Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2017-151, 2017
Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 5 April 2017

The effect of water storage change in ET estimation in humid catchments based on Budyko framework and water balance models

Tingting Wang[1,2], Fubao Sun[1,2,3*], Hong Wang[1], Wenbin Liu[1], Hao Wang[4]

1. Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Science and Natural Resources Research, Chinese Academy of Sciences, Beijing, China

2. College of Resources and Environment, University of Chinese, Academy of Sciences, Beijing, China

3. School of Civil Engineering, Hexi University, Zhangye City, Gansu Province, China

4. China Institute of Water Resources and Hydropower Research, State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, Beijing 100038, China

Corresponding Author: Fubao Sun (Sunfb@igsnrr.ac.cn), from Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences

2017/03/27

Keywords: evapotranspiration, humid catchments, water storage change, water balance, Budyko hypothesis

Abstract

An accurate estimation of evapotranspiration (ET) in humid catchments is essential in water-energy budget research and water resource management. While it remains a huge challenge and there is no well accepted explanation for the difficulty of annual ET estimation in humid region so far. Here we present the ET estimation in 102 humid catchments over China based on the Budyko framework and two hydrological models: abcd model and Xin'anjiang model, in comparison with ET calculated from the water balance equation (ET_{wb}) on the ground that the ΔS is approximately zero at multiannual and annual time scale. And we provide one possible explanation for the poorly annual ET estimation in humid catchments as well. The results show that the Budyko framework works fine in ET estimation in humid catchments at multi-annual timescale, while neither the Budyko framework nor the hydrological models can estimate ET well at annual timescale. One major cause for this poorly annual ET estimation is the neglecting of ΔS in ET_{wb} since it enlarges the variability of real actual ET. Much improvement has been made when comparing estimated ET + ΔS with those ET_{wb}, and the bigger the catchment area is, the better this improvement can be. This provides an acceptable explanation for the poorly estimated annual ET and reveals the important role of annual ΔS in ET estimation and validation in humid catchments. We highlight that the annual ΔS shouldn't be taken as zero in water balance equation in humid catchments.

1 Introduction

The evapotranspiration (ET) over terrestrial surface is the second largest component of the global terrestrial water cycle since it returns about two thirds of precipitation (P) that falls over the land. The partitioning of P into streamflow (Q) and ET is captured by the ratio of potential evapotranspiration (PET) to precipitation ($\bar{\phi}$ =PET/P, dryness index), i.e., the Budyko hypothesis (Milly, 1994;Yang et al., 2006;Donohue et al., 2007;Tekleab et al., 2011), and it is further constrained by physical limits, namely, the limitation of available water (ET<P) in non-humid catchments and limitation of available energy (ET<PET) in humid catchments (Fu, 1981;Milly and Dunne, 2002). In non-humid catchments, the Budyko hypothesis and many other approaches, e.g., abcd model (Sankarasubramanian and Vogel, 2002;Martinez and Gupta, 2010) and remote sensing outputs (Zhang et al., 2008b), have been well proceeded in ET estimation and thus Q prediction and water resource management around the global (Ukkola and Prentice, 2013;Xu et al., 2013) and regional like America (Chen et al., 2013), Australia (O'Grady et al., 2011) and China (Yang et al., 2006;Yang et al., 2007). While in humid region, the quantity of research are limited (Tekleab et al., 2011;Zhang et al., 2012;Carmona et al., 2016). Proportional relationship is discovered between PET and ET (Wang and Hejazi, 2011;Cong et al., 2008) but the estimated ET is less well based on the Budyko hypothesis and other models (Wang and Hejazi, 2011;Zhu et al., 2013). Zhang et al (2012) compared ET based on the PML model (Leuning et al., 2008;Zhang et al., 2012), products from Jung (Jung et al., 2010)

and the Budyko framework against ET from water balance equation (ET_{wb}) in 110 humid catchments around the global, but found that their R^2 were very small and the trends didn't match well, showing that these approaches are, as yet, not sufficiently accurate to explain ET in humid regions.

However, there is no widely well accepted explanations for the difficulty of annual ET estimation in humid catchments so far as there are some unknown obstacles exist. The poorly estimation of ET in humid catchments remains to be a huge challenge for bridging the important gap in our knowledge of the hydrologic cycle. Hence, researchers have made their attempts based on the commonly used Budyko framework with one or more parameters included (Fu, 1981;Wang and Tang, 2014;Peter et al., 2016;Carmona et al., 2016) to better estimate ET in humid catchments, and try to build some kind of relationship with possible factors, e.g., vegetation (Donohue et al., 2007;Ye et al., 2015), water storage change (Chen et al., 2013;Zeng and Cai, 2015a), topographic factors (Xu et al., 2013) and integrative of various controls (Ye et al., 2015;Chen et al., 2013) to further investigate the possible explanation.

The water storage change (ΔS), in particular, has been considered to be one important factor that affects ET estimation in humid catchments. The soil water storage performs as a filter from P to Q in catchments (Daly and Porporato, 2006), and this filter effect and water storage change would introduce a bias into ET estimation, especially in humid catchments. Milly (1994) discussed the effect of soil moisture on ET theoretically and indicated a mediating effect on ET based on the Budyko framework. Sound evidence suggests that the ΔS cannot be neglected at both annual (Zhang et al., 2008a;Wang, 2012;Bai et al., 2016) and intra-annual (Chen et al., 2013;Ye et al., 2015) timescales. Liu et al. (2016) specific present a worldwide evaluation of nine ET products with consideration of ΔS. Mao et al. (2016) found that the ΔS in reservoirs altered the calculated ET trends of almost zero increase to a 4.2% increase per decade when not taking ΔS into account over China. Moreover, the ΔS can affect the variability of ET in humid catchment as well. (Wang and Alimohammadi, 2012;Chen et al., 2013;Ye et al., 2015;Zeng and Cai, 2015a) Zeng and Cai (2015a) pointed out that the variability of the ΔS made some contribution to the variability of intra-annual ET in humid catchments, through much smaller than that in non-humid catchments (Wang et al., 2009;Wang and Zhou, 2015). Wang (2012) concluded that the inter-annual variability of ET is not strongly correlated with P variability but with the variations of P-ΔS.

People try their best to improve the models with consideration of ΔS to meet ET_{wb} so as to reveal the trend and pattern of ET. Specifically, improved version of the Budyko framework of using P-ΔS as equivalent precipitation has been used and improvement has been reported in ET estimation in non-humid catchments (Zhang et al., 2008a;Du et al., 2016). However, there are not much reported in humid catchments based on this kind of improvement. In addition, one would wonder why the results are always so poor based on these approaches when compared with ET_{wb}.

From another angle, the ΔS is often taken as zero in ET_{wb} on both multi-annual and annual timescales (Donohue et al., 2007;Yang et al., 2007). In detail, the calculated ET_{wb} works both as real actual ET in hydroclimatology and as the standard actual evapotranspiration to calibrate/validate ET based on other hydrological models. It would prone to errors associated with ungauged subsurface runoff transfer and therefore produce relatively unreliable estimation of ET (Zhang et al., 2008a;Wang, 2012). Hence, unreliable input of ΔS would probability lead to an unexpected consequence to both ET_{wb} and modelled ET (Mao et al., 2016;Chen et al., 2013).

Here we are motivated to reveal one possible consequence caused by neglecting ΔS in annual ET_{wb} in humid catchments over China. The aim of this study is (1) demonstrating the ET estimation based on the commonly used Budyko framework and hydrological models, i.e., abcd model and Xin'anjiang model, when compared with ET_{wb} on the ground that the annual ΔS is approximately zero in 102 humid catchments over China, and (2) presenting one possible explanation of poorly estimated annual ET in humid catchments, and (3) revealing the importance of annual ΔS in ET_{wb} calculation and thus validation. Section 2 provides a brief summary of methods used in ET estimation for humid catchments, while section 3 documents the data sources and selected catchments used in this study. Results and discussion are presented in section 4, followed by the conclusion and summary in section 5.

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2 Methodology

The water balance equation has been widely used in ET calculation and model calibration/validation at multi-annual and annual timescales, since P and Q are measured reliably in catchment hydrologic cycle and the ΔS is assumed to be zero (Yang et al., 2006). For any time period, the water balance equation can be written as:

$$ET_{wb} = P - Q - \Delta S \tag{1}$$

Here, we first use ET_{wb} as standard ET to validate modelled ET in humid catchments.

2.1 Hydrological models: abcd and Xin'anjiang models

However, the water balance equation is often limited within observed variables and related hydrological models have been widely used. The abcd model is chosen for its simplicity of monthly inputs and 4 parameters only, and Xin'anjiang model is for its fine runoff simulation in humid catchments.

The abcd model is a well-known conceptual hydrological model with 4 parameters (a, b, c, and d) developed by Thomas (1981) at annual timescale, and later tested and recommended by Alley (1984) at monthly time step in water resources assessment (Martinez and Gupta, 2010) and climate change (Sankarasubramanian and Vogel, 2002). Compared with other sophisticated water balance models, the abcd model is quite simple and the inputs are monthly P and PET while outputs include monthly Q, soil moisture, groundwater storage and ET.

The partitioning of monthly P_t, which is determined by PET_t and the initial storages in soil moisture and groundwater, S_{t-1} and G_{t-1}, into Q_t, ET_t, soil moisture storage S_t, and groundwater storage G_t is as follows:

$$Y_t(W_t) = \frac{W_t + b}{2a} - \sqrt{(\frac{W_t + b}{2a})^2 - \frac{W_t b}{a}} \quad (2)$$

where Y_t is the sum of monthly evapotranspiration and soil moisture storage at the end of the month, namely evapotranspiration opportunity, and W_t is the sum of monthly precipitation plus initial soil moisture, named as available water. The soil moisture at the end of period t is written as:

$$S_t = Y_t \exp(-PET_t / b) \quad (3)$$

the ET at the period t is the difference between evapotranspiration opportunity and soil moisture ($Y_t - S_t$). The G_t and Q_t are computed based on:

$$G_t = G_{t-1} + c(W_t - Y_t) - dG_t \quad (4)$$

$$Q_t = (1-c)(W_t - Y_t) + dG_t \quad (5)$$

the four parameters: a, the propensity for runoff to occur before the soil is saturated to capacity, b, the upper bound of Y_t. c is equal to the fraction of streamflow, which arises from groundwater, equivalent to the base flow index and d is proportional to the base flow recession constant (Thomas, 1981). We adopt the abcd model to provide monthly ET (hereafter ET_{abcd}) and ΔS (soil moisture change plus groundwater change) in this study.

The Xin'anjiang model is a widely used lumped rainfall-runoff model developed by Zhao et al. (1980) and Zhao (1992) consisting three sub-models, a three layer

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evapotranspiration sub-model, a runoff generation sub-model and a runoff routing sub-model (Zhao, 1992). The parameters and schematic diagram can be found in many references (Li et al., 2009;Zhao, 1992) so we won't give any unnecessary details. It has been widely used in runoff simulation and hydrological processes modelling in humid and semi-humid regions (Rui et al., 2012). Here we use the Xin'anjiang model in ET estimation in one selected typical humid catchment and in supporting the results from abcd model.

2.2 The Budyko framework

The widely used Budyko framework, derived by Budyko(1963;1974) based on findings of Schreiber (1904) and Ol'Dekop (1911), describes the water-energy balance status of a catchment using the well-known "Budyko curve", which is empirically derived based on energy supply (represented by PET) and water availability (represented by P) on ET. Fu (1981) gave the differential forms and achieved the analytical solutions of the Budyko hypothesis, providing a theoretical basis for the Budyko framework. Subsequently analysis on annual water-energy balance have proofed that the Fu's equation can be used in both long-term and annual water-energy balances in non-humid catchments (Yang et al., 2007) and humid catchments as well (Tekleab et al., 2011;Xu et al., 2013). The Fu's type of equation is as:

$$\frac{ET}{P} = f(\frac{PET}{P}) = 1 + \frac{PET}{P} - (1 + (\frac{PET}{P})^{w})^{1/w} \tag{6}$$

where w is a dimensionless parameter related to the local factors. PET is estimated based on the widely used FAO (Food and Agricultural Organization) Penman-Monteith reference evaporation (FAO-Penman model) (Allen et al., 1998):

$$PET = \frac{0.408\Delta(R_n - G_s) + \gamma \frac{900}{T+273} u_2 e_s (1 - Rh/100)}{\Delta + \gamma(1 + 0.34u_2)} \tag{7}$$

where R_n is net radiation (MJ/(m^2·day)), Δ is slope of the vapor pressure curve in kPa/℃, G_s is soil heat flux (MJ/(m^2·day)), u_2 (m/s) is the wind speed at 2 m height, γ (kPa/℃) is the psychometric constant, e_s (kPa) is saturation vapor pressure at a given air temperature, Rh is the relative humidity. We apply the standard algorithm to estimate PET as per recommended by the FAO based on daily meteorological data series, namely, wind speed, air temperature, sunshine duration and relative humidity.

A more accurate and quantitative understanding of ET variability is essential for evaluation and validation of climate models and climate change impact assessment (Zeng and Cai, 2015a). Zeng and Cai (2015b) extended the theoretical framework, which was first employed by Koster and Suarez (1999) to derived inter-annual ET variability from variability of P, and accounted for the effect of the P, PET and ΔS on intra- and inter-annual ET variability. A detailed annual ET variance based on the Fu's type of Budyko framework is decomposed into variance/covariance of P and PET:

$$\sigma_{ET}^2 = w_p \sigma_P^2 + w_{PET} \sigma_{PET}^2 + w_{p,PET} \operatorname{cov}(P, PET) \tag{8}$$

where σ and cov represent the standard deviation and covariance, and w_p, w_{PET}, and $w_{p,PET}$ are the weighting factor quantifying the contribution from P, PET and their interaction to ET variability with analytically calculation as:

$$\begin{aligned} w_p &= (f(\bar{\phi}) - f'(\bar{\phi})\bar{\phi})^2 \\ w_{PET} &= (f'(\bar{\phi}))^2 \\ w_{p,PET} &= 2(f(\bar{\phi}) - f'(\bar{\phi})\bar{\phi})f'(\bar{\phi}) \end{aligned} \tag{9}$$

where $\bar{\phi}$ is the dryness index calculated based on the multiannual mean of P and PET in each catchment.

We adopt the Budyko framework as one major approach to estimate ET and to further analyze the ET variability so as to better understand ET in humid catchments.

3 Data

To demonstrate the ET estimation, existing problems and possible causes in humid region, we choose 102 humid catchments ($\bar{\phi} < 1$) over southern part of China (Figure 1) with continuous monthly P, PET and observed Q (hereafter Q_{obs}) mainly for 1960-2013 (some catchments miss several years of Q_{obs} during this period while a few others can trace back to 1950s): P, observed from daily meteorological dataset from China Meteorological Data Network (http://data.cma.cn/); PET, calculated using equation 7 based on daily meteorological datasets containing the surface air temperature, sunshine duration, wind speed and the relative humidity from China Meteorological Data Network as well, and Q_{obs}, obtained from Annual Hydrological Report P. R. China: hydrological data from Yangtze River Basin, Pearl River Basin and Southeast Rivers Bain. The ΔS, is obtained from the output of abcd model. Both P and PET are interpolated and extracted at catchment scale and then form the monthly and annual time series along with Q and ΔS in the following estimation and analysis.

What's more, the daily P, PET and Q_{obs} for the selected typical catchment (black bold line defined and railed out by hydrological station Dongbei in Figure 1) over 2001-2012 are used for parameters calibration in Xin'anjiang model. And then we simulate daily Q (hereafter Q_{XAJ}) and ET (hereafter ET_{XAJ}) for 1957-2013 (with available observed monthly Q for this period as validation). The Xin'anjiang model is chosen for its fine runoff simulation in humid catchment in order to further verify the results from abcd model, which requires monthly inputs instead of that for the Xin'anjiang model at daily timescale.

<Figure 1>

4 Results and discussion

We adopt the commonly used Budyko framework and hydrological models: abcd model and Xin'anjiang model in ET estimation in humid catchments. First, we calibrate the parameter *w* in Fu's type of Budyko framework (Figure 1) with annual P, PET, and Q_{obs} for each catchment, respectively. Then we estimate ET based on these approaches and make comparison with ET_{wb} on the ground that the ΔS is approximately zero at both multiannual and annual timescales. The results of ET estimation in humid catchments in 4.1 and 4.2 are at multiannual and annual time scales, respectively and possible causes for poorly estimated annual ET is shown in 4.3.

4.1 ET estimation at multiannual timescale

There is common sense that the ΔS is approximately zero at long term water balance (Donohue et al., 2007;Tekleab et al., 2011). We adopt the Fu's type of Budyko formula and abcd model to estimate ET in 102 humid catchments over China and compare with the ET_{wb} at multiannual timescale. The relationship between the dryness index ($\bar{\phi}$) and the evaporative index (ET/P) based on the Budyko framework for 102 selected humid catchments are plotted in Figure 2a, which fits the Budyko hypothesis, showing a clear feature of energy control in these humid catchments.

The comparison of estimated ET using the Budyko hypothesis (denoted ET_{budyko}) and abcd model against ET_{wb} in humid catchments at multiannual timescale are shown in Figure 2b. Excellent agreement has achieved with very high determination coefficient ($R^2 \approx 1.0$) and slope of 0.95 when using the Budyko framework. However, the comparison between ET_{abcd} and ET_{wb} shows that the abcd model works less well with R^2 of 0.82 and the slope of 0.57, which underestimate the ET in humid region, especially in those catchments where the ET are relatively large. As for those catchments where ET are small, the abcd model works just as fine as the Budyko framework. The Budyko framework is well recommended in ET estimation in humid catchments at multiannual time scale since its reliability is greatest when applied using long-term averages in both non-humid and humid catchments.

<Figure 2>

4.2 ET estimation at annual timescale

ET estimation at annual time scale has drawn more of our attention since it is closely related to the runoff simulation, water resource management, etc. We adopt the Fu's type of Budyko framework and hydrological models, i.e., the abcd model and Xin'anjiang model in annual ET estimation and make comparison with ET_{wb} on the ground that the ΔS is zero at annual time scale, which is as common practice. The ET estimation in humid catchment using the Budyko framework is in 4.2.1 and the results based on the hydrological models mentioned above are in 4.2.2.

4.2.1 Annual ET estimation based on the Budyko framework

The Budyko framework works very well in ET estimation at multiannual time scale, while whether it is the same or not at annual time scale remains unknown. Hence, we adopt the Fu's type of Budyko framework first to demonstrate the estimation at annual timescale. The parameter *w* calibrated in 102 humid catchments are shown spatially in Figure 1 and statistical in Figure 3a. The results show that the value of *w* varies greatly with maxima and minima of 4.16 and 1.33 and the majority distributed around 1.8~2.4 (25%~75% percentile), which indicating more about terrestrial feature (Figure 1). The R^2 between ET_{wb} and ET_{budyko} (Figure 3b) in more than 90% of the humid catchments over China are lower than 0.2 at annual time scale. Specifically, the average Root Mean Square Error (RMSE) for 102 humid catchments is about 20.0% when comparing

ET_{budyko} against their multiannual average of ET_{wb}. The ratio ($RMSE/ET_{wb}$) in about half of the catchments are greater than 17% and more than 90% of humid catchments are greater than 12.5% (Figure 3c). Hence, the Budyko framework works poorly in humid catchments over China at annual timescale as some stressed (Zhang et al., 2012).

<Figure 3>

4.2.2 Annual ET estimation based on the hydrological models

The hydrological models provide as a useful tool in runoff simulation, ET, soil moisture and groundwater storage estimation in both humid and non-humid catchments. Since the Budyko framework works poorly in annual ET estimation in humid catchments, we are attempt to present and evaluate how the commonly used hydrological models work in ET estimation here at annual time scale.

First, we adopt the famous and widely used abcd model in estimating monthly and thus annual ET in 102 humid catchments. The inputs includes the monthly P, PET and the outputs are simulated monthly streamflow (Q_{abcd}), ET and ΔS. The Nash-Sutcliffe efficiency coefficient (NSE) between annual Q_{abcd} and Q_{obs} in these 102 selected humid catchments are all higher than 0.65 (Figure 4), and mostly are around 0.8. However, the R^2 between ET_{abcd} and ET_{wb} are all almost very small, i.e., smaller than 0.4 in each corresponding catchments at annual time scale. And the R^2 in bout 60% of these humid catchments are smaller than 0.1, showing poor ET estimation when using the abcd model in humid catchments over China.

<Figure 4>

<Figure 5>

To further verify the results above, we adopt the well-known Xin'anjiang model, which is famous for its well streamflow simulation in humid catchments, to estimate ET in the selected catchment governed by hydrological station Dongbei (shown in Figure 1). The inputs include continuously daily P and PET for 2001-2012, since we have access to observed daily streamflow in this catchment for model calibration. The NSE of daily Q_{obs} and Q_{XAJ} over this period is 0.786 in this humid catchment. We then use the calibrated parameters to run Xin'anjiang model for 1957-2013 since monthly Q_{obs} is available for this period. The NSE of observed and simulated monthly streamflow is 0.913 based on the Xin'anjiang model (Figure 5b), and 0.890 when using the abcd model for 1957-2013 (Figure 5c). Strikingly, the NSE are 0.917 and 0.776 based on Xin'anjiang and abcd models in streamflow simulation at annual timescale. Hence, both two models work fine in streamflow simulation in humid catchments and the Xin'anjiang model achieve better. However, when it comes to annual ET estimation, the R^2 are very small, 0.056 and 0.002 for ET_{XAJ} and ET_{abcd} against ET_{wb} in this selected catchment. The two hydrological models can well simulate streamflow while poorly in annual ET estimation in this humid catchment. And we can easily speculate that the Xin'anjiang model wouldn't work well in annual ET estimation in other humid catchments as well. From above, the results based on the Xin'anjiang model well support the estimation using the abcd model, and again verify the poorly ET estimation in humid catchment at annual time scale.

In summary, both the Budyko framework and the hydrological models work poorly in ET estimation in humid catchments when compared with ET_{wb} on the ground that the ΔS is approximate zero at annual time scale. These approaches are, as yet, not sufficiently accurate in annual ET estimation in humid catchments. This poorly annual ET estimation remains to be a universal challenge for bridging the important gap in our knowledge of the hydrologic cycle.

4.3 Potential reason for poorly-estimated annual ET in humid catchments

The above results at annual timescale is quite confusing. Since the P is observed, the Q can be well simulated, and ΔS is zero as common practice, how come the annual ET estimation is that terrible? From another perspective, there may some other not-well-known problems exist in annual ET estimation in humid catchments more than just the hydrological models. What if the ΔS shouldn't been seen as zero in water balance at annual time scale? The unreliable input of ΔS would probability lead to an unexpected consequence to both ET_{wb} calculation and modelled ET calibration/validation. Since the majority of catchments in west are distributed in karst region with ungauged subsurface runoff transfers (Figure 1), and the catchments in the east and southeast along the coastal area, where urbanization expansion accompanied with groundwater extraction, inter-basin water transfer, etc, which would definitely introduce large bias to annual ΔS. And the unreliable ET_{wb} with assuming zero change in annual ΔS may thus lead to irresponsible real actual evapotranspiration, and further poorly modelled ET calibration and validation in humid catchments. Hence, a probable explanation based on the role of the ΔS in annual ET_{wb} is launched.

4.3.1 Analytical explanation of the effect of neglecting ΔS to annual ET_{wb}

At a given time of a catchment, we estimate the annual ET using annual P and PET, based on the Budyko framework, and then make comparison against corresponding ET_{wb}, i.e., P-Q, on the ground that the annual ΔS is zero (Figure 6). Extra deviation would emerge when annual ΔS is not neglectable, and the comparison made above is between ET_{wb} and modelled ET+ΔS. Moreover, the larger the ΔS is, the larger this extra deviation could be. The annual ΔS is often seen as zero in non-humid catchments since most of P turns into ET (Yang et al., 2007), leaving the majority of the rest P to Q and very small proportion to ΔS. Therefore it would be acceptable to take ΔS as zero in ET_{wb} calculation and calibration/validation in non-humid catchments. While it is uncertain whether taking annual ΔS as zero is applicable in humid catchments. Besides, the low R^2 between ET_{budyko} and ET_{wb} in humid catchments above can to some extent, reflect the effect of annual ΔS to ET_{wb}.

<Figure 6>

<Figure 7>

To further explain the effect of ΔS to annual ET_{wb} calculation and thus calibration/validation, we first make analytical explanation as below. There is no available observed annual ΔS at catchment scale, and inaccuracy and uncertainty exist in almost all models to simulate ΔS so far. It would be acceptable to make simple assumption that annual ΔS is linearly related to annual P as well, since clear linear relation between annual P and observed annual Q (Figure S1). The R^2 in almost all the humid catchments over China are higher than 0.6 and about 65% of the catchments are higher than 0.75 (Figure S1). The relation between annual P and ΔS, Q are assumed as,

$$Q = \alpha P \tag{10}$$

$$\Delta S = \beta P \tag{11}$$

where β is a dimensionless parameter, and α is the runoff coefficient. The ratio of estimated ET against ET_{wb} is as,

$$\frac{ET}{ET_{wb}} = \frac{ET}{ET+\Delta S} = \frac{1-\alpha-\beta}{1-\alpha} \tag{12}$$

which indicates the effect of ΔS to annual ET_{wb} and thus modelled ET estimation and calibration/validation. We further set the range of parameter β to be -0.5~0.5 and runoff coefficient, α, to be 0~1.

Then we plot the change of this ratio in Figure 7a with both the change of parameter β in the range of (-0.5, 0.5) and parameter α in the range of (0, 1). The range of this ratio varies greatly, which indicates the effect of ΔS to ET_{wb} variously. The smaller the ΔS is, the more approaching to 1.0 this ratio could be, showing more insignificant effect of ΔS to ET_{wb} estimation and validation.

We choose a few typical value of parameter β, representing different amount of ΔS. The change of ratio in different partition of P into Q are shown in Figure 7b. Apart from the various effect of ΔS to ET_{wb}, the runoff coefficient can affect the ratio as well. We choose two runoff coefficient, 0.57 (average of runoff coefficients over 102 humid catchments here, blue dash in Figure 7b) and 0.11 (average of runoff coefficients over 108 non-humid catchments in China, red dash, the relevant data are provided by Fubao Sun (Yang et al., 2007)). The result shows that the larger the runoff coefficient is, the greater effect of ΔS to ET_{wb} under the same proportional of ΔS from P. Hence, it is worth noticing that the neglecting of annual ΔS would add more inaccuracy and uncertainty in ET_{wb} and modelled ET estimation and calibration/validation in humid catchments than that in non-humid catchments.

4.3.2 The effect of ΔS in ET_{wb} in humid catchments over China

To verify the effect of annual ΔS to ET_{wb}, we adopt the estimated ET_{budyko}, the ΔS from abcd output and make the following comparison below. The ΔS here includes the soil moisture change, groundwater change and other causes that lead to water loss other than Q and ET. We first use the selected typical catchment mentioned above as case study and then expand it to all the 102 humid catchments to test the effect of ΔS in annual ET_{wb}.

The time series of ET_{wb}, ET_{budyko} and $ET_{budyko}+\Delta S$ for 1957-2013 in the selected typical catchment (Figure 8) shows that through the ET_{wb} and ET_{budyko} are both fluctuated around their multiannual average (about 761.8 mm/yr, 755.8 mm/yr), the ET_{wb} fluctuates more severe with variance of about 12518 mm^2/yr^2 than the variance of ET_{budyko}, which is about 745 mm^2/yr^2. Interestingly, the comparison of the variabilities of ET_{wb} and $ET_{budyko}+\Delta S$ are quite similar, 12518 mm^2/yr^2 Versus 10611 mm^2/yr^2, and so does their multiannual average of about 761.8 mm/yr and 757.2 mm/yr as well. Furthermore, the R^2 of original comparison between ET_{wb} and ET_{budyko} of 0.02 improves to 0.58 between ET_{wb} and $ET_{budyko}+\Delta S$ when taking the ΔS into consideration. This shows that the neglecting of ΔS can enlarge the fluctuations of annual ET_{wb}. Therefore, the ΔS plays an important role in annual ET_{wb} and thus in modelled ET calibration and validation.

<Figure 8>

<Figure 9>

With the same approach, we expand this explanation to all 102 humid catchments to verify the effect of neglecting annual ΔS, and the results are shown in Figure 9. Much improvement has been made when taking the ΔS into consideration in annual ET validation instead of making direct comparison between ET_{budyko} and ET_{wb} in humid catchments. For all 102 humid catchments categorized into three categories based on

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Manuscript under review for journal Hydrol. Earth Syst. Sci.
Discussion started: 5 April 2017

their area, the original averaged R^2 between ET_{wb} and ET_{budyko} are smaller than 0.1 for both small sized (41 catchments with the area all smaller than 5000 km^2) and moderate sized catchments (33 catchments, and the area greater than 5000 km^2 but smaller than 10000 km^2), and about 0.12 for large sized catchments (28 catchments with area greater than 10000 km^2). As for the R^2 within 10%~90% percentile, the small and moderate sized catchments distribute around 0~0.15, and large catchments varies about 0~0.4. The newly R^2 between ET_{wb} and $ET_{budyko}+\Delta S$ promisingly show that, their average improve to 0.18, 0.33 and 0.48 for three categories, respectively. In particular, the newly R^2 within 10%~90% percentile, all showing satisfactory improvements with about 0.02~0.38 for small sized catchments, 0.11~0.50 for moderate sized catchments and 0.25~0.65 for large sized catchments. All above indicates that when using annual ET_{wb} as standard ET and thus assessing modelled ET in humid catchments, the ΔS should not be seen as zero in water balance equation. Besides, the larger the catchment area is, the better estimation of ET+ΔS compared with ET_{wb} in annual ET assessment.

<Figure 10>

For further interpretation, we present the variabilities of P, PET, ET_{wb}, ET_{budyko} and $ET_{Budyko} + \Delta S$ using the results of 102 humid catchments (Figure 10a), and variance decomposition results based on Equation 9 (Figure 10b). The variability of P varies mainly about 20,845~97,071 mm^2/yr^2 within 10%~90% percentile for 102 humid catchments. While the range is only about 1,465~4,008 mm^2/yr^2 for the variability of PET, which shall limit the variability of ET in humid catchments since it is controlled by PET (Fu, 1981). The variability of ET_{budyko} meets this limitation with min-max of 186~2,414 mm^2/yr^2, and 412~1355 mm^2/yr^2 within 10%~90% percentile for 122 humid catchments. While the variability of ET_{wb} (min-max of 2,835~50,114 mm^2/yr^2, and 7,161~26,142 mm^2/yr^2 within 10%~90% percentile) goes far beyond this limitation of PET variability (Figure 10a). This may because most of the P variability transfers to the variability of Q, and the majority of the rest transfers to the variability of ΔS and covariance between relative components. This is in line with Wang and Alimohammadi (2012) and very small proportional of P variability is left to the variability of ET, which is further controlled by the variability of PET. This proves that PET not only controls how much the ET is in a humid catchment, but also its variability. The annual ET_{wb} with assuming zero change in ΔS would in fact enlarge the variability of real ET greatly in humid catchments.

Furthermore, the comparisons of variance of ET_{wb}, ET_{budyko} (Var(ET) in Figure 10b) against variance of sum of three components: the decomposed variance of P, PET and their covariance (Var(ET_{cal}) in Figure 10b) further prove this conclusion. The Var(ET_{cal}) is almost linearly correlated with variance of ET_{budyko} with R^2 of 0.966 and slope of almost 1.0 in 102 humid catchments. However, the R^2 and the slope become 0.005 and 1.61 when compared Var(ET_{cal}) with the variance of ET_{wb}, showing that the neglecting annual ΔS changes the variability of ET_{wb} in almost all the humid catchments. In summary, the ET_{wb} with assuming that the annual ΔS is zero, is not the accurate actual evapotranspiration in humid catchments, and thus not suitable for modelled ET assessment.

5 Conclusion and summary

Attempts on improving the ET estimation in humid catchments based on the Budyko framework or other hydrological models have been made to meet the ET_{wb} on the ground that ΔS is zero at multiannual and annual timescales. While not much improvement has been achieved, and an accurate estimation of annual ET in humid catchments remains to be a huge challenge. In this research, we adopt the commonly used Budyko framework and hydrological models, i.e., the abcd model and Xin'anjiang model in ET estimation in 102 humid catchments over China. We are motivated to explore the possible explanation of poorly annual ET estimation in humid catchments from another perspective: the consequence caused by neglecting annual ΔS in ET_{wb}.

We present the estimated ET in humid catchments and make comparison with ET_{wb} on the ground that the multiannual and annual ΔS are approximate zero, the same as common practice. At multiannual timescale, the Budyko framework works very well while the abcd model underestimate the ET to some extent, especially in those catchments where ET are large (Figure 2). Hence, the Budyko framework is well recommended in ET estimation in humid catchments at multiannual timescale. While at annual time scale, both the Budyko framework and two hydrological models work poorly, with very small R^2 in all cases when compared with ET_{wb} (Figure 3~5), showing that these approaches are not sufficiently accurate in annual ET estimation in humid catchments. From another perspective, there may some other not-well-known problems exist in annual ET estimation in humid catchments more than the models.

To explore the possible explanation for the poorly estimate annual ET in humid catchments, we set out from the effect of neglecting annual ΔS in water balance equation and adopt ET from the Budyko framework (ET_{budyko}) and ΔS from abcd output. We make comparison of ET_{budyko} and $ET_{budyko}+\Delta S$ against ET_{wb} and find that much improvement has been made when comparing $ET_{budyko}+\Delta S$ with ET_{wb} (Figure 8~9). The larger the catchment area is, the better this improvement could be. The ET_{wb} enlarges the variability of real actual evapotranspiration due to the variability of the ΔS (Figure 10), since PET controls both the ET and its variability in humid catchments. Hence, the neglecting of annual ΔS in ET_{wb} leads to the unreliable real ET in humid catchments, and this is one major reason for the poorly estimated results since they are all validated against ET_{wb}.

Above all, we are highlighting that the annual ΔS shouldn't be seen as zero in water balance equation in humid catchments. The ET_{wb} with original assumption that annual ΔS is approximate zero is not the accurate ET and thus not suitable for modelled ET calibration and validation in humid catchments.

Acknowledgements

This research was supported by the National Key Research and Development Program of China (2016YFA0602402 and 2016YFC0401401), the CAS Pioneer Hundred Talents Program (Fubao Sun), an Open Research Fund of State Key Laboratory of Desert and Oasis Ecology in Xinjiang Institute of Ecology and Geography, Chinese Academy of Sciences (CAS), and the International Science and Technology Cooperation Program of China (2014DFA71910), the CPSF-CAS Joint Foundation for Excellent Postdoctoral Fellows and National Science Foundation of China (41601035 and 41401037)

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Figure captions

Figure 1 Spatial distribution of humid catchments ($\bar{\phi}$ > 1) over southern part of China along with their corresponding parameter *w* in Fu' equation, and one selected typical catchment used as case study accompanied with its controlling hydrological station: Dongbei Station.

Figure 2 The Budyko framework for 102 humid catchments over China in (a), and the comparison of ET_{wb} (ET calculated based on water balance equation) against ET_{budyko} (ET estimated based on Fu's equation) and ET_{abcd} (ET estimated using abcd model) at multi-annual timescale for these humid catchments in (b).

Figure 3 The statistical information for estimated ET_{Budyko} in 102 humid catchments: (a) the calibrated parameter *w* in the Fu's equation, (b) the R^2 between annual ET_{wb} and ET_{budyko}, and (c) the ratio of their RMSE and ET_{wb} ($RMSE/ET_{wb}$) in percentage.

Figure 4 the Nash-Sutcliffe efficiency coefficient (NSE) between observed and simulated (based on the abcd model) annual Q along with corresponding R^2 of annual ET_{wb} and ET_{abcd} in 102 humid catchments over China.

Figure 5 The time series of monthly P over 1957-2013 for the selected typical catchment in (a), and (b) the corresponding observed monthly streamflow (Q_{obs}) and simulated one based on the Xin'anjiang model (Q_{XAJ}), along with the observed and modelled Q using the abcd model (Q_{abcd}) in (c).

Figure 6 The schematic of ΔS in Budyko framework and water balance equation in humid catchments (energy limited). ET is estimated based on given P and PET, and validated against ET_{wb} based on P and Q_{obs} on the ground that the ΔS is zero, which can affect the ET validation to some extent.

Figure 7 The effect of ΔS to ET_{wb} on various proportion of Q and ΔS. (a) The changes of ratio (ET/(ET+ΔS)) with the change of parameter p1 in range of (-0.5, 0.5) in vertical axis, and parameter p2 of (0, 1) in horizontal axis (parameters p1 and p2 are in equations 10 and 11, respectively). The value of ratio (ET/(ET+ΔS)) in range of (0, 2) are colored as color bar, and value greater than 2 in right-bottom triangle area is set as wine red. (b) The changes of ratio with the change of runoff coefficient (i.e., parameter p2) in several selected typical proportion of ΔS (i.e., parameter p1), the red dash is the chosen runoff coefficient representing the effect of ΔS to ET in non-humid ($\bar{\phi} > 1$) region, and blue dash for humid ($\bar{\phi} < 1$) region.

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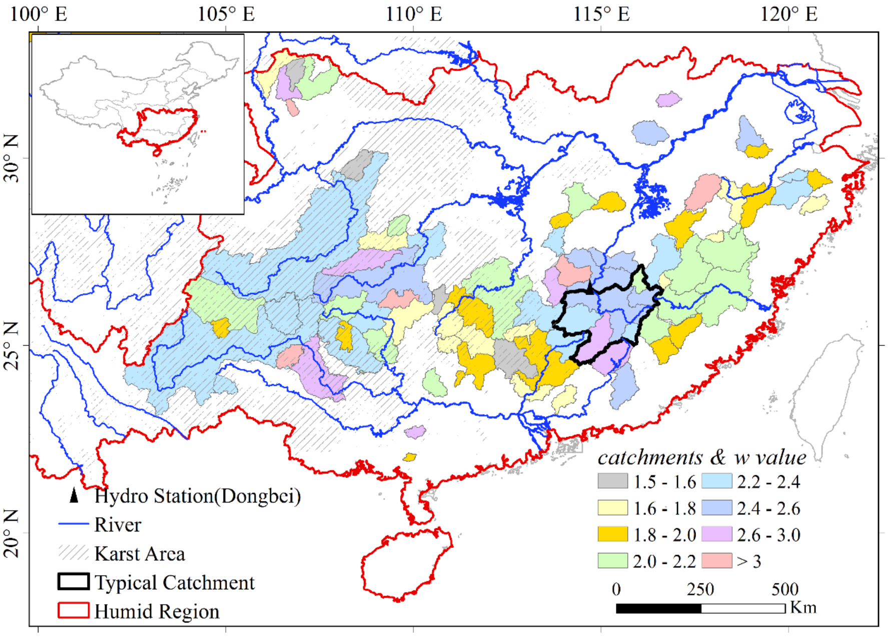
Figure



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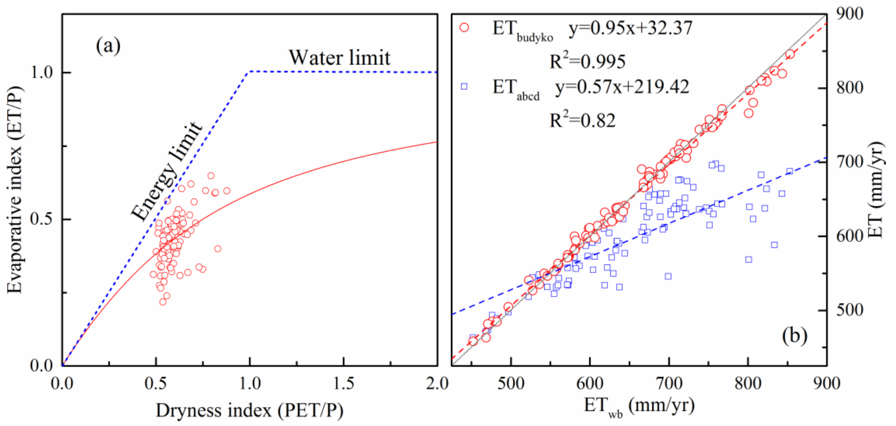

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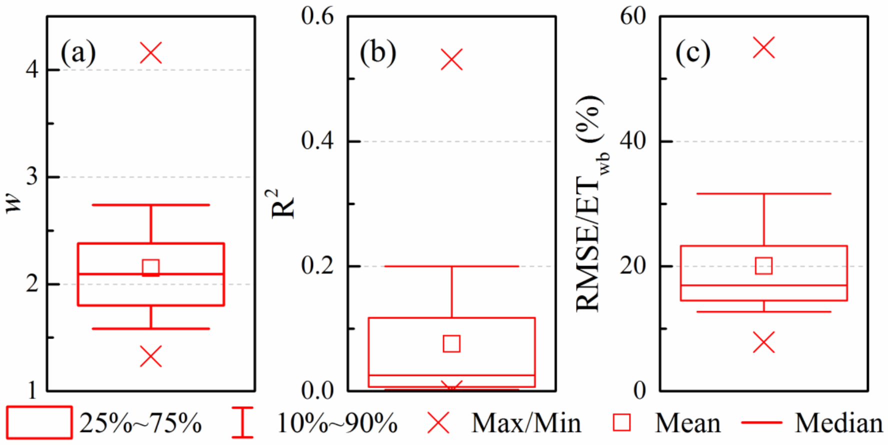

Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2017-151, 2017
Manuscript under review for journal Hydrol. Earth Syst. Sci.
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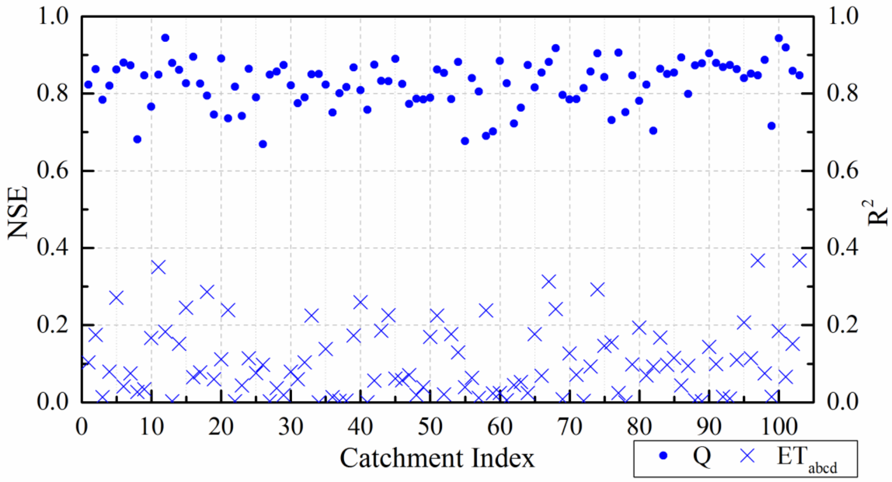

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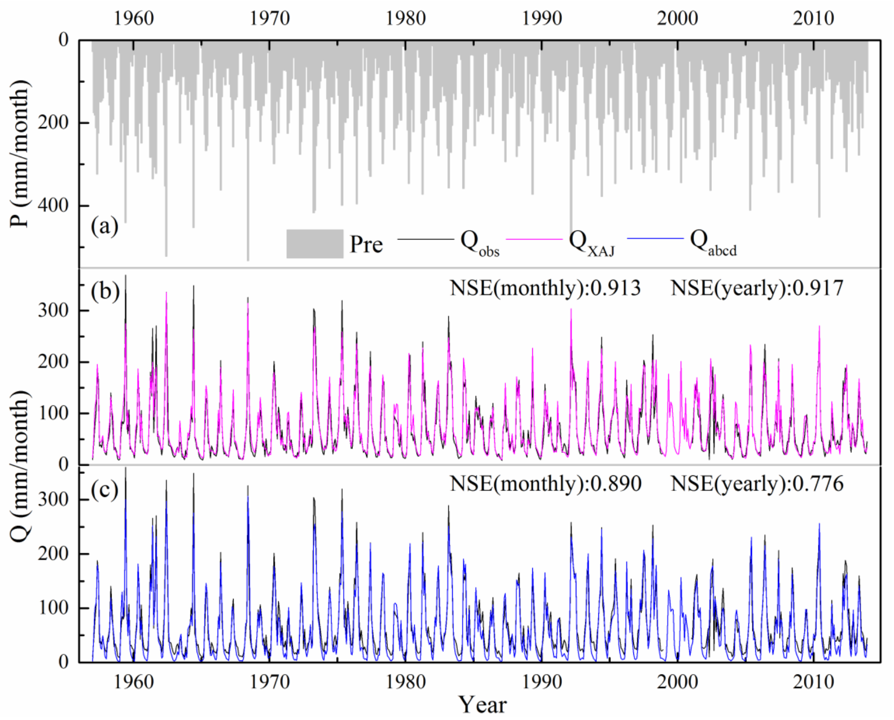

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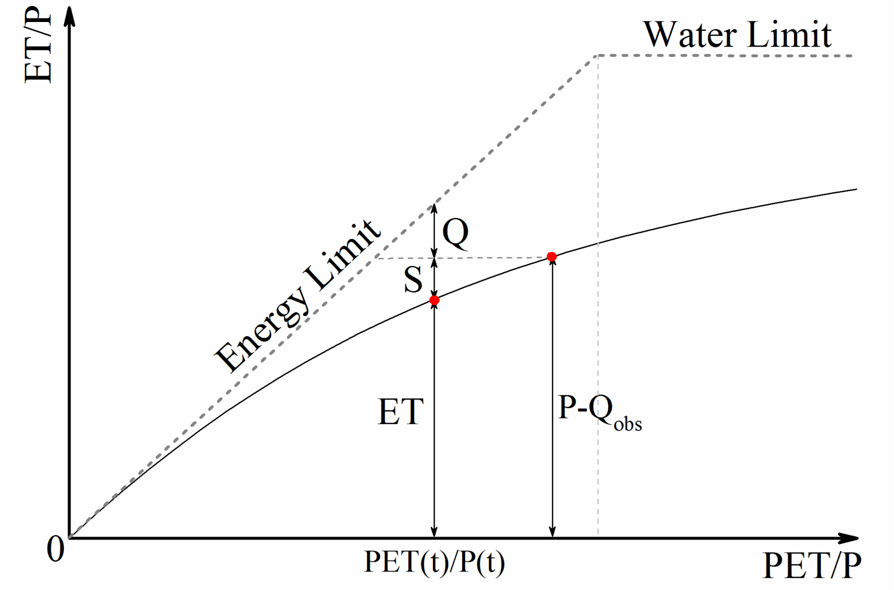

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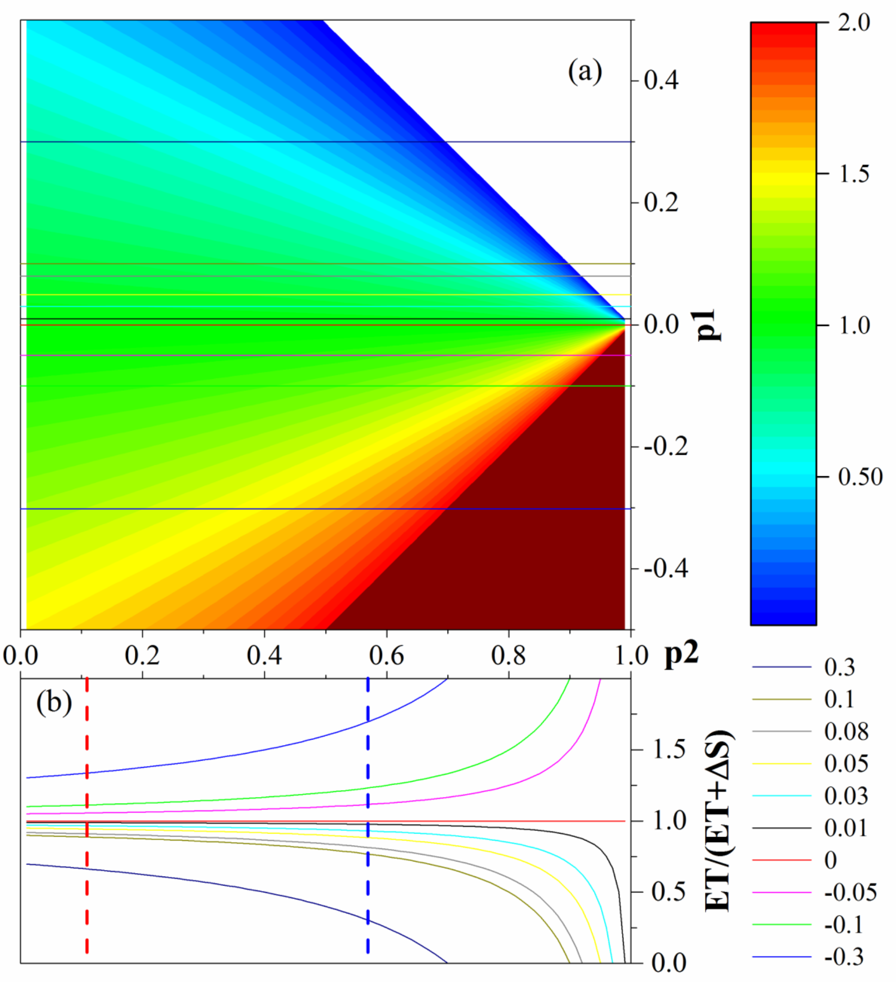

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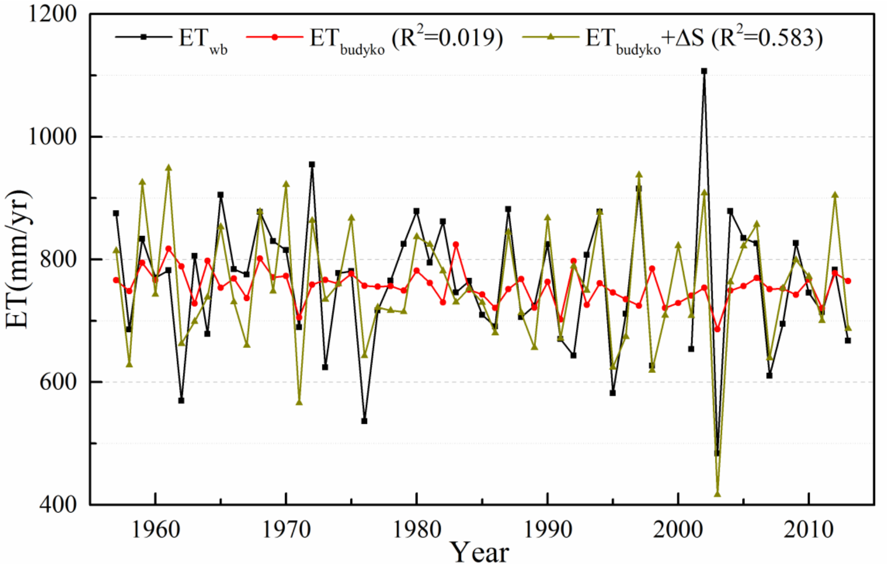

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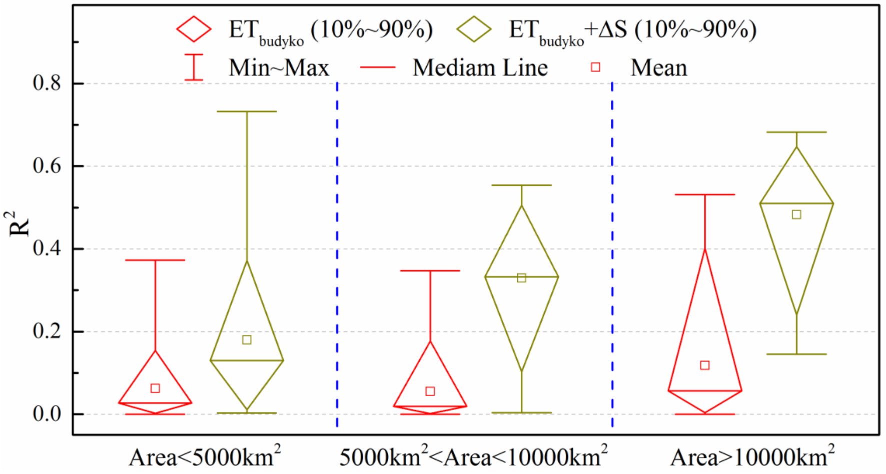

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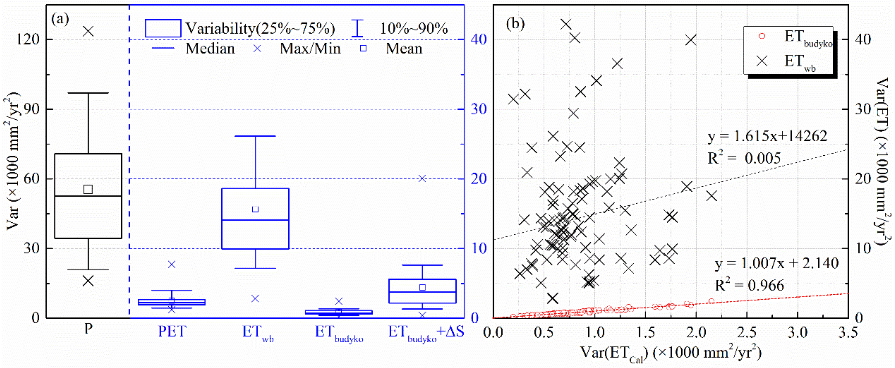

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List of notations

Variable name	Variable description	Units
water balance components		
P	Precipitation	mm
PET	Potential evaporation	mm
ET	Evapotranspiration	mm
Q	Streamflow	mm
ΔS	Water storage change	mm
$\bar{\phi}$	Dryness index	
α	Runoff coefficient	
β	Proportional of ΔS to P	
w	parameter in Fu's equation	
abcd model		
a	Propensity for runoff to occur before the soil is saturated to capacity	
b	Upper bound of Y_t	
c	Base flow index	
d	Proportional to the base flow recession constant	
S_t	Soil moisture storage at the end of period t	mm
G_t	Groundwater storage at the end of period t	mm
Y_t	Evapotranspiration opportunity at the end of period t	mm
W_t	Available water at the end of period t	mm
FAO-Penman model		
R_n	Net radiation	$\mathrm{MJ/(m^2 \cdot day)}$
G_s	Soil heat flux	$\mathrm{MJ/(m^2 \cdot day)}$

Δ	Slope of the vapor pressure curve	kPa/℃
u_2	Wind speed at 2 m height	m/s
γ	Psychometric constant	kPa/℃
e_s	Saturation vapor pressure	kPa
Rh	Relative humidity	
w_p	Weighting factor for contribution of P to ET variability	
w_{PET}	Weighting factor for contribution of PET to ET variability	
$w_{p,PET}$	Weighting factor for contribution of interaction between P and PET to ET variability	