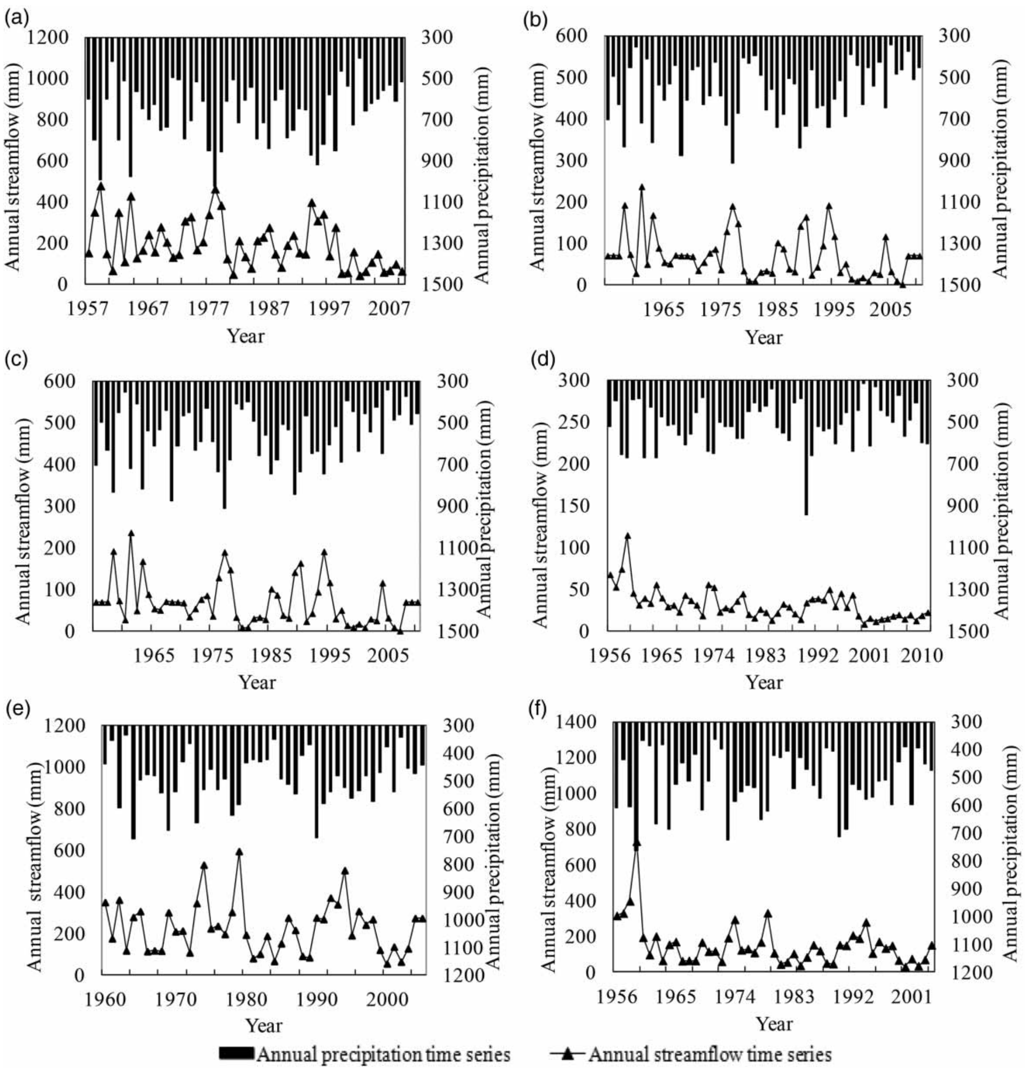

Figure 2 | Annual runoff and precipitation time series of the selected sub-basins. (a) Liuhe sub-basin, (b) Baohe sub-basin, (c) Laoniuhe sub-basin, (d) Sandaohezi sub-basin, (e) Yixunhe sub-basin, (f) Wuliehe sub-basin.

be determined from precipitation and net radiation, known as the 'Budyko curve'. Based on worldwide data on a large number of watersheds, Budyko (1974) developed a framework for estimating actual evapotranspiration based on a dryness index. Dooge (1992) studied how the decomposition method might approach the problem of analyzing the sensitivity of streamflow to climate change. In 1999, Dooge *et al.* (1999) considered that both precipitation and potential evapotranspiration can lead to changes in water balance. On this basis, Ma *et al.* (2008) postulated that the total change in MAR can be estimated as the change in MAR due to climate variability and the change in MAR caused by land use/cover change.

The concept of water balance provides a framework for basin hydrological processes, and it can also provide the conditions for Budyko hypothetical analysis. The simplified water balance equation for the long-term annual timescales for a river basin can be expressed as:

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

where ΔS_W is the watershed storage change, and for a series of consecutive years, the amount of water stored in the watershed is minimized, which is often considered to be zero ($\Delta S_W = 0$). The runoff (Q) is a function of precipitation (P) and evaporation (E) ratio:

$$Q = P(1 - E/P) \tag{2}$$

The energy balance equation reads as:

$$Rn = L \cdot E + H + \Delta S_e \tag{3}$$

where R_n denotes net radiation, the latent heat flux LE (i.e., L multiplied by E) and the sensible heat flux H, L denotes the latent heat of vaporization and ΔS_e is the energy storage change. For a series of consecutive years, we consider ΔS_e as zero.

The Budyko decomposition method was used to analyze the water-energy balance over a long-term temporal scale. Previous studies have proposed the Budyko framework in different functional forms (Pike 1964; Fu 1981; Zhang *et al.* 2004; Yang *et al.* 2008). A widely used form of the Budyko decomposition method is Fu's (1981) equation expressed as:

$$\frac{E}{P} = 1 + \frac{E_P}{P} - \left[1 + \left(\frac{E_P}{P}\right)^{\omega}\right]^{1/\omega} \tag{4}$$

where E_p is potential evaporation and ω is a single parameter. Each basin has emerged as different Budyko curves due to a different value of ω (Figure 3).

Both precipitation and potential evaporation can lead to changes in water balance (Dooge *et al.* 1999), so first order, total runoff change can be computed by:

$$\Delta Q = Q_2 - Q_1 \tag{5}$$

where Q is calculated by Equation (2). Q_1 and Q_2 are the MAR in the pre-change period and post-change period, respectively.

The total change in MAR can be estimated as:

$$\Delta Q = \Delta Q_C + \Delta Q_H \tag{6}$$

where ΔQ_C is the change in MAR caused by climate variability, ΔQ_H represents the change in MAR due to human activities.

Changes in mean annual precipitation and potential evaporation can lead to changes in annual runoff and their relationship can be approximated as (Milly & Dunne

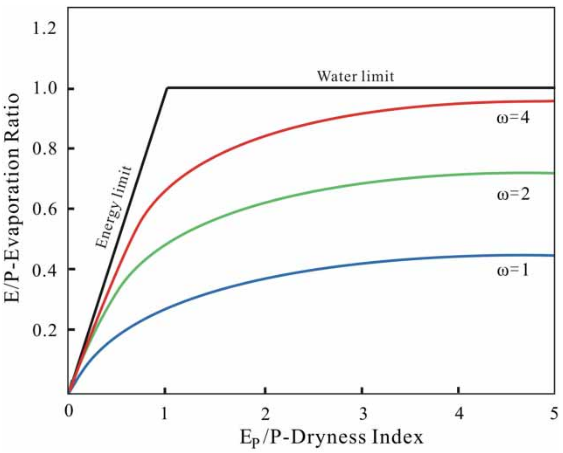

Figure 3 | Relationships between elements of the catchment water balance as per the Fu's formulations of the Budyko framework (Equation (4)) for the typical range in ω.

2002; Ma *et al.* 2008):

$$\Delta Q_C = \frac{\partial Q}{\partial P}\Delta P + \frac{\partial Q}{\partial E}\Delta E_P \quad (7)$$

where ΔP, ΔE_P are changes in precipitation and potential evaporation, respectively, and:

$$\frac{\partial Q}{\partial P} = P^{(\omega-1)}(E_P^{\omega} + P^{\omega})^{1/\omega-1} \quad (8)$$

$$\frac{\partial Q}{\partial E_P} = E_P{}^{(\omega-1)}(E_P^{\omega} + P^{\omega})^{1/\omega-1} - 1 \quad (9)$$

are obtained from Equations (1) and (4).

The climate-caused and human-induced percentage changes of annual runoff have been estimated for some specific watersheds (Zhang *et al.* 2008), expressed as:

$$\begin{aligned} C_b &= 100(\Delta Q_C/\Delta Q) \\ H_b &= 100(\Delta Q_H/\Delta Q) \end{aligned} \quad (10)$$

Geometric approach

The geometric approach was proposed by Tomer & Schilling (2009). They use this concept model to distinguish the effects of climate change from land use change effects on streamflow. Two dimensionless variables were described as relative excess water demand (W) and energy demand (U), respectively. Both variables can be derived by the water balance equation with precipitation and the energy balance equation with the potential evaporation (E_P) or water equivalent of net radiation (Rn/L) (Renner & Bernhofer 2012a). More details of the relationship can be found in Renner & Bernhofer (2012a), Renner *et al.* (2012b). Both of the variables are expressed as:

$$\begin{aligned} W &= 1 - \frac{E}{P} = 1 - q, \\ U &= 1 - \frac{E}{Rn/L} = 1 - \frac{E}{E_P} = 1 - g \end{aligned} \quad (11)$$

where W and U are the values within the interval (0, 1). The relative excess water W is equal to the proportion of available unused water; the relative excess energy U is equal to the proportion of available unused energy. q and g are the two dimensionless variables to describe water partitioning and energy partitioning expressed as:

$$q = E/P; \quad g = E/E_P. \quad (12)$$

Figure 4 shows the principle of quantifying the contributions of climate and human activities to runoff change (Renner *et al.* 2012b). (q_0, g_0) represents the pre-change point, and (q_1, g_1) represents the post-change point in the diagram, and the position of the point (q_b, g_b) is determined by the geometric approach method. The full arrow line is determined by both climate- and human-induced components. The green arrow line (from the point (q_b, g_b) to the point (q_1, g_1)) and the blue arrow line (from the point (q_0, g_0) to the point (q_b, g_b)) depict the climate- and human-induced components of this transition, respectively.

In order to calculate the contribution of climate- and human-induced impact on the runoff, the specific steps (referred to by Renner *et al.* (2014)) are as follows:

1. Calculate the annual average of water partitioning and energy partitioning in the pre-change and post-change periods, respectively, i.e., $q_0 = E_0/P_0$ and $g_0 = E_0/E_{P0}$, $q_1 = E_1/P_1$ and $g_1 = E_1/E_{P1}$, where P_0, P_1, E_0, E_1, E_{P0} and E_{P1} represent the average annual precipitation,

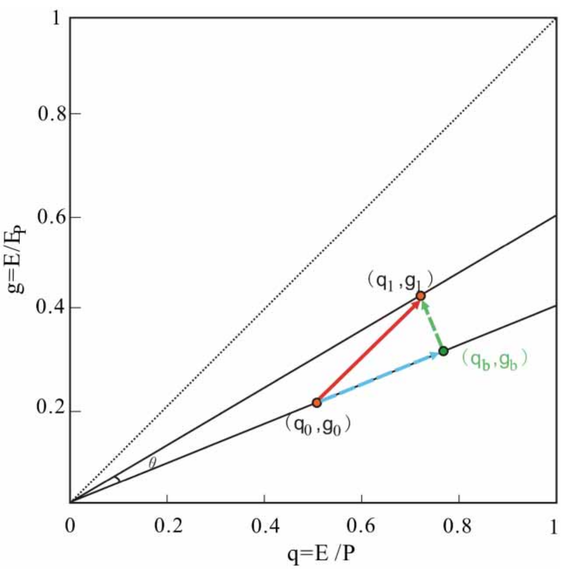

Figure 4 | Illustration of the separation of climate and human impacts in the diagram (Renner *et al.* 2012b).

actual evaporation and the potential evaporation in different periods, respectively.

2. Solve the angle of θ, the angle between both vectors, which can be described by the scalar product divided by the vector magnitudes in two different ways, given as:

$$\sin(\theta) = \frac{q_0 g_1 - q_1 g_0}{\sqrt{q_0^2 + g_0^2}\sqrt{q_1^2 + g_1^2}}$$
$$\sin(\theta) = \frac{\sqrt{(q_b - q_1)^2 + (g_b - g_1)^2}}{\sqrt{q_1^2 + g_1^2}} \quad (13)$$

3. Derive the numerical of g_b and q_b alternating the use of Equations (12) and (13). After conversion, the mathematical expressions are as follows:

$$g_b = q_b g_0 / q_0 \quad (14)$$

$$q_b = \frac{g_0 g_1 q_0 + q_0^2 q_1}{g_0^2 + q_0^2} \quad (15)$$

4. E_b at point (q_b, g_b) can be computed as $E_b = q_b P_0$. The absolute differences between evaporation rate (E_0, E_1) and E_b can be available for determining the climatic (ΔE_C) and human-induced (ΔE_H) parts of change:

$$\Delta E_C = E_b - E_0$$
$$\Delta E_H = E_1 - E_b \quad (16)$$

5. Calculate the climate- (ΔQ_C) and human-induced (ΔQ_H) contributions to the runoff change. They can be computed directly by assuming zero storage change in the water balance equation. The specific expressions are:

$$\Delta Q = Q_2 - Q_1 = \Delta Q_C + \Delta Q_H$$
$$\Delta Q_C = Q_b - Q_0 \quad (17)$$

RESULTS

The change in the precipitation–runoff relationship

In order to assess the influence of environmental change on runoff variation, the change point of the runoff series should be detected first in the six sub-watersheds. Wang *et al.* (2013) identified 1979 as the change point of streamflow time series in the Luanhe river basin by Pettitt's test; Li & Feng (2007) gave the same change point in the six sub-watersheds. Therefore, we divided the long-term period into two periods: the reference period, 1956–1979, was the pre-change period, and the impaired period, 1980–2011, was the post-change period.

The relationship between annual precipitation and runoff in the six sub-basins during the two periods is shown in Figure 5. The points in blue represent the precipitation-runoff relationship before 1980, and the points in red denote those after 1980. It can be seen that the blue points are higher than the red points, which implies that the amount of runoff after 1980 was less than that before 1980 with the same precipitation, suggesting that the precipitation was not the only reason for the reduction of runoff. Feng *et al.* (2008) analysed the water resource trends and causes of Panjiakou reservoir. They revealed that the main causes of the reduction before and after 1980 were the construction of a water diversion project, the increasing demand of water resources and the increasing impact of human activities.

To quantify the magnitude of the MAR decrease, we calculated the MAR in the pre-change and post-change periods of the six sub-basins. The results are shown in Table 1. As can be seen, MAR decreased 22–44% relative to that in the pre-change period.

However, the contributions of the driving factors were unclear, and should be quantified by the methods in the following sections.

The contributions of climate change and human activities

Results of Budyko decomposition method

At the first step, the single parameter was computed to the prechange period; that is, separate Budyko curves were fitted for each watershed. The results show that the range of the ω parameter was 1.31–3.65 in the six sub-basins. The value of ω in the Sandaohezi sub-basin was the highest, almost close to the water limit line, and equal to 3.65. The Budyko curve of the Yixunhe sub-basin had the smallest ω of all the sub-basins (Figure 6). Zhang *et al.* (2004) found that the smaller ω parameter was associated with a steep slope of the watershed and higher precipitation intensity, while the higher ω parameter reflected a lower slope and lower rainfall intensity.

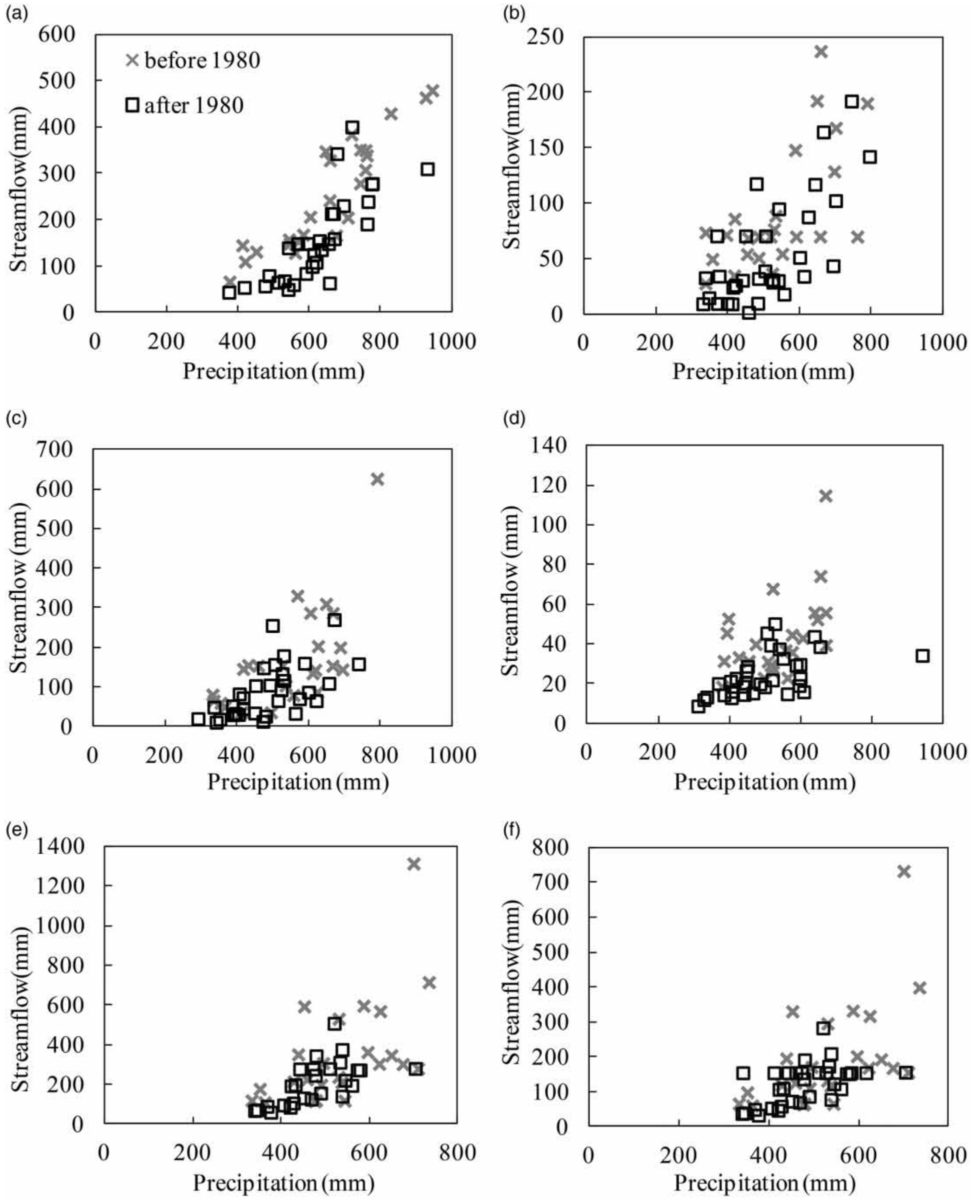

Figure 5 | Relationships between annual precipitation and runoff during the two periods (before and after the change point of 1980) in six sub-basins. (a) Liuhe sub-basin, (b) Baohe sub-basin, (c) Laoniuhe sub-basin, (d) Sandaohezi sub-basin, (e) Yixunhe sub-basin, (f) Wuliehe sub-basin.

The climate- and human-induced percentage changes of MAR using Equation (10) are shown in Table 2. Human activities have mainly driven the decrease of runoff, which was consistent with results obtained in previous studies (Liu *et al.* 2013a, 2013b). Human activities accounted for more than 70% in five sub-basins out of six. The contribution of human activity to the reduced runoff in the Sandaohezi sub-basin was estimated as 85%, which was the highest among all the six sub-basins. Seventy-nine and 76% were the human-induced percentage of annual runoff decrease in the Liuhe and Wuliehe sub-basins, respectively. The smallest contribution of human activities occurred in the Baohe sub-basin, which was 62%. By contrast, the climate contribution was less than 30% in five sub-basins except in the Baohe sub-basin which accounted for 38%.

Table 1 | The annual average runoff in the reference period and the impaired period

Sub-basin	MAR		
	Pre-change Q_1 (mm)	Post-change Q_2 (mm)	Change percent (%)
Liuhe	249	154	−38
Laoniuhe	167	86	−22
Sandaohezi	43	24	−44
Yixunhe	349	202	−42
Wuliehe	195	121	−38
Baohe	91	54	−41

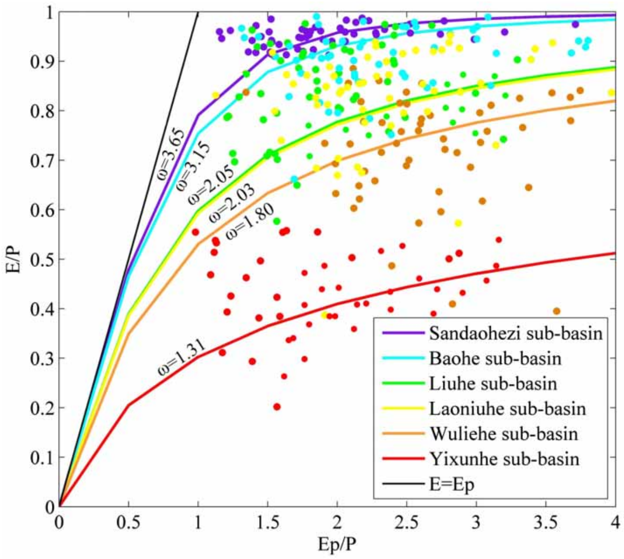

Figure 6 | Relationships between elements of the catchment water balance as per Fu's equation of the Budyko framework (Equation (4)) for the six sub-basins. The dots show the *E/P* versus the E_P/P in different basins.

Results of geometric approach

Using the geometric approach illustrated above under 'Geometric approach', we calculated the climate- and human activity-related contributions to annual streamflow. Figure 7 shows the locations of (*q*, g). The percentage changes of MAR attributed to climate-caused and human-induced impacts, respectively, have been estimated and the results are listed in Table 2.

As can be seen, the human-induced percentage change ranges from 51 to 93%. For the six sub-basins, the quantified results were almost the same as those estimated by Liu *et al.* (2013a) via the SWAT model. In the Baohe sub-basins, climate-caused impact accounted for a part of the change in MAR, though the human-induced impact was still an important factor, accounting for more than 50%. Therefore, the impact of human activities is the main driving factor for the decline of annual runoff.

Comparison of the two methods

The Budyko decomposition method and the geometrical approach were employed in this study. Both methods required the same basic meteorological data such as precipitation, wind speed, humidity, and temperature, and the same hydrological data such as the observed runoff series. The absolute differences in the human-induced contribution, i.e., $\Delta/H/=/H_g$-$H_b/$, derived using the two methods are shown in Table 2.

From Table 2, the differences in human-induced percentage change were from 1 to 17%. The largest difference in human contribution was 17% in the Sandaohezi sub-basin, and it was 11% less by the geometric approach for the Baohe sub-basin.

Table 2 | Climate-caused and human-induced percentage change of annual runoff by Budyko decomposition method and geometric approach, and the absolute differences of human-induced contribution by the two methods

Sub-basin	ΔQ (mm)	ΔQ_C (mm)	ΔQ_H (mm)	C_b (%)	H_b (%)	C_g (%)	H_g (%)	$\Delta/H/$ (%)
Liuhe	−95	−20	−75	21	79	7	93	14
Baohe	−37	−14	−23	38	62	49	51	11
Laoniuhe	−81	−19	−62	23	77	14	86	9
Sandaohezi	−19	−3	−16	15	85	32	68	17
Yixunhe	−147	−43	−104	29	71	22	78	7
Wuliehe	−74	−18	−56	24	76	25	75	1

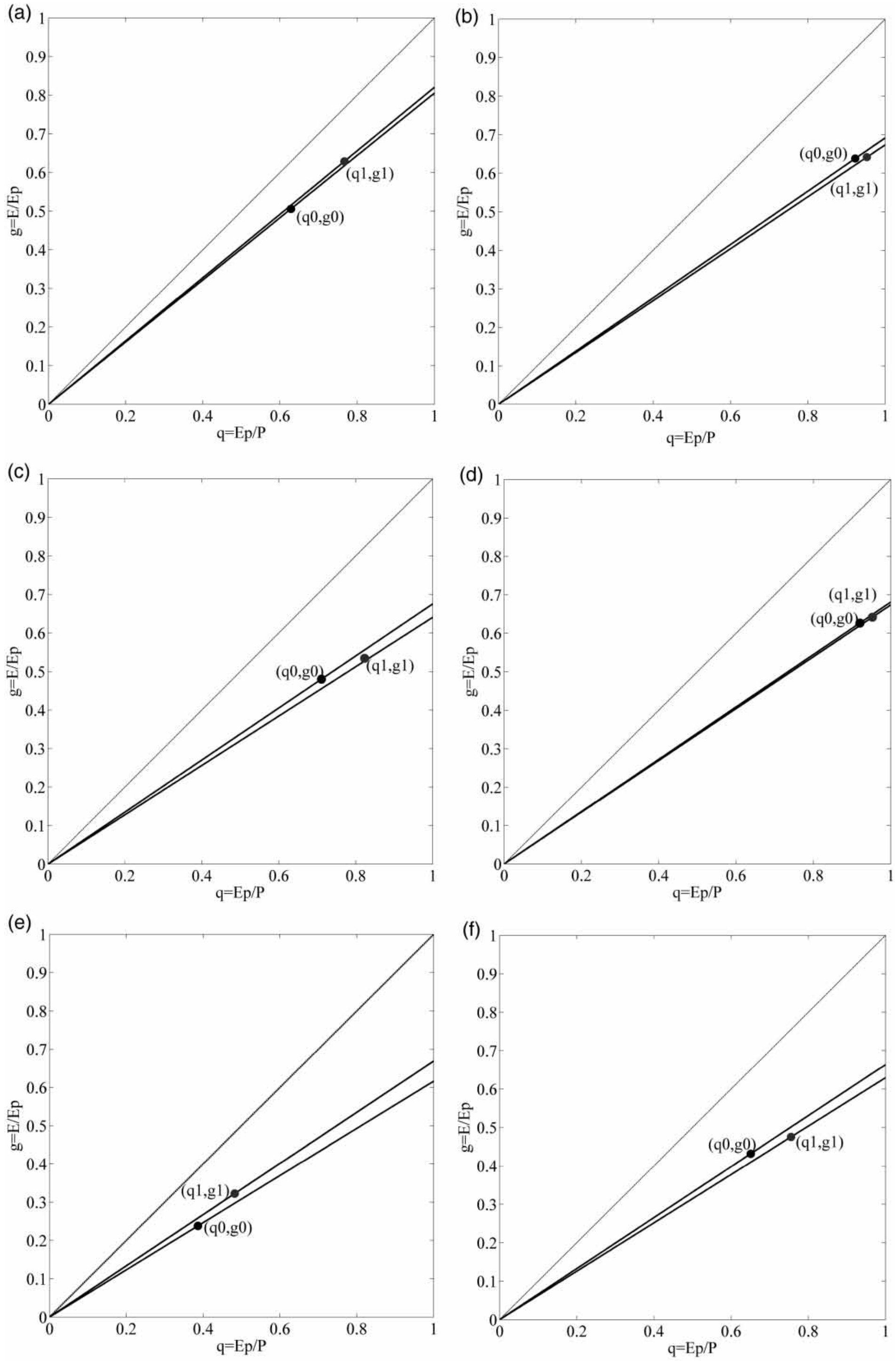

Figure 7 | The actual situation of the separation of climate and human impacts changes in q-g space diagram. The position of point (q_0, g_0) to the position of point (q_1, g_1) depicts the climate- and human-induced components of the transition. (a) Liuhe sub-basin, (b) Baohe sub-basin, (c) Laoniuhe sub-basin, (d) Sandaohezi sub-basin, (e) Yixunhe sub-basin, (f) Wuliehe sub-basin.

The differences between the Budyko decomposition method and the geometric approach were mainly: (1) the Budyko decomposition method provided more explicit physical meaning (Renner *et al.* 2012b; Wang *et al.* 2013), but the geometric approach was a conceptual model (Renner *et al.* 2012b); (2) a single-parameter Budyko-type curve was used as the Budyko decomposition method, and the parameter was related to the complex interaction between vegetation types, soil properties, and topography (Ma *et al.* 2008), although the geometric approach required two non-dimensional hydrologic state variables to describe the hydro-climatic state of a basin; and (3) the largest difference between both approaches occurred under limiting conditions. The geometric approach did not adhere to the water and energy limits, while the Budyko decomposition method accounted for limiting conditions, and was the reason why the difference in the human contribution from those two approaches in the Sandaohezi sub-basin was the highest of all. The value of ω was 3.65 in the Sandaohezi sub-basin, almost close to the water limit line (see Figure 6).

DISCUSSION AND CONCLUSIONS

Runoff decrease in the Luanhe river basin was assessed by the rainfall–runoff relationship in our study. Runoff in most sub-basins was affected by climate change and human activities, such as agricultural irrigation, industry development and dam construction. According to Wang *et al.* (2013), the change points of runoff in the Luanhe river basin occurred in the year 1979 using Pettitt's test. The late 1970s saw the start of the construction of hydraulic structures and land reform in China, and the increasing agricultural land and the amount of irrigation water led to a large increase in water use, which was the main driving factor of runoff decline (Yang & Tian 2009; Wang *et al.* 2013).

In this study, the Budyko decomposition method and the geometric approach were adopted to explicitly quantify the relative contributions of climate and human activities to MAR in the Luanhe river basin during the period 1956–2011. Using the change point of 1979 (Li & Feng 2007; Wang *et al.* 2013), we split the time period into two sub-periods: 'pre-change' and 'post-change'. In addition, the Budyko decomposition method and the geometric approach rely on the assumption of zero storage change. The period (1956–2011) is long enough to make sure that the assumption holds, since the significant interannual storage change can be attributed to the human contribution.

Both the Budyko decomposition method and the geometric approach obtained similar results for the impact of human activities on runoff, which inspired great confidence in the impact assessment of this study. The quantitative evaluation of climate impacts in these six sub-basins was 15–40%, approximately, and the contribution of human activities was 60–85%, based on the Budyko decomposition method. According to the geometric approach, the effects of climate change in these six sub-basins was 7–49%, and the contribution of human activities was approximately 51–93%.

Other researchers have carried out this work in the Luanhe river basin using different methods. Wang *et al.* (2013) quantified the impact of climate variability and human activities for the reduction of runoff during 1957–2000 in the Luanxian hydrological station. They used the hydrological model method, the hydrological sensitivity method and the climate elasticity method, and found that the relationship between precipitation and runoff had changed abruptly. Sixty-one, 67 and 57% of runoff reduction were attributed to human activities by these three methods, respectively. Xu *et al.* (2013) adopted the geomorphology-based hydrological model (GBHM) and a climate elasticity model to distinguish effects of climate change and human activities during 1956–2005 at Sandaohezi station. The contributions of human activities and climate variability were 61% and 39%, respectively. The major causes of runoff decrease in the Luanhe river basin were consistent with our findings. However, there was a degree of difference in the climate-caused percentage change. These differences might come from the different model structures, the drainage area, the study period and the uncertainty of the model parameters. Additionally, the geometric approach, rarely used in China, can be demonstrated to be an alternative way to separate the effects of streamflow by comparing its consistent results with other methods in the Luanhe river basin.

The uncertainties should be noted and are related to separating the effects of climate variability and human activities on streamflow. Firstly, the one-parameter model of the Budyko composition method easily satisfies the data requirement, but it can provide less information about a detailed description of the hydrological process. Secondly, both of the methods would be uncertain when the distribution of precipitation changes. At the same time, the streamflow can be influenced by changes in other precipitation characteristics, such as seasonality, intensity and concentration. For example, we generally used *P-Q* to estimate *E*. However, in a wet year (high *P*, low aridity index E_P/P), if we still assumed $\Delta S_W = 0$ (Equation (1)), basin *E* would be overestimated. Whereas, in a dry year (low *P*, higher aridity index E_P/P), basin *E* would be underestimated. Furthermore, in order to simplify the issue, we assume the soil moisture change to be zero. Actually, the assumption could lead to an error in the final results. The change of soil water storage (ΔS_W) is assumed to be imbalanced between *P-E* and *Q*. For example, in a wet year, high infiltration and high precipitation would lead to high soil moisture ($\Delta S_W > 0$), when we ignore the soil moisture change, *P-Q* would result in the overestimation of *E*. Therefore, the uncertainty may be caused by assuming the soil moisture change to be zero. Moreover, these uncertainties can inevitably affect the results. Therefore, future studies should take them into consideration to improve the accuracy of the results.

Our research could be useful for water resources planning and management to choose the methodology and to separate the effects of climate change and human impacts on MAR. The deficiency is that we assumed the soil moisture change to be zero, which would result in a small error in the water budget. In the future, the extension of this work will take the soil moisture change into consideration, and further, the impact of different human activities on streamflow will also be considered.

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REFERENCES

Allen, R., Smith, M., Pereira, L. & Perrier, A. 1994 An update for the calculation of reference evapotranspiration. *ICID Bull.* **43**, 35–92.

Bao, Z., Zhang, J., Wang, G., Fu, G., He, R., Yan, X., Jin, J., Liu, Y. & Zhang, A. 2012 Attribution for decreasing runoff of the Haihe River basin, northern China: climate variability or human activities? *J. Hydrol.* **460**, 117–129.

Barnett, T. P., Pierce, D. W., Hidalgo, H. G., Bonfils, C., Santer, B. D., Das, T., Bala, G., Wood, A. W., Nozawa, T., Mirin, A. A., Cayan, D. R. & Dettinger, M. D. 2008 Human-induced changes in the hydrology of the western United States. *Science* **319**, 1080–1083.

Berry, S. L., Farquhar, G. D. & Roderick, M. L. 2005 Co-evolution of climate, vegetation, soil and air. Theory, organization and scale. In: *Encyclopedia of Hydrological Sciences* (G. Bloschl & M. Sivapalan, eds). Vol. 1. Wiley, New York, pp. 177–192.

Budyko, M. 1948 *Evaporation Under Natural Conditions*. Gidrometeorizdat, Legingrad, English translation by IPST, Jerusalem.

Budyko, M. I. 1974 *Climate and Life*. Acdemic, New York. 508 pp.

Budyko, M. I. & Zubenok, L. I. 1961 The determination of evaporation from the land surface. *Izv. Akad. Nauk SSSR Ser. Geogr.* **6** (3), 3–17.

Donohue, R. J., Roderick, M. L. & McVicar, T. R. 2007 On the importance of including vegetation dynamics in Budyko's hydrological model. *Hydrol. Earth Syst. Sci.* **11**, 983–995.

Dooge, J. C. I. 1992 Sensitivity of runoff to climate change: a hortonian approach. *Bull. Am. Meteorol. Soc.* **73** (12), 2013–2024.

Dooge, J., Bruen, M. & Parmentier, B. 1999 A simple model for estimating the sensitivity of runoff to long-term changes in precipitation without a change in vegetation. *Adv. Water Resour.* **23** (2), 153–163.

Feng, P., Li, J. Z. & Xu, X. 2008 Analysis of water resources trend and its causes of Panjiakou Reservoir (in Chinese). *Geograph. Res.* **27**, 213–220.

Fu, B. P. 1981 On the calculation of the evaporation from land surface (in Chinese). *Sci. Atmos. Sin.* **5**, 23–31.

Huo, Z., Feng, S., Kang, S., Li, W. & Chen, S. 2008 Effect of the climate changes and water-related human activities on annual stream flows of the Shiyang river basin in arid north-west China. *Hydrol. Process.* **22**, 3157–3167.

Karl, T. R., Knight, R. W., Easterling, D. R. & Quayle, R. G. 1996 Indices of climate change for the United States. *Bull. Am. Meterol. Soc.* **77**, 278–292.

Lane, P. N. J., Best, A. E., Hikel, K. & Zhang, L. 2005 The response of flow duration curves to afforestation. *J. Hydrol.* **310**, 253–265.

Li, D. 2014 Assessing the impact of interannual variability of precipitation and potential evaporation on evapotranspiration. *Adv. Water Resour.* **70**, 1–11.

Li, J. Z. & Feng, P. 2007 Runoff variations in the Luanhe river basin during 1956–2002. *J. Geograph. Sci.* **17**, 339–350.

Li, J. Z., Tan, S. M., Chen, F. L. & Feng, P. 2014 Quantitatively analyze the impact of land use/land cover change on annual runoff decrease. *Nat. Hazards* **74**, 1191–1207.

Liu, J. G. & Wu, Y. 2012 Water sustainability for China and beyond. *Science* **337**, 649.

Liu, C., Dong, Z., Fang, Q. & Shan, C. J. 2013a Runoff change in response to climate change and human activities scenarios of Luanhe River basin (in Chinese). *Water Resour. Power* **31**, 12–15.

Liu, X., Xiang, L. & Zhai, J. 2013b Quantitative study of Impacts for environmental change on runoff in Luanhe river basin (in Chinese). *J. Nat. Resour.* **28**, 244–252.

Ma, Z., Kang, S., Zhang, L., Tong, L. & Su, X. 2008 Analysis of impacts of climate variability and human activity on runoff for a river basin in arid region of northwest China. *J. Hydrol.* **352**, 239–249.

Milly, P. C. D. & Dunne, K. A. 2002 Macroscale water fluxes 2. Water and energy supply control of their inter-annual variability. *Water Resour. Res.* **38** (10), 241–249.

Piao, S., Ciais, P., Huang, Y., Shen, Z. H., Peng, S. S., Li, J. S., Zhou, L. P., Liu, H. Y., Ma, Y. C., Ding, Y. H., Friedlingstein, P., Liu, C. Z., Tan, K., Yu, Y. Q., Zhang, T. Y. & Fang, J. Y. 2010 The impacts of climate change on water resources and agriculture in China. *Nature* **467**, 43–51.

Pike, J. G. 1964 The estimation of annual runoff from meteorological data in a tropical climate. *J. Hydrol.* **2**, 116–123.

Renner, M. & Bernhofer, C. 2012a Applying simple water-energy balance frameworks to predict the climate sensitivity of streamflow over the continental United States. *Hydrol. Earth Syst. Sci.* **16** (8), 2531–2546.

Renner, M., Seppelt, R. & Bernhofer, C. 2012b Evaluation of water-energy balance frameworks to predict the sensitivity of runoff to climate change. *Hydrol. Earth Syst. Sci.* **16**, 1419–1433.

Renner, M., Brust, K., Schwärzel, K., Volk, M. & Bernhofer, C. 2014 Separating the effects of changes in land cover and climate: a hydro-meteorological analysis of the past 60 yr in Saxony, Germany. *Hydrol. Earth Syst. Sci.* **18**, 389–405.

Rodriguez-lturbe, I. & Porporato, A. 2005 *Ecohydrology of Water-controlled Ecosystems: Soil Moisture and Plant Dynamics*. Cambridge University Press, Cambridge, 442 pp.

Sankarasubramanian, A., Vogel, R. & Limbrunner, J. 2001 Climate elasticity of streamflow in the United States. *Water Resour. Res.* **37**, 1771–1781.

Schilling, K. E., Chan, K., Liu, H. & Zhang, Y.-K. 2010 Quantifying the effect of land use land cover change on increasing discharge in the Upper Mississippi River. *J. Hydrol.* **387**, 343–345.

Siriwardena, L., Finlayson, B. L. & McMahon, T. A. 2006 The impact of land use change on catchment hydrology in large catchment: the Comet River, central Queensland, Australia. *J. Hydrol.* **326**, 199–214.

St. Jacques, J. M., Sauchyn, D. J. & Zhao, Y. 2010 Northern Rocky Mountain runoff records: global warming trends, human impacts or natural variability? *Geophys. Res. Lett.* **37**, 53–67. Doi:10.1029/2009GL042045.

Sun, F. 2007 *Study on Watershed Evaporation based on the Budyko Hypothesis* (in Chinese). PhD Thesis, Tsinghua University, Beijing, China.

Tomer, M. & Schilling, K. 2009 A simple approach to distinguish land-use and climate-change effects on watershed hydrology. *J. Hydrol.* **376**, 24–33.

Tuteja, N. K., Vaze, J., Teng, J. & Mutendeudzi, M. 2007 Partitioning the effects of pine plantations and climate variability on runoff from a large catchment in southeastern Australia. *Water Resour. Res.* **43**, 199–212. Doi:10.1029/2006WR005016.

Wang, D. & Cai, X. 2010 Comparative study of climate and human impacts on seasonal base flow in urban and agricultural watershed. *Geophys. Res. Lett.* **37**, 460–472. Doi:10.1029/2009GL041879.

Wang, D. & Hejazi, M. 2011 Quantifying the relative contribution of the climate and direct human impacts on mean annual runoff in the contiguous United States. *Water Resour. Res.* **47**, 1995–2021. Doi:10.1029/2010WR010283.

Wang, W., Shao, Q., Yang, T., Peng, S. Z., Xing, W. Q., Sun, F. & Luo, Y. F. 2013 Quantitative assessment of the impact of climate variability and human activities on runoff changes: a case study in four catchments of the Haihe River basin, China. *Hydrol. Process.* **27**, 1158–1174.

Wei, X. H. & Zhang, M. F. 2010 Quantifying runoff change caused by forest disturbance at a large spatial scale: a single watershed study. *Water Resour. Res.* **46**, 439–445. Doi:10.1029/2010WR009250.

Xu, X., Yang, D. & Ma, H. 2013 Assessing the impacts of climate variability and human activities on annual runoff in the Luanhe River Basin, China. *Hydrol. Res.* **44**, 940–952.

Xu, X., Yang, D., Yang, H. & Lei, H. 2014 Attribution analysis based on the Budyko hypothesis for detecting the dominant cause of runoff decline in Haihe basin. *J. Hydrol.* **510**, 530–540.

Yang, Y. H. & Tian, F. 2009 Abrupt change of runoff and its major driving factors in Haihe River Catchment, China. *J. Hydrol.* **374**, 373–383.

Yang, H., Yang, D., Lei, Z. & Sun, F. 2008 New analytical derivation of the mean annual water-energy balance equation. *Water Resour. Res.* **44**, W03410. Doi:10.1029/2007WR0061.

Yi, L. L., Jiao, W. T., Chen, X. N. & Chen, W. 2011 An overview of reclaimed water reuse in China. *J. Environ. Sci.* **23** (10), 1585–1593.

Zeng, S., Xia, J., Du, H., Zhang, L. P., Chen, X. D., Wang, R. C. & Sood, A. 2014 Effects of climate change, land use and cover change and CO_2 enrich on runoff: a case study of the Luanhe River basin (in Chinese). *Adv. Water Sci.* **25**, 10–19.

Zhang, L., Dawes, W. R. & Walker, G. R. 2001 Response of mean annual evaporation to vegetation changes at catchment scale. *Water Resour. Res.* **37**, 701–708.

Zhang, L., Hickel, K., Dawes, W. R., Chiew, F. H. S., Western, A. W. & Briggs, P. R. 2004 A rational function approach for estimating mean annual evaporation. *Water Resour. Res.* **40**, 89–97. Doi:10.1029/2003WR002710.

Zhang, X., Zhang, L., Zhao, J., Rustomji, P. & Hairsine, P. 2008 Responses of runoff to changes in climate and land use/cover in the Losess Plateau, China. *Water Resour. Res.* **44**, 2183–2188. Doi:10.1029/2007WR006711.

Zheng, H., Zhang, L., Zhu, R., Liu, C., Sato, Y. & Fukushima, Y. 2009 Responses of streamflow to climate and land surface change in the headwaters of the Yellow River Basin. *Water Resour. Res.* **45**, W00A19. Doi:10.1029/2007WR006665.

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