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The application of Budyko framework to irrigation districts in China under various climatic conditions

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Abstract

Budyko's framework has been widely used to study basin-scale water balance. In this study, we focus on the extended application of Fu's equation (one formulation of the Budyko-type curves) to 371 large irrigation districts in China over a period of 2010-2017. Water balance method was used to estimate actual evapotranspiration (ET) in the irrigated areas. Considering the contribution of shallow groundwater to ET, the water availability in the Budyko framework defined as equivalent precipitation (P_e) for irrigation areas is the sum of irrigation water (I), precipitation (P) and groundwater evaporation (ET_{gw}). Results showed that the relationships between evapotranspiration (ET), water availability (P_e) and energy supply (ET_0) can be accurately described by the Budyko's curves. The Fu's equation performed better in humid and semi-humid regions than arid and semi-arid regions. The comparison between $\partial ET/\partial P_e$ and $\partial ET/\partial ET_0$ confirmed the relative effect of water availability and energy supply on ET according to the variation of climatic conditions. The optimal values of Budyko parameter ω for each irrigation district was obtained with multi-annual data using least square method. Normalized Difference Vegetation Index (NDVI) and soil property (denoted by the proportion of clay and sand) were selected to develop empirical equation for parameter ω using multiple linear regression analysis method. This study showed that the Budyko framework can be extended to irrigation areas and provide useful information on evapotranspiration to assist in water management in irrigation areas.

Keywords: Budyko hypothesis; irrigation districts; NDVI and soil property; empirical equation

1. Introduction

Quantifying the partitioning of precipitation (P) at land surface into evapotranspiration (ET) and runoff (R) is of great importance in hydrology and water resources management.

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Serving as an effective tool to assess the partitioning, the Budyko framework proposed by Budyko (1974) has been widely used in global and regional scales within the past several decades (Caracciolo et al., 2018; Gerrits et al., 2009; Moussa and Lhomme, 2016; Roderick and Farquhar, 2011; Troch et al., 2013; Wang and Hejazi, 2011). The original Budyko formulation without parameters was assumed to be used in large basins at time scale significantly longer than 1 year (Gentine et al., 2012; Roderick and Farquhar, 2011), in which the evapotranspiration is dependent on the balance between energy supply and water availability. With the emergent deviation of measured data from the Budyko curve, however, more attention has been recently focused on the influence of catchment features or scales analysis on ET (Donohue et al., 2007). In this context, many studies subsequently derived Budyko-type formulations are parametric. For example, by building on the water balance for soil vadose zone, Milly (1994) developed one-parameter model to evaluate the dependence of water balance on water storage variation. Using the field observation data, Choudhury (1999) evaluated the performance of an empirical Budyko-based equation for estimating annual ET with precipitation, net radiation, and an adjustable parameter n, which was found to be fairly effective in explaining the ET variation. On the basis of previous works, Zhang et al. (2001) introduced a plant-available water coefficient (w) with a range of 0.5-2.0 to assess the long-term average effect of vegetation changes on catchment evapotranspiration. Based on a generalization of proportionality hypothesis of the Soil Conservation Service model, Wang and Tang (2014) derived a single-parameter Budyko-type model for mean annual water balance. The equations mentioned above work better to control the partition of water availability and determine the shape of Budyko curves by incorporating the influence of specific catchments characteristics on regional hydrological cycles (Xiong and Guo, 2012; Xu et al., 2013).

Among the equations proposed for the Budyko framework, Fu's equation (Fu, 1981) with an empirical parameter ω introduced has been used worldwide since recommended by Zhang et al. (2004):

$$\frac{ET}{P} = 1 + \frac{ET_0}{P} - [1 + (\frac{ET_0}{P})^{\omega}]^{1/\omega} \quad (1)$$

where ET is the actual evapotranspiration, mm; ET_0 is the potential evapotranspiration, mm; P is the precipitation, mm; ω is a dimensionless empirical parameter that determines the shape of the Budyko curve. Interestingly, parameter ω was found to be closely related to parameter n of Choudhury's method through $\omega = n + 0.72$ (Yang et al., 2008).

Previous studies showed that the variation of parameters in the Budyko-type equations can be influenced by catchment characteristics (Berghuijs et al., 2014; Gentine et al., 2012; Potter et al., 2005; Shao et al., 2012; Williams et al., 2012; Yang et al., 2009; Yokoo et al., 2008). The consideration of vegetation can improve the performance of the Budyko framework when extended into small regions (Donohue et al., 2007). Soil texture affects the vegetation growth through the water-holding capacity (Porporato et al., 2004; Yang et al., 2007). The shallow groundwater that contributes to ET, especially in arid and semi-arid areas, is taken as potential water resource for water availability (Istanbulluoglu et al., 2012; Wang, 2012; Wang and Zhou, 2016); and topography embedded its influence in hydrological cycle by regulating the partition of precipitation into runoff (Yao et al., 2016; Zhang et al., 2004). For agricultural areas with increasing food demand, the wide range of human activities including irrigation events have already altered land cover and regional ET (Xing et al., 2018), and half of the irrigation water is consumed through evaporation globally (Jackson et al., 2001). In China, 40% of total arable lands rely on irrigation events (Jin and Young, 2001). The application of water diversion for irrigation districts has transferred the local natural hydrological processes to a new water balance. For the areas with shallow groundwater, the groundwater evaporation also contributes to crop growing. Thus, the hydrological impact of irrigation events and shallow groundwater should be taken into account while the Budyko framework is used to regulate precipitation partitioning in irrigation districts. In this study, using the data collected from 371 large-sized irrigation districts under various climatic conditions across China, we aim 1) to assess the performance of Fu's equation in the irrigation districts in China by including external water resource into water availability; then 2) to evaluate which factors affect the variation of Fu's parameter ω; and 3) to develop an empirical relationship for estimating model parameter ω using readily available data from irrigation areas in China.

2. Materials and methods

2.1 Study area and data processing

A total of 371 large-sized artesian diversion irrigation districts with designed irrigation area covering from 200 to 10000 km^2 across China were selected in this study (Fig.1A). The irrigation areas are classified as arid, semi-arid, semi-humid and humid areas according to the values of aridity index (Tab.1). The information about each irrigation district including the location of centre (longitude and latitude), irrigation area, groundwater depth, annual gross irrigation water (I), and irrigation water use efficiency (η) over the period of 2010-2017 were measured and provided by China Irrigation and Drainage Development Centre. The detailed measurement processes and methods of net irrigation water and irrigation water use efficiency are shown in Fig.B1 and Tab.C1. Daily precipitation and monthly meteorological data including wind speed, air temperature, and relative humidity from weather stations on or around the selected irrigation districts covering the same period were downloaded from China meteorological data network (http://data.cma.cn/) (Fig.1A). The potential evapotranspiration (ET_0) is estimated as suggested by Shuttleworth (1993):

$$ET_0 = \frac{\Delta}{\Delta+\gamma}(R_n - G) + \frac{\gamma}{\Delta+\gamma}0.26(1 + 0.54u_2)(e_s - e_a) \quad (2)$$

where Δ is the slope of the saturation vapor pressure curve, kPa°C^{-1}; γ is the psychometric constant (approximately 0.067 kPa°C^{-1}); R_n and G are the net radiation and ground heat, MJm^{-2}day^{-1}; u_2 is the mean wind speed at 2 m height above the ground, m/s; e_s is the saturated water vapor pressure and e_a is the actual saturated water vapor pressure, kPa. The estimated mean monthly values of ET_0 were accumulated into annual values.

Tab.1 Climatic diversion according to aridity index

Aridity condition	Aridity index	Aridity condition	Aridity index
Humid	$ET_0/P \leq 1.0$	Semi-humid	$1.0 < ET_0/P \leq 1.5$
Semi-arid	$1.5 < ET_0/P \leq 4.0$	Arid	$ET_0/P > 4.0$

Due to the lack of shape maps of each irrigation district, the circles with same area as irrigation districts were used to locate the irrigation districts on map in present study. The values of NDVI (Normalized Difference Vegetation Index) were extracted from MOD13A1 products with spatial-temporal resolution of 500 m and 16 d (Fig.1B), which were available to download from the NASA Data Centre at https://reverb.echo.nasa.gov. All original images were pre–projected in a Universal Transverse Mercator (UTM) projection by Modis Reprojection Tool (MRT). The Digital Elevation Model (DEM) data with a spatial resolution of 1 km were downloaded at http://srtm.csi.cgiar.org/. The distribution map of soil texture denoting the proportion of sand and clay was provided by Data Centre for Resources and Environmental Sciences, Chinese Academy of Sciences (RESDC) (http://www.resdc.cn) (Fig.1CD).

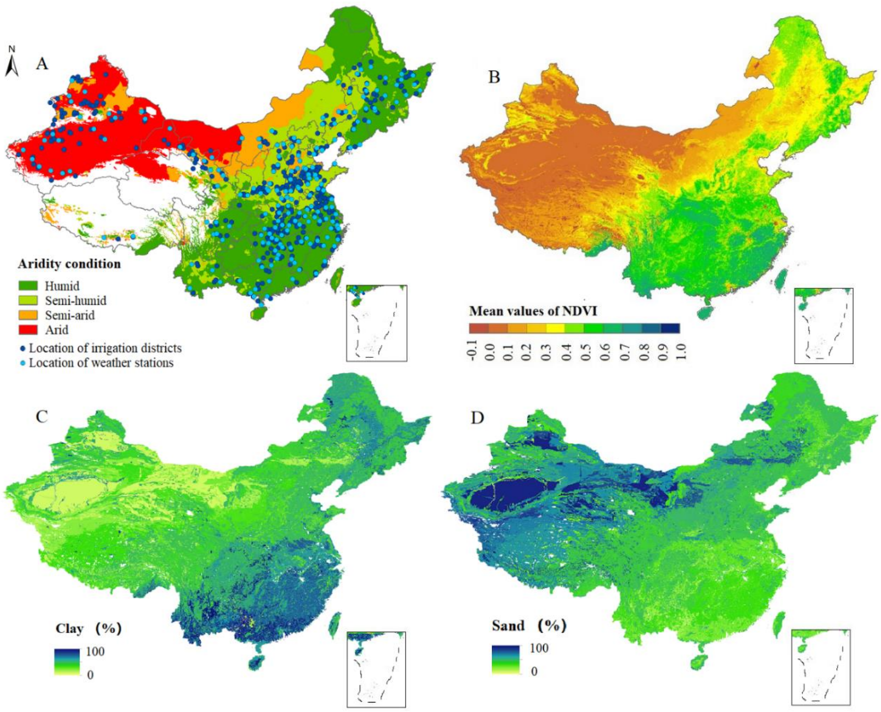

Fig.1 Location of the selected irrigation districts in this study (A) and the distribution map of mean values of NDVI (B), proportion of clay (C) and sand (D) in China

2.2 Theoretical framework

Precipitation is taken as water availability in original Budyko framework when applied in natural and closed catchments (Budyko, 1974). When extended into areas with irrigation activities, however, precipitation is no longer the only water source for evapotranspiration. For irrigation districts in arid and semi-arid regions, the agricultural productivity relies heavily on the irrigation events. For humid and semi-humid regions, most of the concentrated rainfall leaves irrigation districts by runoff and is not consumed for crop growth. A certain amount of water is still employed to achieve the optimal agricultural productivity. In addition to providing water for crop growth in arid and semi-arid regions, the irrigation events are also responsible to offset water deficit caused by the unevenly distributed rainfall in humid and semi-humid regions. Thus, the irrigation water should be included in water availability when the Budyko framework is applied in agricultural irrigation districts (Han et al., 2011). In addition, the groundwater evaporation consumed for crop growth, especially in arid and semi-arid areas with shallow groundwater depth, contributes to the water availability. According to our previous study (Chen et al., 2020), the modified Aver'yanov's phreatic equation is applicable to estimate the groundwater consumption for the irrigation districts with shallow groundwater depths lower than 3 m:

$$ET_{gwi} = K_C \times E_{pani} \times (1 - \frac{H_i}{H_{max}})^n \quad (3)$$

where K_C is crop coefficient related to the crop growth and root length (Cheng, 1993); E_{pani} is the monthly water surface evaporation measured by pan evaporation, (mm); H_i is the mean annual groundwater depth, (m); H_{max} is the critical groundwater depth at which the phreatic evaporation will vanish (m); and n is a dimensionless empirical coefficient related to soil texture ranging from 1 to 3. Since the irrigation districts with groundwater depth less than 3 m only make up 1/5 of the total, the annual change of water storage were assumed to be negligible, the sum of irrigation water, precipitation, and groundwater consumption can be used as water availability for upper soil layers based on water balance in large irrigation districts (refer to Fig.3B in study of Chen et al. (2020)), similar to the equivalent precipitation P_e defined by Wang (2012):

$$P_e = I + P + ET_{gw} \quad (4)$$

where ET_{gw} is groundwater evaporation, indicating the contribution of shallow groundwater to ET. When the groundwater depth is larger than 3 m, no groundwater contributes to evaporate any more, i.e., $ET_{gw} = 0$. With the newly defined P_e, the Fu's equation can be expressed as:

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$$\frac{ET}{P_e} = 1 + \frac{ET_0}{P_e} - [1 + (\frac{ET_0}{P_e})^{\omega}]^{1/\omega} \tag{5}$$

Affected by the natural factors, the variation of ET can be determined by the variation in water availability and energy supply while the land surface conditions for given districts are assumed to be constant (Yang et al., 2006). The relative magnitude of $\frac{\partial ET}{\partial P_e}$ and $\frac{\partial ET}{\partial ET_0}$ can reflect the relative effect of P_e and ET_0 on ET variation, respectively (Han et al., 2011):

$$\delta ET = \frac{\partial ET}{\partial P_e}\delta P_e + \frac{\partial ET}{\partial ET_0}\delta ET_0 \tag{6a}$$

$$\frac{\partial ET}{\partial P_e} = 1 - \left[1 + \left(\frac{P_e}{ET_0}\right)^{\omega}\right]^{\frac{1}{\omega}-1}\left(\frac{P_e}{ET_0}\right)^{\omega-1} \tag{6b}$$

$$\frac{\partial ET}{\partial ET_0} = 1 - \left[1 + \left(\frac{ET_0}{P_e}\right)^{\omega}\right]^{\frac{1}{\omega}-1}\left(\frac{ET_0}{P_e}\right)^{\omega-1} \tag{6c}$$

where δET, δP_e and δET_0 are the variability in actual evapotranspiration, water availability and energy supply. The elasticity, defined as the indicator to reflect the sensitivity of dependent variable to the change in other variables, is further applied to separate and evaluate the influence of irrigation water, precipitation, and energy supply on the variation of ET:

$$S_I = \frac{\partial ET}{\partial I}\frac{I}{ET} \tag{7a}$$

$$S_P = \frac{\partial ET}{\partial P}\frac{P}{ET} \tag{7b}$$

$$S_{ET0} = \frac{\partial ET}{\partial ET_0}\frac{ET_0}{ET} \tag{7c}$$

where S_I, S_P, and S_{ET0} are the elasticities of evapotranspiration to irrigation water, precipitation and energy supply, respectively. According to the definition, a positive elasticity indicates that an increase in the independent variables will bring an increase in ET. The impact of groundwater variation on ET is not discussed in this study as the groundwater evaporation in most of irrigation districts were out of consideration.

2.3 Methodology for estimating actual evapotranspiration

According to the report released by China Irrigation and Drainage Development Centre (Dang and Feng, 2016), the measured net irrigation water denotes the fraction of total irrigation water that stored in soil layers and available for crop growth, which is divided by the gross irrigation water to obtain the irrigation water use efficiency (Dang and Feng, 2016). The remaining serves to leach accumulated salt from soil surface, leaks or evaporates unproductively. Similarly, the fraction of precipitation actually used by plants or evapotranspiration can be approximately estimated following the U.S. Department of Agriculture Soil Conservation Method (Smith, 1992), as widely used by numerous study and crop models including in China (Cao et al., 2014a; Cao et al., 2014b):

$$P_{effd} = P_d(4.17 - 0.2P_d)/4.17 \qquad \text{for } P_d < 8.3 \text{ mm/d}$$
$$P_{effd} = 4.17 + 0.1P_d \qquad \text{for } P_d \geqslant 8.3 \text{ mm/d} \qquad (8)$$

where P_{effd} is the daily effective precipitation, mm/d; P_d is the actual daily precipitation, mm/d. The sum of daily values is regarded as annual values. Assuming the variation of soil water storage is negligible, the water balance equation at annual scale for irrigation district is expressed as follow:

$$ET = I + P - D_i \qquad (9)$$

where D_i is the outflow of irrigation districts that cannot be used as crop water consumption, including deep seepage, runoff and drainage through ditches. The actual evapotranspiration can be further approximated as the sum of net irrigation water and effective precipitation (Döll and Siebert, 2002; Smith, 1992):

$$ET = I_{net} + \sum P_{effd} = \eta \times I + \sum P_{effd} \qquad (10)$$

where I_{net} is net irrigation water, mm; $\sum P_{effd}$ is the annual effective precipitation calculated as the sum of daily values, mm.

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3. Results

3.1 Validation of water balance equation

The values of annual *ET* derived from MOD16 products from the year of 2010-2017 are used to validate the accuracy of water balance equation. As shown in Fig.2, the water balance equation performed well in estimating the values of *ET* compared with that of MOD16 products with RMSE of 124.4 mm, MRE of 18.6%, and R^2 of 0.6. It's reasonable to believe that the simulated results of water balance equations were accurate in the following study.

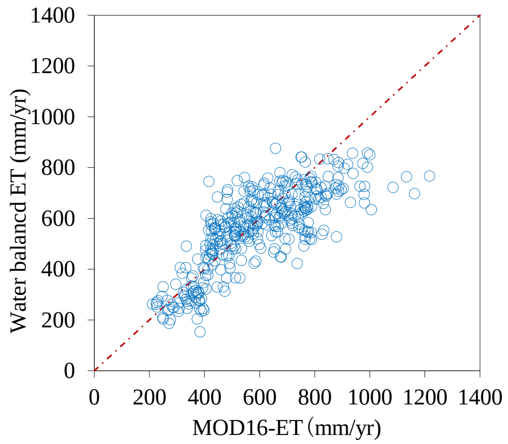

Fig.2 Comparison of annual *ET* between water balance equation and MOD16 products

3.2 Analysis of annual Budyko curves

With the use of equivalent precipitation, the ratio of evapotranspiration to the water availability for the irrigation districts is plotted against the ratio of potential evapotranspiration to the water availability as shown in Fig.3. The discrete data were observed in arid and semi-arid regions contrasted to relatively convergent data in the humid and semi-humid regions. The ranges of ω values derived from the data scatted in arid and semi-arid areas varied from 1.25 to 2 and 1.4 to 2 respectively, while those in humid and semi-humid areas were relatively stable. The distinguishing performances of data in various climatic regions are mainly attributed to

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the different dominant roles on evapotranspiration under various climatic conditions. The dominant role of energy supply in evapotranspiration variation in humid and semi-humid regions was highlighted via the form of $ET/P_e \sim ET_0/P_e$ since ET_0 was placed in the position of numerator, leading to the convergently distributed data trend with unfluctuating values of ω. Similarly, the control role of water availability on ET in arid and semi-arid regions was weakened by the exaggerated influence of catchment characteristics through the form of $ET/P_e \sim ET_0/P_e$ as P_e was placed in the position of denominator, mainly reflected in the different values of ω and dispersion of data points (Yang et al., 2007).

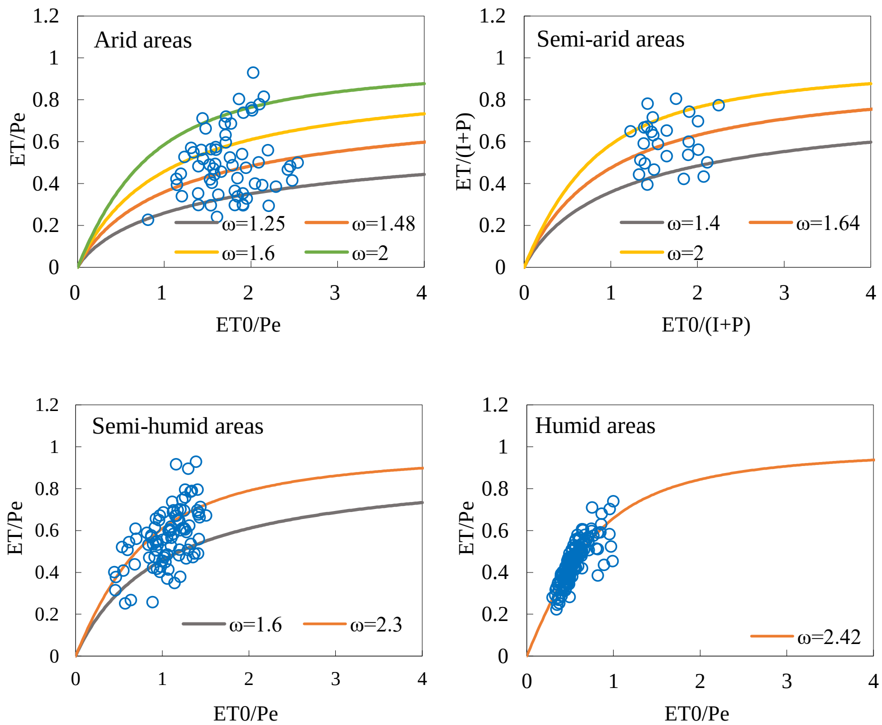

Fig.3 Mean annual values of actual evapotranspiration, potential evapotranspiration, and equivalent precipitation data plotted in Fu's equation over 2010-2017 for irrigation areas under various climate conditions

3.2 Controlling factors on the variation of *ET*

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Fig.4 shows the relationship between $\partial ET/\partial ET_0$ and ET_0/P_e, as well as the relationship between $\partial ET/\partial P_e$ and ET_0/P_e under various climatic conditions, respectively. All the irrigation districts are further classified into three climate conditions as follows: water-limited condition ($ET_0/P_e > 1.35$), equitant condition ($0.76 < ET_0/P_e \leqslant 1.35$), and energy-limited condition ($ET_0/P_e \leqslant 0.76$) (McVicar et al., 2012). Under the water-limited condition, the values of $\partial ET/\partial ET_0$ are smaller than $\partial ET/\partial P_e$ and insensitive to the variation of ω, highlighting the dominant role of water availability on evapotranspiration; under energy-limited condition, the values of $\partial ET/\partial P_e$ are smaller than $\partial ET/\partial ET_0$ and insensitive to the variation of ω, highlighting the dominant role of energy supply; under equitant condition, the overlaps of plotted points are observed and emphasize the combined effect of water availability and energy supply on ET variation. These results are consistent with original Budyko hypothesis (Carmona et al., 2016; Fu, 1981; Zhang et al., 2001; Zhang et al., 2004).

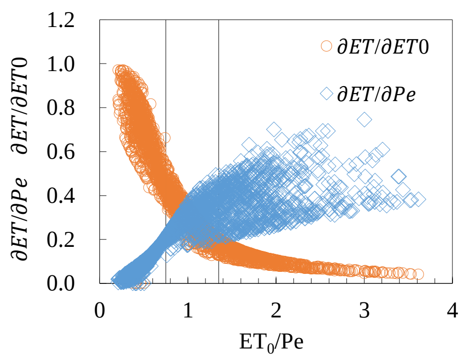

Fig.4 Plot of $\frac{\partial ET}{\partial P_e}$ and $\frac{\partial ET}{\partial ET_0}$ with aridity index ($\frac{ET_0}{P_e}$) for the large irrigation districts in China

3.3 Sensitivity of ET to I, P and ET_0

Fig.5 shows the variation of elasticities among 371 irrigation districts and the statistical results are grouped by arid, semi-arid, semi-humid and humid conditions. The larger values of S_{ET_0} and S_{I+P} occurred respectively in non-arid (humid and semi-humid) areas and non-humid

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(arid and semi-arid) areas, suggesting that the variation of ET is more sensitive to energy supply in humid and semi-humid areas or water availability in arid and semi-arid areas. Except in arid areas, the values of S_I is generally smaller than S_P. This is because the irrigation water serves as the main water resource for crop growth in arid areas due to the severe water shortage (the mean annual precipitation is 95.6 mm/yr) but supplemental water of precipitation in other climatic conditions. The mean values of S_I for four climatic conditions are 0.529, 0.350, 0.118, and 0.038; and the mean values of S_P are 0.097, 0.290, 0.216, and 0.111. These results indicate that a 10% increase in irrigation water could cause evapotranspiration increase by 5.29%, 3.50%, 1.18%, and 0.38% in arid, semi-arid, semi-humid and humid areas; a 10% increase in precipitation could cause evapotranspiration increase by 0.97%, 2.90% 2.16%, and 1.11%. Similarly, a 10% increase in potential evaporation could cause evapotranspiration increase by 3.93%, 3.83%, 6.79%, and 8.61%, respectively.

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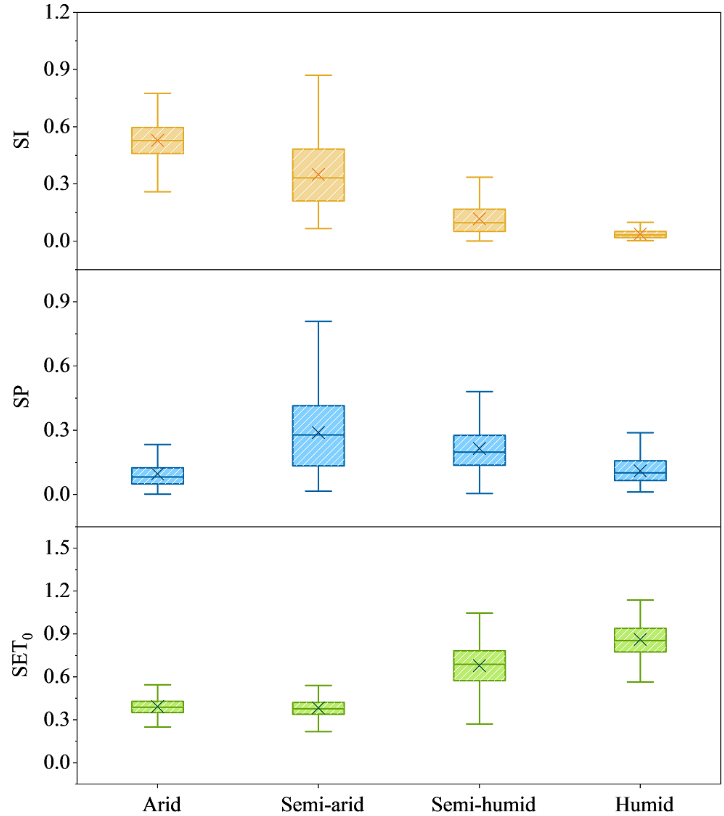

Fig.5 Comparison between elasticities of irrigation water (S_I), precipitation (S_P) and energy supply (S_{ET0}) for arid, semi-arid, semi-humid and humid regions in China

3.4 Characteristics of ω and influence factors

As a parameter to represent the integrated effects of catchment characteristics on *ET* variation, the optimal values of ω for all irrigation districts were obtained by minimizing the values of RMSE between the Budyko modelled annual ET/ET_0 and the estimated ones using the data from 2010-2017. The values of ω in humid and semi-humid regions are generally larger than those in arid and semi-arid regions (Fig.6). Range of the ω values obtained from this study (1.24-3.34) compares favourably with the results from previous studies. Applying a neural network model in 224 small basins (ranging from ~100 to 10000 km^2) with the data from MOPEX, Xu et al. (2013) observed that the values of ω varied from 1.0 to 4.9 with a median value of 2.6. Based on the features of vegetation cover, Zhang et al. (2004) selected forested and grassed catchments as two typical types and found the averaged ω values for the two catchments were 2.84 and 2.55 with data ranging between 1.7 to 5.0. In China, the range of ω obtained from 108 arid and semi-arid basins varied from 1.3 to 4.6 (Yang et al., 2007), a little higher than the results from 97 basins in Australia (1.8-3.8) using Murray Darling Basin data (Donohue et al., 2011).

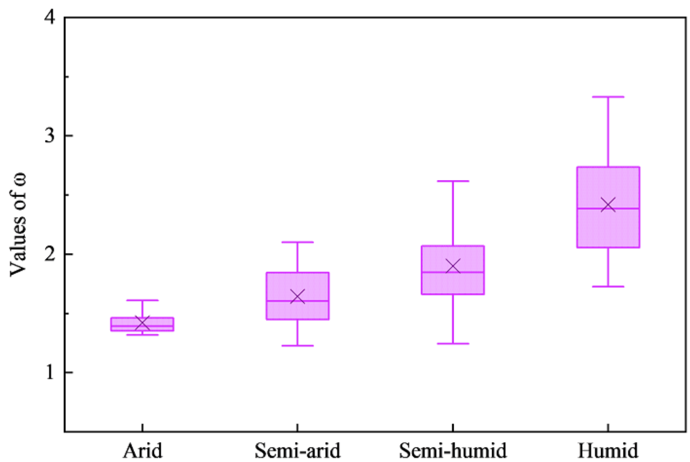

Fig.6 Distribution of the optimal ω values grouped by four climate conditions

Besides the water availability and energy supply, the catchments characteristics also play a significant role in determining the shape of Budyko curves (Potter and Zhang, 2009; Roderick and Farquhar, 2011; Woods, 2003; Yuan et al., 2010). Since more than 95% of irrigation districts locate in plain areas with slopes ranging from 1 to 5 degree, the influence of terrestrial slope on ω is neglected in this study. The mean values of NDVI were selected to represent the differences in vegetation cover across the irrigation districts. The vegetation coverage in southeast of China is significantly higher than that in northwest with mean NDVI values of 0.51 and 0.17, respectively (Fig.1B). Meanwhile, the proportion of clay and sand is supposed

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to be another influence factor on *ET* variation owing to the different water-holding capacities (Fig.1CD). For dimensional analysis, the ratio of clay to sand content expressed as P_{cl}/P_{sa} is used to represent the soil property. As shown in Fig.7, the parameter ω in Fu's equation is closely correlated with the long-term vegetation coverage and soil property. Using the multiple linear regression analysis method (MLRA), the empirical equation of parameter ω can be determined as follows:

$$\omega = 0.537exp\ (2.08NDVI)(\frac{P_{clay}}{P_{sand}})^{0.28} + 1 \quad (11)$$

As shown in Fig.8A, the model explains 48% of the observed variance with R of 0.693 and RMSE of 0.315.

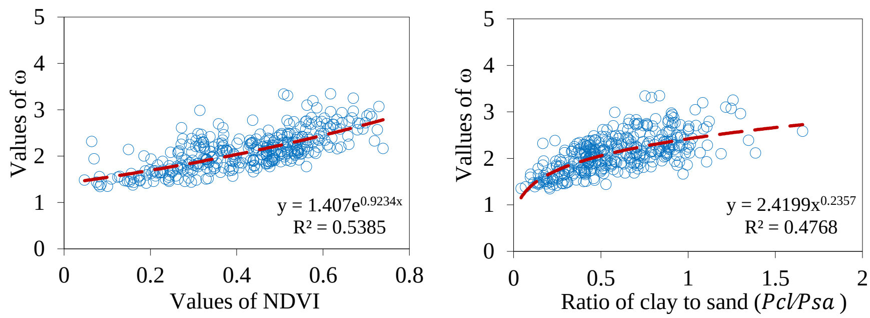

Fig.7 Relationships between ω and NDVI and soil texture

Various models have been proposed to establish relationship between ω and influence factors, including soil hydrological features, terrestrial slope, vegetation coverage and climatic factors (Donohue et al., 2012; Li et al., 2013; Shao et al., 2012; Yang et al., 2009; Yang et al., 2007). However, in the view of the consideration of climatic conditions in the original Budyko framework, it's better to estimate ω with climate factors excluded to avoid cross-correlation issues (Xu et al., 2013). Also, the expression of soil texture denoted by the ratio of clay and sand content is more accessible than other soil properties such as relative infiltration capacity and relative soil water storage (Yang et al., 2009). With the estimated values of parameter ω,

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Fu's equation reproduced mean annual *ET* well for irrigation districts with R^2 of 0.74 and RMSE of 63.08 mm/yr (Fig.8B).

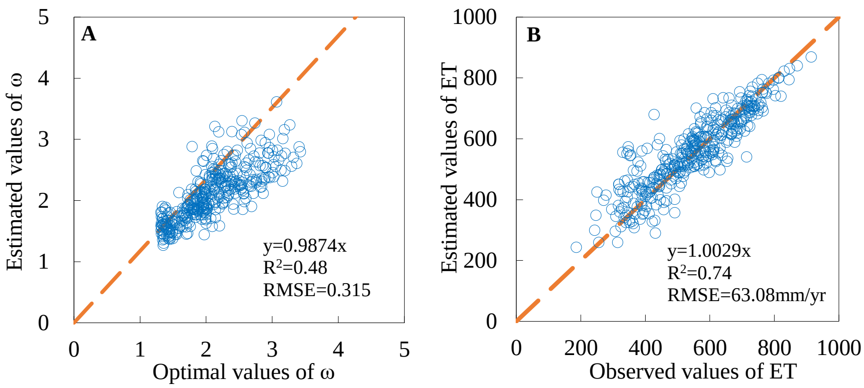

Fig.8 A: Comparison between optimal values of ω and estimated ones from multiple linear regression analysis; B: Relationship between actual *ET* and estimated *ET* using ω calculatd by Equation (11)

4. Discussion

4.1 Uncertainty about the annual water balance and influence factors on ω

For long-term water balance in large natural catchments, evapotranspiration can be regarded as the partitioning of precipitation which is serving as water availability in Budyko formulations ($ET = P - R$) while water storage is assumed to be negligible (Donohue et al., 2010; Hobbins et al., 2001; Rodell, 2004; Xue et al., 2013). Recently, the estimation of water balance at finer time scales has attracted more attentions in many studies and these studies showed that the water storage change (including soil moisture and groundwater) played a significant role in annual water balance and made a great contribution to meet the deficit of water supply for crop water demand (Chen et al., 2018; Flerchinger and Cooley, 2000; Ghamarnia et al., 2013; Leblanc et al., 2009; Namuburg et al., 2005; Valayamkunnath et al., 2019). The application of equivalent precipitation incorporating water storage change is able to work better at improving the performance of Budyko predictions in annual scale (Chen et al., 2013; Istanbulluoglu et al., 2012; Wang, 2012; Wang and Zhou, 2016), especially for basins in arid and semi-arid regions (Du et al., 2016; Milly and Dunne, 2002; Xing et al., 2018). In this study, we assume the water storage changes at annual scale are negligible, which may lead to errors in accurate estimation of water availability, and then influence the analysis about the shape of Budyko curves and the variation of ω values. Furthermore, the uncertainty of the influence factors on the variation of ω should be recognized as well. The variation of ω in irrigation districts is associated with NDVI and soil property. Due to the differences in water requirement between crop types, however, the evapotranspiration from the pixels with same NDVI differs as a response to crop planting patterns (Bai et al., 2017; Eichelmann et al., 2018; Mo et al., 2015). Thus, the influence of water storage change and crop planting patterns (i.e., the fraction of each crop type) on the allocation of water availability should be accommodated for detailed analysis in further study.

4.2 Water use efficiency in irrigation districts

By selecting 108 arid and semi-arid catchments and 102 humid catchments in China, Wang et al. (2018) estimated that the mean values of ω for normal and karst humid catchments are 2.23 and 2.03, while for arid and semi-arid catchments is 3.18. In present study, however, the results shown in Fig.6 indicate that the values of ω increased from arid to humid regions. The smaller values of ω in arid and semi-areas produced smaller values of ET/P_e varying from 0.4 to 0.6. In this context, ET is hardly approaching to the total water availability even under extremely arid condition. As shown in Fig.9, only 30% to 70% of rainfall are consumed for crop use and the effective precipitation efficiency in arid and semi-arid regions are generally larger than those in humid and semi-humid regions. The arid and semi-arid regions are generally suffering from severe soil salinization (Jiang and Shu, 2018; Peng et al., 2019; Qian et al., 2019) and a series of ecological environment problems caused by it (Besser et al., 2017;

Haj-Amor et al., 2017) owing to the scarcity of rainfall and high potential evaporation. To alleviate the negative influence of soil salinization on crop yield, part of irrigation water is applied to flush accumulated salt from soil surface to prepare for the next season's crop (Tang, 2018; Wei and Xu, 2005; Zhang, 1993), finally resulting in small fraction of water availability used by ET. The amount of irrigation water used to leach salt mainly depends on local irrigation technology and water management. In semi-humid and humid areas with relatively abundant precipitation, the application of irrigation events aims to regulate the unevenly distributed rainfall in a year. The small values of ET/P_e reflect the generally low water use efficiency of irrigation districts in China and indicate the significance of water saving measurements. For arid and semi-arid areas with relatively higher rainwater utilization, the improvement of drainage systems can effectively remove the accumulated salt from soil surface, further reducing the fraction of irrigation water used to alleviate soil salinization. For semi-humid and humid areas with enough precipitation, the judicious regulation of rainfall including the effective rainwater harvesting and reuse is expected as helpful way to improve water use efficiency. Reducing unproductive evapotranspiration through canal lining or drip irrigation is applicable to improve water use efficiency as well.

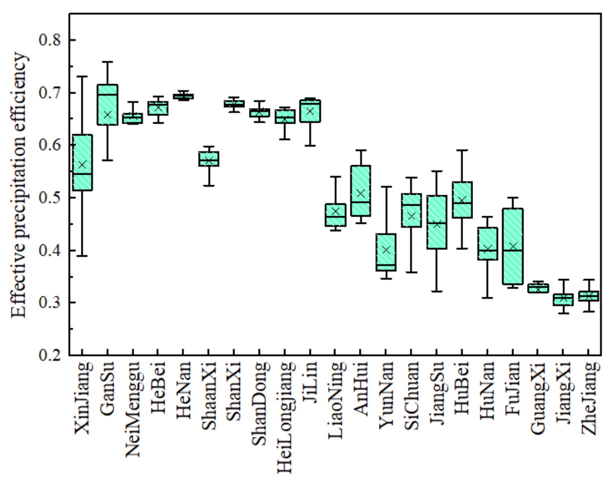

Fig.9 Range of effective precipitation efficiency across study area

5. Conclusions

This paper aims to examine the performance of Budyko framework in agricultural irrigation regions using Fu's equation. A total of 371 large irrigation districts across China were selected as study areas, which were grouped by arid, semi-arid, humid and semi-humid areas. With the precipitation replaced by equivalent precipitation ($P \rightarrow P_e = (I + P + ET_{gw})$), the data of $ET/P_e \sim ET_0/P_e$ were plotted well in Budyko areas. The values of ω increased from arid and humid regions. Smaller values in arid and semi-arid regions were attributed to the low water use efficiency. Part of irrigation water is not consumed by crop growth but serving to leach salt to alleviate salinization. Surface runoff or deep seepage caused by concentrated rainfall in humid and semi-humid regions is invalid for crop growth and irrigation is still applied to regulate water deficit caused by it. Corresponding water-saving measures should be taken to improve water use efficiency in different climatic areas. In this study, the variation of ω was found to be closely related with NDVI and soil texture (denoted by the ratio of clay and sand content, P_{cl}/P_{sa}). The simple empirical model of ω developed using NDVI and soli properties performed well in reproducing ET in irrigation districts.

Appendix

Section 1 Estimation of irrigation water use efficiency η

Irrigation water use efficiency η denotes the fraction of the total irrigation water actually used by crop growth, i.e., the ratio of net irrigation water to total irrigation water. Referring to the report released by China Irrigation and Drainage Development Centre, two methods are alternative in large irrigation districts to estimate the irrigation water use efficiency when applied to at least three selected typical patches of each crop type: direct measurement method and head-end measurement method (Fig.B1). For direct measurement, the increase in the depth of water surface or in soil water content in soil moist layer (the applicability of methods

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depends on crop types, i.e., dry farming or rice) after irrigation events is measured as the net irrigation water; for head-end measurement, the difference between inflow to and outflow from irrigation districts is regarded as the amount of net irrigation water. Details of the measurement methods are shown in Tab.C1.

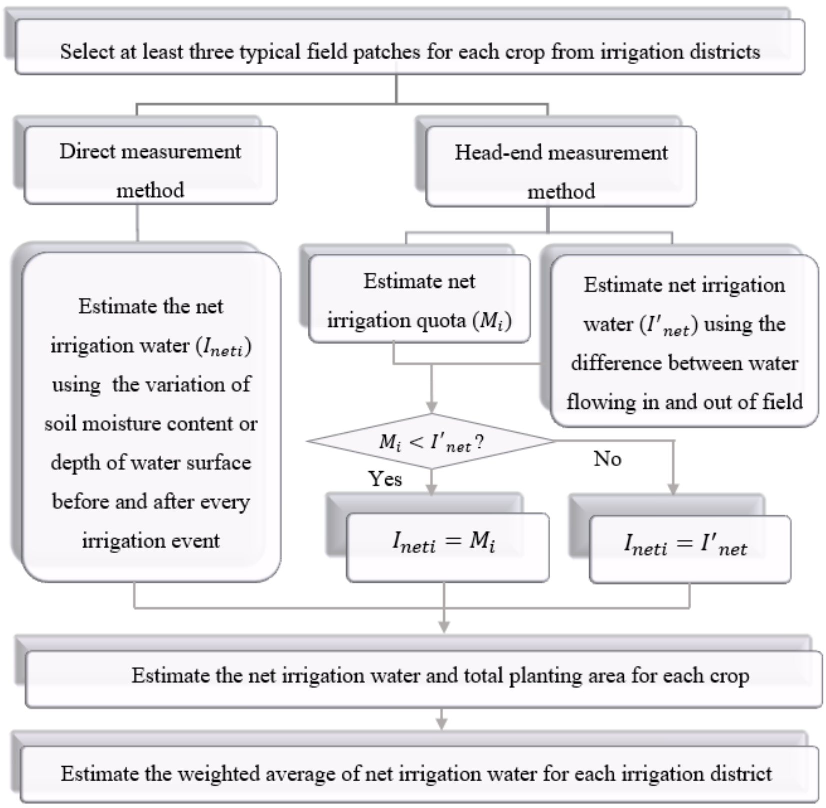

Fig.B1 Calculation process of net irrigation water for field patches and large irrigation districts

Tab.C1 Methods for calculating irrigation water use efficiency for irrigation districts

Direct measurement method				Head-end measurement method
Crop type	Dry farming		$I_{neti} = H(\theta_{v2} - \theta_{v1})$	$I_{neti} = \min\left(\frac{I_{ini} - D_i}{A_i}, M_i\right)$
	Rice	Submerged irrigation	$I_{neti1} = H_2 - H_1$	
		Damp irrigation	$I_{neti2} = H(\theta_{v2} - \theta_{v1})$	

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Net irrigation water of irrigation district: $I_{net} = \frac{\sum_i^n I_{neti} \cdot A_i}{\sum A_i}$	Utilization coefficient: $\eta = \frac{I_{net}}{I}$

Note: I_{neti} is the net irrigation water amount for each crop estimated from selected typical field patches, mm; i denotes the crop type; I_{net} is the weighted average of net irrigation water for the whole irrigation districts, mm; I is the total irrigation water diverted from water-supplying area for irrigation districts, mm. For dry farming and damp irrigation stage of rice fields, H is the depth of moist soil layer, mm; θ_{v1} and θ_{v2} are the soil volumetric water content before and after irrigation events, %. For the submerged irrigation stage of rice fields, H_1 and H_2 are the depth of water surface before and after irrigation events, mm. When applying the head-end measurement method, the judgement of whether sufficient irrigation is the premise for accurate estimation of net irrigation water. I_{ini} and D_i are the water amount flowing in and out of fields, mm; M_i is the estimated net irrigation quota for each crop, mm; and A_i is the total cover area of each crop. Notably, rice fields have no drainage during crop growth period.

Data availability

The observed data used in this study are not publicly accessible. These data have been collected and supported by China Irrigation and Drainage Development Centre. Anyone who would like to use these data should contact Hang Chen and Zailin Huo to obtain permission.

Author contributions

JC, YS and ZH provided the data. HC and ZH contributed to the development of the model. Preparation and revision of the paper were done by ZH, under the supervision of LZ.

Competing interests

The authors declare that they have no conflict of interest.

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