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ORIGINAL PAPER

Impacts of climate change on the water balance of a large nonhumid natural basin in China

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Abstract Water resources are contingent on the combined effects of climate change and watershed characteristics. An analytical model devised from the Budyko framework was used to investigate the partitioning of precipitation (*P*) into actual evapotranspiration (*E*) and streamflow (*Q*) parameters for the Yellow River Basin (YRB), a water-limited basin, to estimate the response of *E* and *Q* to *P* and potential evapotranspiration (E_p). Although a steady state was assumed, the analytical model, incorporating an adjustable parameter characteristic of catchment conditions (ω), can be run to analyze the sensitivity of catchment characteristics on water resources. The theory predicts that *Q* and *E* are more sensitive to *P* than to E_p. For example, a 10 % increase in *P* will result in a 22.8 % increase in *Q*, while a 10 % increase in E_p will decrease *Q* by 13.2 %. The model shows that, to some extent, water balance is governed by changing catchment characteristics (such as changes in vegetation on annual scales). These findings indicate that additional elucidative data can be drawn from the Budyko framework when taking into account catchment characteristics. Furthermore, the model can analyze the response of water resources to climate change on different temporal and spatial scales.

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1 Introduction

Hydrological processes are contingent on the combined effects of climate, vegetation, and soil properties (Berry et al. 2005; Rodriguez-Iturbe and Porporato 2005; Donohue et al. 2012), resulting in basin-scale changes in streamflow or the water balance (Koster and Suarez 1999; Chen et al. 2007; Sun et al. 2007; Zhang et al. 2008; Luo et al. 2013; Bian et al. 2014). Understanding the components that constitute the water balance of a catchment system has been regarded as the traditional realm of the hydrological community (Donohue et al. 2007; Zhang et al. 2008; Hidalgo et al. 2009; Li et al. 2011; Li et al. 2013; Stewart 2013). In order to characterize these components, Budyko (1958, 1974) developed what is now considered one of the most important and enduring frameworks that links climate to the catchment parameters streamflow (*Q*) and actual evapotranspiration (*E*) through the tenet that long-term average annual catchment *E* is determined by available water (represented by precipitation, *P*) and energy conditions (represented by potential evaporation, E_p). To date, a number of studies have been published on this topic using the Budyko framework (Koster and Suarez 1999; Zhang et al. 2001; Arora 2002; Koster et al. 2006; Donohue et al. 2007; Yang et al. 2007; Gerrits et al. 2009; Gentine et al. 2012). The importance of these studies, as pointed out by Zhang et al. (2008), has been to show a hierarchy of control exercised by climate and catchment characteristics on water balance over various temporal scales.

The original idea behind the Budyko framework, assuming that a catchment maintains a steady state and is driven by macroclimate stimuli, sought to understand overall catchment behavior and function based on observed data (Zhang et al. 2008). In this context, the model used in this study, devised from the Budyko framework (Budyko 1958, 1974), is simply expressed as a function of *P* and E_p. The equation, developed by Fu (1981) to improve the Budyko framework, is fitted with an added parameter to reflect the influence of watershed characteristics on specific watershed conditions. When this type of model is run at finer temporal and spatial scales, specific catchment characteristics and precipitation processes must be incorporated into the equation in order to improve prediction accuracy (Zhang et al. 2001; Porporato et al. 2004; Donohue et al. 2007; Yang et al. 2008; Yokoo et al. 2008; Gerrits et al. 2009; Roderick and Farquhar 2011). Given this, the objective of this study was to contribute to the overall understanding of climate and catchment characteristics on water-limited basin ($P<E_p$) water resources. Taking this into account, Fu's general analytical framework equation was used to estimate impacts of climate change on water resources. The Yellow River Basin (YRB, a large water-limited basin in China) was selected to validate the model.

1.1 Theoretical framework: climate change impact on water resources

Changes in Q are contingent on the complex relationships that take place between hydrological processes, watershed characteristics, and changes in climate conditions. Budyko (1958, 1974) provided a simple framework linking climate to catchment Q and E, defined here as the "Budyko hypothesis," which is a partition of the annual water balance as a function of the relative magnitude of water and energy supply. It is expressed as follows:

$$\frac{E}{P}=\left(\frac{E_p}{P}\tanh\left(\frac{E_p}{P}\right)^{-1}\left(1-\cosh\left(\frac{E_p}{P}\right)+\sinh\left(\frac{E_p}{P}\right)\right)\right)^{0.5}. \quad (1)$$

In order to understand the effects of climate and catchment characteristics on the partitioning of mean annual P into mean annual E, Fu (1981) combined dimensional analysis with mathematical reasoning to develop analytical solutions for mean annual E. He provided the different forms of the Budyko hypothesis as follows: $\frac{\partial E}{\partial P}=f(E_P-E,P)$ when E_p= constant; and $\frac{\partial E}{\partial E_p}=f\left(P-E,E_p\right)$ when P=constant. This study exploits the Budyko hypothesis from another angle, previously reported by Zhang et al. (2004). Fu's equation (1981) and the Budyko hypothesis, in general, have been regarded as the two ongoing empirical pieces of work to explain the "Budyko curve" (Zhang et al. 2004; Roderick and Farquhar 2011). Fu's equation can be expressed as an analytical solution to the Budyko hypothesis as follows:

$$\frac{E}{P}=1+\frac{E_p}{P}-\left(1+\left(\frac{E_p}{P}\right)^{\omega}\right)^{1/\omega} \quad (2)$$

or

$$\frac{E}{E_p}=1+\frac{P}{E_p}-\left(1+\left(\frac{P}{E_p}\right)^{\omega}\right)^{1/\omega} \quad (3)$$

where ω is an integration constant and its range values (1, ∞). In this study, Fu's equation was used to explore the response of water resources to climate change.

Changes in E can be expressed as changes in climate conditions (P and E_p) and catchment characteristics (ω) (Roderick and Farquhar 2011). First-order changes in E are

$$dE=\frac{\partial E}{\partial P}dP+\frac{\partial E}{\partial E_p}dE_p+\frac{\partial E}{\partial \omega}d\omega \quad (4)$$

with associated partial differentials given as follows:

$$\frac{\partial E}{\partial P}=1-\frac{E_p}{P}\left(1+\left(\frac{P}{E_p}\right)^{\omega}\right)^{(1/\omega)}\left(\frac{P}{E_p}\right)^{\omega}\left(1+\left(\frac{P}{E_p}\right)^{\omega}\right)^{-1} \quad (5)$$

$$\frac{\partial E}{\partial E_p}=1-\left(1+\left(\frac{P}{E_p}\right)^{\omega}\right)^{(1/\omega)}+\left(1+\left(\frac{P}{E_p}\right)^{\omega}\right)^{(1/\omega)}\left(\frac{P}{E_p}\right)^{\omega}\left(1+\left(\frac{P}{E_p}\right)^{\omega}\right)^{-1} \quad (6)$$

$$\frac{\partial E}{\partial \omega}=-E_p\left(1+\left(\frac{P}{E_p}\right)^{\omega}\right)^{(1/\omega)}\left(\frac{-1}{\omega^2}\log\left(1+\left(\frac{P}{E_p}\right)^{\omega}\right)+\frac{1}{\omega}\left(\frac{P}{E_p}\right)^{\omega}\log\left(\frac{P}{E_p}\right)\left(1+\left(\frac{P}{E_p}\right)^{\omega}\right)^{-1}\right) \quad (7)$$

Allowing for long-term changes and when ignoring changes in storage capacity (regarded as a steady state by Roderick and Farquhar (2011)), changes in Q can be expressed as follows:

$$dQ=dP-dE \quad (8)$$

According to Roderick and Farquhar (2011), changes in Q in combination with Eq. (4) can be expressed as follows:

$$dQ=\left(1-\frac{\partial E}{\partial P}\right)dP-\frac{\partial E}{\partial E_p}dE_p-\frac{\partial E}{\partial \omega}d\omega \quad (9)$$

$$\frac{dQ}{Q}=\left[\frac{P}{Q}\left(1-\frac{\partial E}{\partial P}\right)\right]\frac{dP}{P}-\left[\frac{E_p}{Q}\frac{\partial E}{\partial E_p}\right]\frac{dE_p}{E_p}-\left[\frac{\omega}{Q}\frac{\partial E}{\partial \omega}\right]\frac{d\omega}{\omega} \quad (10)$$

Roderick and Farquhar (2011) defined the terms within the square brackets as sensitivity coefficients specific to the different variables constituting Eq. (10).

By substituting Q by $(P-E)$ in the sequence specific to Eq. (10), the equation can be expressed as follows:

$$\frac{dQ}{Q}=\left[\frac{P}{P-E}\left(1-\frac{\partial E}{\partial P}\right)\right]\frac{dP}{P}-\left[\frac{E_p}{P-E}\frac{\partial E}{\partial E_p}\right]\frac{dE_p}{E_p}-\left[\frac{\omega}{P-E}\frac{\partial E}{\partial \omega}\right]\frac{d\omega}{\omega} \quad (11)$$

where E is estimated by means of Eq. (3). Equation (11) implies that the fractional change in annual Q is a function of fractional changes in P, E_p, and watershed characteristics. Equation (11) is similar to the one reported by Dooge (1992). Dooge et al. (1999) and Arora (2002), who express their formula in terms of the humidity index or the aridity index, respectively, did not incorporate watershed characteristics into their models. Since E_p can be estimated by means of the Penman equation (which is physically based and explicitly incorporates both radiative and aerodynamic parameters) (McVicar et al. 2007) by applying net radiation (R_n), wind speed (u), and relative humidity (rh), and since air temperature (T_a) can be substituted with E_p using the four meteorological variables presented in Eq. (11), relative changes in Q are represented thus:

$$\frac{dQ}{Q}=\left[\frac{P}{P-E}\left(1-\frac{\partial E}{\partial P}\right)\right]\frac{dP}{P}-\left[\frac{R_n}{P-E}\frac{\partial E}{\partial E_p}\frac{\partial E_p}{\partial R_n}\right]\frac{dR_n}{R_n}-\left[\frac{u}{P-E}\frac{\partial E}{\partial E_p}\frac{\partial E_p}{\partial u}\right]\frac{du}{u}$$
$$-\left[\frac{rh}{P-E}\frac{\partial E}{\partial E_p}\frac{\partial E_p}{\partial rh}\right]\frac{drh}{rh}-\left[\frac{T_a}{P-E}\frac{\partial E}{\partial E_p}\frac{\partial E_p}{\partial T_a}\right]\frac{dT_a}{T_a}-\left[\frac{\omega}{P-E}\frac{\partial E}{\partial \omega}\right]\frac{d\omega}{\omega} \quad (12)$$

In this way, impacts on Q due to climate change and catchment characteristics can be revealed by means of Eqs. (11) and (12). Furthermore, the slope of Q can also be expressed as a change in climate and watershed characteristics:

$$\frac{dQ}{dt}=\left[\frac{Q}{P-E}\left(1-\frac{\partial E}{\partial P}\right)\right]\frac{dP}{dt}-\left[\frac{Q}{P-E}\frac{\partial E}{\partial E_p}\frac{\partial E_p}{\partial R_n}\right]\frac{dR_n}{dt}-\left[\frac{Q}{P-E}\frac{\partial E}{\partial E_p}\frac{\partial E_p}{\partial u}\right]\frac{du}{dt}$$
$$-\left[\frac{Q}{P-E}\frac{\partial E}{\partial E_p}\frac{\partial E_p}{\partial rh}\right]\frac{drh}{dt}-\left[\frac{Q}{P-E}\frac{\partial E}{\partial E_p}\frac{\partial E_p}{\partial T_a}\right]\frac{dT_a}{dt}-\left[\frac{Q}{P-E}\frac{\partial E}{\partial \omega}\right]\frac{d\omega}{dt} \quad (13)$$

2 YRB and the steady state of its water balance

YRB is approximately 5,400 km long with a basin drainage area of 7.95×10^5 km^2. Its headwaters originate from the Tibetan Plateau, flowing through the Loess Plateau and the North China Plain before finally emptying into the Bohai Sea (Fig. 1). Since most of the river flows through arid and semiarid regions, increased agricultural and industrial water usage in combination with decreases in P has led to decreases of Q (McVicar et al. 2002; Liu and Yang 2008; Fu et al. 2009; Nakayama 2011). YRB is renowned for its high sediment content, frequent floods, unique downstream channel characteristics (where the river bed rises above the surrounding plain), and limited water resources (Nakayama 2011). A number of projects, such as the Sloping Lands Conversion Program situated within the Loess Plateau, have been established in the YRB region in order to reduce effects of soil erosion (McVicar et al. 2007). Changes in ecohydrological patterns have contributed to changes in hydrological processes, such as those related to evapotranspiration and runoff (Liu and Yang 2010).

Data from the National Climate Center (NCC) of the China Meteorological Administration (CMA) were used to investigate impacts of climate change on water resources. The Yellow River Conservancy Commission (YRCC) provided Q data ranging from 1961 to 2005. Monthly wind speed, daylight hours, relative humidity, air temperature (T_a), and P records taken from 80 meteorological stations located near the study region throughout 1961 to 2010 were also used. Monthly E_p was calculated by means of monthly wind speed, daylight hours, relative humidity, and average T_a via the Penman equation (Shuttleworth 1993). Mean annual P, E_p, and Q were 469.80, 1,230.49, and 48.61 mm a^{-1}, respectively, throughout the 1961 to 2005 study period. These data were used to investigate the water balance component by applying the Budyko framework.

3 Response of water resources to climate change in YRB

3.1 Relationships between precipitation, T_a, and Q

Annual Q change (ΔQ%) as a function of annual percentage precipitation change (ΔP%) and T_a change (ΔT_a) throughout 1961 to 2010 is provided for in Fig. 2. Changes in Q exhibited a nonlinear relationship with P and T_a. To some extent, Q exhibited increasing trends with increases in P while exhibiting decreasing trends with increases in T_a. For example, a 20 % P increase resulted in a 25.29 % increase in Q when T_a was normal but a 41.58 % increase in Q when T_a was 0.50 °C lower than normal. A 20 % decrease in P resulted in a 19.70 % decrease in Q when T_a was normal but a 29.29 % decrease in Q when T_a was 1.0 °C higher than normal. As

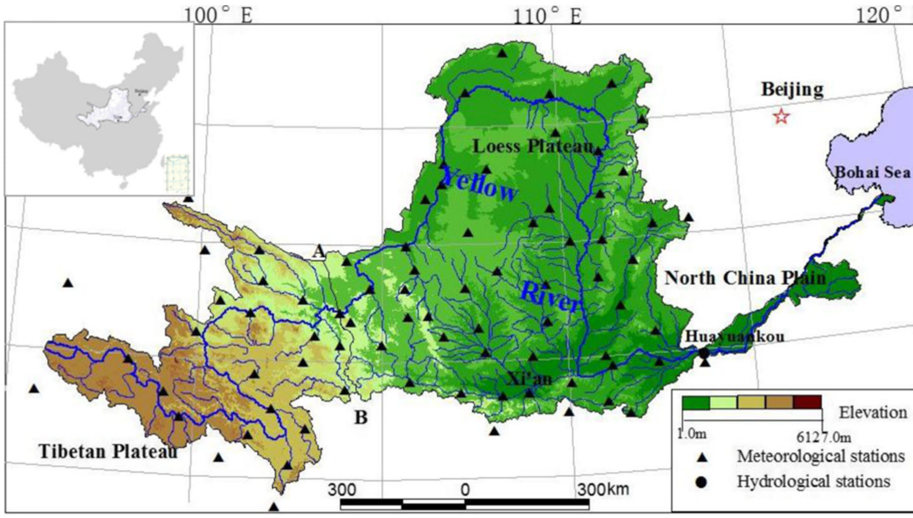

Fig. 1 Meteorological stations (*black triangles*) and hydrological stations (*black circles*) used in this study as well as the location of YRB in China

expected, changes in Q were primarily controlled by precipitation. Similar results have also been obtained by Risbey and Entekhabi (1996) and Fu et al. (2007). As pointed by Donohue et al. (2007) and Yang et al. (2011), the partition of P into Q and E can be controlled by available energy and the state of water resources. T_a, reflecting the state of energy, influenced E to a certain extent.

In order to ascertain a clearer picture of the relationship between Q and P, the average $\Delta Q\%-\Delta P\%$ values over a range of temperature departures (Fig. 2) were used to produce a plot of $\Delta Q\%-\Delta P\%$ as a function of $\Delta P\%$ (Fig. 3). As pointed out by Risbey and Entekhabi (1996), if $P-Q$ transformation is linear, then $\Delta Q\%-\Delta P\%$ would plot in opposition to $\Delta P\%$ with a slope of zero as indicated by the dashed lines in Fig. 3. Figure 3 showed that Q response to P is dependent on the P quantity. During wet years, the greater fraction of P is converted to runoff. Q response to P exhibited weak nonlinearity during years of below-average precipitation.

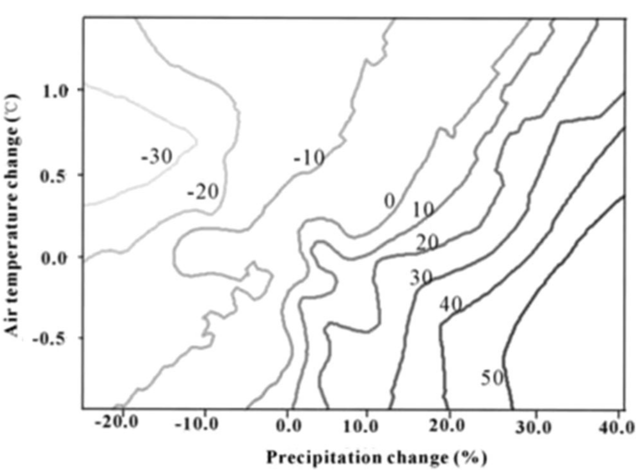

Fig. 2 Contour plot of percentage change in Q for YRB (compared to average Q throughout 1961 to 2000) as a function of percentage precipitation change and T_a calculated using the ArcGIS Geostatistical Analyst model

3.2 Q response to climate change as determined by the Budyko framework

The adjustable parameter (ω) of Fu's equation was obtained by means of the nonlinear fitted model, that is, using the observed E ($P-$observed Q) combined with P and E_p to calculate ω (ω is 2.47 for YRB), and it was this parameter that was used to investigate Q response to climate change. Differences between observed Q (Q_o) and predicted Q determined by Budyko's equation (Q_b) and determined by Fu's equation (Q_{fu}) are provided for in Fig. 4. When the original Budyko model (Eq. (2)) was used to estimate annual Q, the average error prediction was 16.73 mm a^{-1} (Fig. 4a). This error represents approximately 34.78 % of annual average Q throughout 1961 to 2005 (48.61 mm a^{-1}). In Fu's equation, incorporating the adjustable parameter (ω), the average error prediction (Q_{fu}) was approximately 3.67 % of annual average Q (up to 1.76 mm a^{-1}).

The water balance steady state for YRB is shown in Table 1: (i) According to Eq. (5), E was predicted to be more sensitive to changes in watershed characteristics (+27.85) followed by P (+0.76) and E_p (+0.054), (ii) Q was also predicted to be more sensitive to a changes in P (=2.28 dP/P) than to comparable changes in E_p ($-1.32\ dE_p/E_p$) since YRB is water-limited (a 10 % increase in P will increase Q by 22.8 %, while a 10 % increase in E_p will decrease Q by 13.2 %), (iii) changes in T_a reflect just one of two impacts (either E_p on E or E_p on Q), contributing only slightly to the magnitude of change in E or Q, and (iv) using Eq. (13), contributions of P, E_p, and T_a to the slope of Q was −0.29, 0.013, and −0.00013 mm a^{-2}, respectively, for YRB throughout 1961 to 2005, while changes in watershed characteristics contributed a magnitude of $-1.36\frac{Q}{\omega}\frac{d\omega}{t}=\frac{dQ}{dt}-\left(2.28\frac{Q}{P}\frac{dP}{dt}-1.32\frac{Q}{E_p}\frac{dE_p}{dt}\right)=$

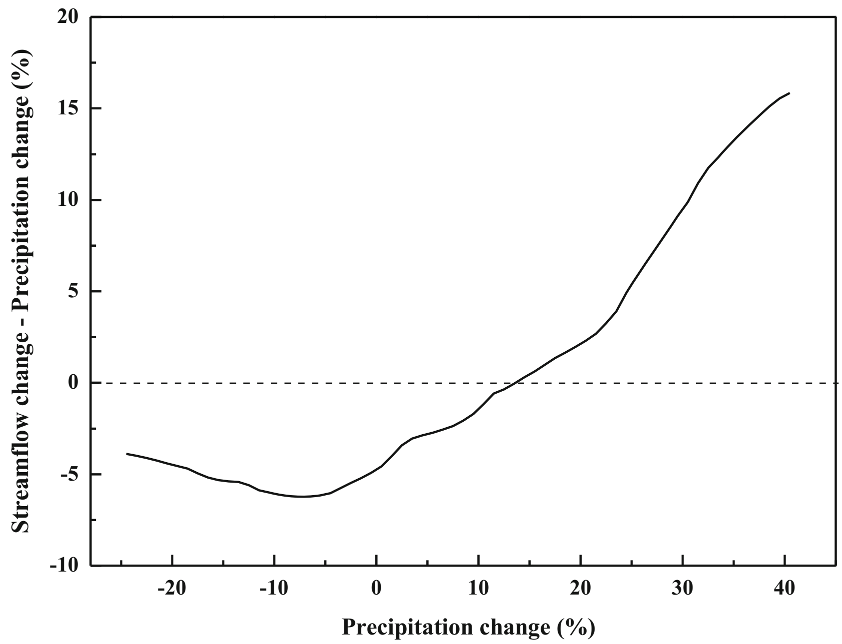

Fig. 3 Average Q change subtracted by average P change as a function of P change in the YRB

−0.75 mm a^{-2}). Results from this study are consistent with that reported by Roderick and Farquhar (2011), and together, these results indicate that changes in watershed characteristics (e.g., extent and type of change in vegetation) can be the primary cause for changes in Q (73 %). Climate change contributed little to changes in Q (approximately 27 %).

3.3 Effects of vegetation characteristics as determined by the Budyko framework

A long-term Budyko scatter plot for YRB is provided for in Fig. 5. For most years, YRB exhibited an aridity index greater than 2.0 throughout the 1961 to 2006 study period with an average aridity index of 2.67 (underscoring the water-limited environment). Locations of scatter points around the Budyko line, at least to some extent, reflect the partition of P into E and Q, that is, the years above the curve exhibit relatively high E, while the years below the curve exhibit relatively high Q. That reflects the complex interaction between climate changes, vegetation, and hydrological processes.

According to the complementary relationship, the relationship between E_p and E is provided for in Fig. 6. Owing to the water-limited state of YRB, this complementary relationship implies that E will decrease and E_p will increase with a reduction in P. The adverse side effect of this complementary

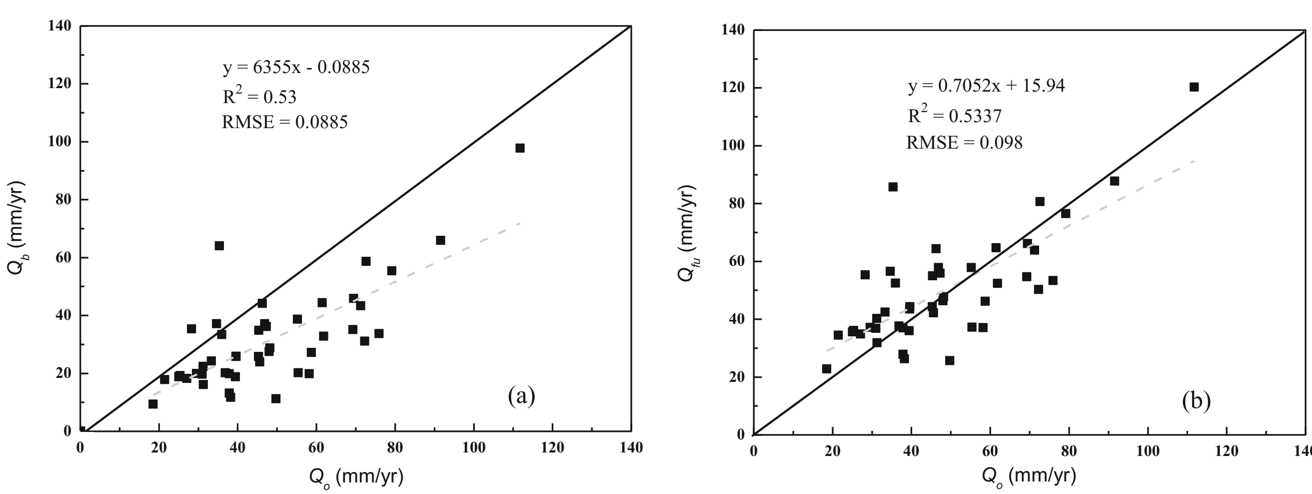

Fig. 4 Plots comparing observed and modeled annual Q for YRB. Observed Q (Q_o) is compared with that predicted by means of the original Budyko model (Q_b, **a**) and with that predicted by means of Fu's (1981) one-parameter model (Q_{fu}, **b**). The *black line* represents the 1:1 line, and the *dotted line* represents the line of best fit (described by means of the linear equation)

Table 1 Comparison of long-term (1961–2005) annual average Q calculated by means of the Budyko equation as well as E and Q observations and sensitivity coefficients

Water balance components for YRB (1961–2005)			Sensitivity coefficients for E	Sensitivity coefficients for Q
Variable		Value		
P (mm a^{-1})		470	+0.76	+2.28
E_p (mm a^{-1})		1210	+0.054	−1.32
Nonlinear fitted for parameter ω	ω	2.44	+27.85	−1.36
	Std. error	0.019		
T_a (°C a^{-1})		7.3	0.0045	−0.0007
Estimated E (mm a^{-1})		420		
P-estimated E (mm a^{-1})		50		
Observed Q (mm a^{-1})		48		

relationship is that E will increase and E_p will decrease with an increase in P.

The extent and type of change in vegetation are regarded as key factors that influence catchment E and Q (Donohue et al. 2007; Yang et al. 2009; Stewart 2013). In particular, Donohue et al. (2010) provided an *fPAR* parameter (the fraction of photosynthetically active radiation that is absorbed by vegetation) to improve the accuracy of the Budyko hydrological model. According to Roderick et al. 1999, the *fPAR* parameter was estimated by means of the Normalized Difference Vegetation Index (NDVI) from the Global Inventory Modeling and Mapping Studies (GIMMS) data set provided by the Global Land Cover Facility, University of Maryland, at 8-km resolution from 1981.7 to 2006.12 (Tucker et al. 2004; Donohue et al. 2008, 2009).

$$F_{pre} = \frac{(F_x - F_n)(V_{cor} - V_n)}{V_x - V_n} + F_n \tag{15}$$

where F_{pre} represents *fPAR*. F_x and F_n are the maximum and minimum possible *fPAR* values set to 0.95 and 0.0, respectively. V_x and V_n are the corresponding maximum and minimum *NDVI* thresholds, respectively. In order to explain the relationship between *fPAR* and E, *fPAR*−mean *fPAR* and $\varepsilon_o - \varepsilon_b$ are provided for in Fig. 7. $\varepsilon_o - \varepsilon_b$ represents scatter points above or below the Budyko curve in Fig. 5 where ε_o and ε_b signify the ratio between E obtained from the water balance and Fu's equation and precipitation, respectively. Results show that for most years, E increased with increases in *fPAR*, indicating that partitions of P into Q and E are controlled by vegetation dynamics.

4 Discussion

4.1 Complementary relationships between evapotranspiration and water resources

Hydrological processes are contingent on the combined effects of climate, vegetation, and soil (Rodriguez-Iturbe and Porporato 2005), resulting in basin-scale changes to water resources (Chen et al. 2007; Yang et al. 2007). In point of fact, the relationship between E_p and E is controlled by available water and energy, namely, precipitation and net radiation (Sun 2007; Cong et al. 2010).

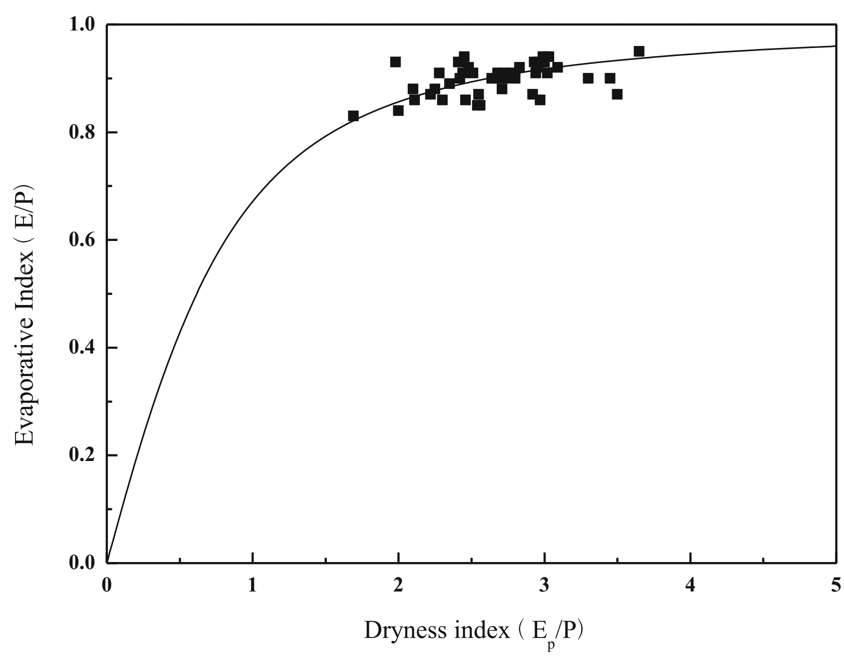

Fig. 5 Annual aridity index (E_p/P) in opposition to annual evaporative index (E/P) for YRB. E is obtained from the water balance

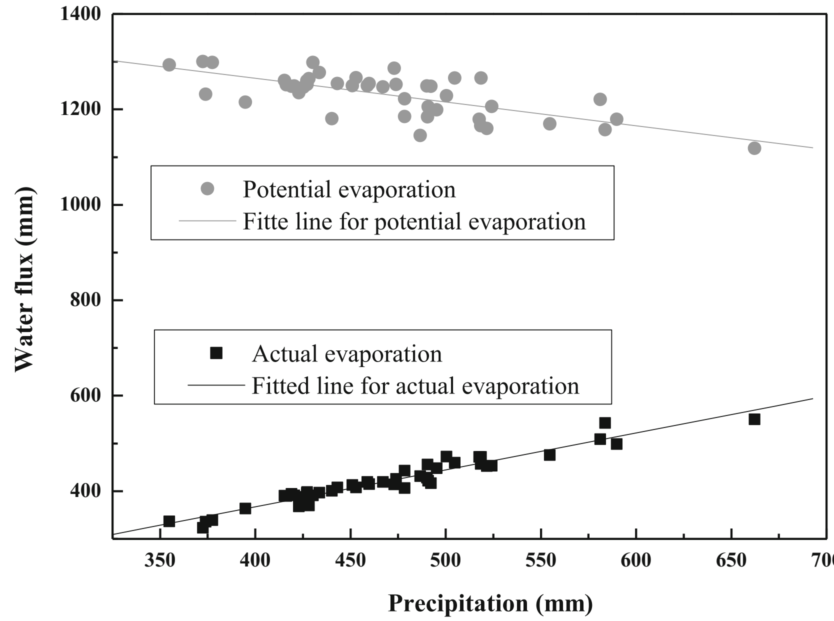

Fig. 6 Complementary relationship between E_p and E. E is calculated from the water balance using P minus observed streamflow

The complementary relationship between E_p and E reflects the complex feedback interactions that exist between processes governing their flow rates based on the degree by which soil can satisfy atmospheric demand for water vapor and by the resultant effect on energy distribution with regard to the land–atmosphere interface (Hobbins et al. 2001; Yang et al. 2011; Hoffman et al. 2011). For example, Szilagyi and Jozsa (2009) combined the complementary relationship between E and the coupled long-term water–energy balance in a Budyko-type framework and, using atmospheric measurements alone, derived ecosystem characteristics from it, such as mean effective relative soil moisture content and maximum soil water storage capacity. The complementary relationship between E and E_p that is provided in Fig. 7 implies complex interaction of climate changes, vegetation, and hydrological processes in different hydrometeorological conditions. These results are similar with Yang and Liu (2011) addressed in the Tibetan Plateau. All these examples provide a suitable method from which to understand the complex interactions that exist between water resources, climate, soil, and watershed terrain.

4.2 Importance of incorporating watershed characteristics into the Budyko hydrological model

The Budyko curve that describes patterns between P, E_p, and Q has been proven to be a useful tool in which to predict catchment energy and water balance (Donohue et al. 2007; Zhang et al. 2008; Yang et al. 2011). In view of the complexity

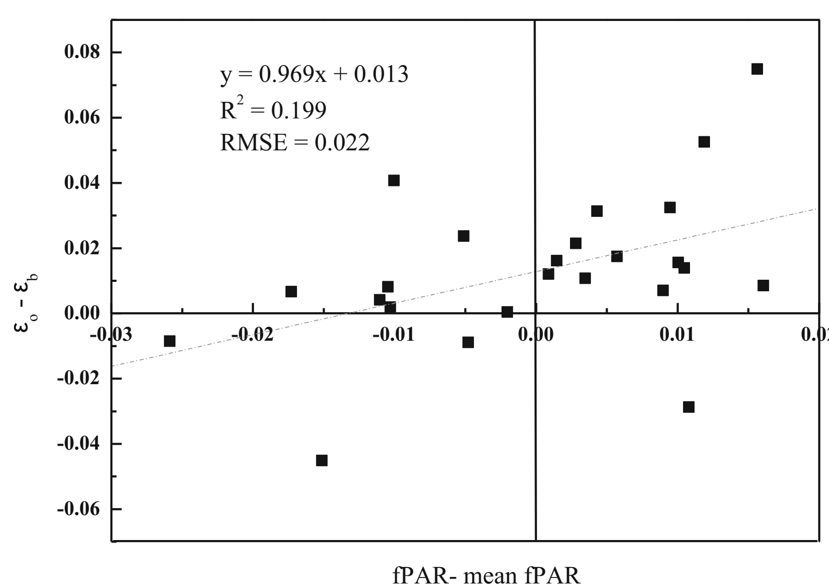

Fig. 7 Plots comparing *fPAR*−mean *fPAR* and $\varepsilon_o - \varepsilon_b$ for YRB from 1982 to 2005. $\varepsilon_o - \varepsilon_b$ represents scatter points above or below the Budyko curve in Fig. 5. ε_o and ε_b are dimensionless

of relationships resulting from variability and seasonality in climate, soil characteristics, vegetation type, and the different scales of analyses, researchers have attempted to incorporate watershed characteristics into the framework (e.g., Zhang et al. 2001, 2008; Donohue et al. 2007; Yang et al. 2007; Roderick and Farquhar 2011). Sankarasubramanian and Vogel (2003) argued that variation in soil-moisture-holding capacity is just as important as variation in watershed aridity in explaining the mean and variance of annual watershed runoff. Zhang et al. (2001) provided a plant-available water coefficient to reflect the differences in the way plant roots use moisture content in soil for purposes of transpiration. Several years later, Zhang et al. (2004) noted that ω could also represent the integrated effect of multiple catchment processes on E of which vegetation is one) and that a priori estimations of catchment ω are very difficult to ascertain. In point of fact, Donohue et al. (2007) demonstrated that leaf area, photosynthetic capacity, and rooting depth of vegetation dynamics affect not only annual and seasonal vegetation water use but also steady-state conditions. They recommended that it is necessary to explicitly include vegetation dynamics into the Budyko framework before it is applied on small scales. Using *fPAR* measurements acquired by means of remote sensing to reflect the dynamics of the ecohydrological properties of vegetation, Donohue et al. (2010) further researched the effect of ecohydrological properties on the Budyko framework. Their findings showed that vegetation data can improve accuracy in long-term annual average Q predictions as spatial scales decrease, and the presence of non-steady-state conditions prohibits the exploration of the hydrological role of vegetation dynamics on annual scales regardless of the analytical spatial scale applied. As shown in Fig. 7, changes in vegetation, demonstrated by *fPAR*, can control partitions of P into Q and E. All of these will help to understand the response of water resources to climate changes in different watershed conditions and help to improve water resource management for better adaptation to climate change.

5 Conclusion

Water resources are contingent on the combined effects of climate change and catchment characteristics. The water balance for YRB is controlled on an annual scale by P rather than by energy conditions (E_p). Fu's equation, incorporating an added parameter to reflect effects of catchment characteristics, was used to devise an analytical model from which to investigate the impact of climate change on water resources. Model results indicate that (i) E is controlled by changes in P rather than changes in E_p for YRB, (ii) Q is predicted to be more sensitive to available water than to comparable changes in E_p, and (iii) changes in catchment characteristics as reflected by the output of the analytical model can themselves drive the components that influence changes in water resources, which is consistent with changes for YRB ecohydrological processes observed in situ. In particular, at least to some extent, vegetation can act as a key factor from which to determine the partition of P into E and Q. This analytical model devised to combine catchment characteristics can thereby typify interactions between climate change, vegetation, and Q.

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