Simulation of Actual Evapotranspiration and Evaluation of Three Complementary Relationships in the Upper Regions of the Mekong River and the Salween River

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**Simulation of actual evapotranspiration and evaluation of three complementary relationships
in the upper regions of the Mekong River and the Salween River**

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30 Yongshan Jiang and Zhaofei Liu contributed to the conception of the study; Yongshan Jiang, Zhaofei Liu, and Rui Wang
31 contributed significantly to analysis and manuscript preparation; Pingcuo Gele provided observed data; Yongshan Jiang
32 performed the data analyses and wrote the manuscript; Zhaofei Liu helped perform the analysis with constructive
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40

Abstract: Based on observed precipitation and runoff data, monthly actual evapotranspiration (ET_a) was calculated by the hydrological budget balance method in the Nu River Basin (NRB) and Lancang River Basin (LCRB). The performance of three developed complementary relationship methods, the nonlinear advection-aridity (nonlinear AA) method, generalized complementary relationship method (B2015), and sigmoid generalized complementary function (H2018), on simulating ET_a were evaluated. The evaluation results showed that three methods were able to accurately simulate monthly ET_a series. The NSE between the monthly ET_a simulated by the nonlinear AA, B2015, and H2018 methods and the water-balance-derived ET_a were 0.89, 0.83, and 0.91, respectively. The R-square were 0.90, 0.84, and 0.93, respectively. Overall, the H2018 method showed the best performance. The parameter α had a negative correlation with regional aridity index. Annual ET_a and precipitation showed significant increasing trends during 1956-2018 in the basins at all temporal scales (dry and wet seasons and annual series). Runoff also exhibited an increasing trend in each sub-basin, except for the downstream region of the LCRB. The increasing magnitudes of wet season precipitation and runoff in the mid-stream region was the highest, with the value of 73.7 mm/10a and 44.9 mm/10a, respectively. The ET_a increased dramatically in the downstream region, the magnitude reached 25.9 mm/10a. Precipitation was the main factor leading to ET_a change. The increasing magnitude of ET_a accounted for 42.4% of the precipitation increment. Research on the influence mechanism between meteorological factors and ET_a showed that the contribution rate of air temperature to ET_a was the highest, reaching 23.5%, which showed a significant positive correlation. The second was wind speed, whose contribution rate was -10.2% on average, and even reached -14.1% in the upstream region of the NRB. The correlation coefficient between ET_a and wind speed was highest in mid-stream region of the NRB, which was greater than 0.80. The contribution rates of increasing humidity to ET_a were -12.5% and -9.2% in the NRB and LCRB, respectively. ET_a was negatively correlated with humidity. The negative correlation was especially strong in the mid-stream region, with coefficients were greater than -0.65. The sunshine hours had the least effect on ET_a , and the contribution rates were -6.5% and -4.1%, respectively.

Keywords: complementary relationship method; generalized complementary relationship; hydrological budget balance; actual evapotranspiration

1. Introduction

Actual evapotranspiration (ET_a) plays a crucial role in the global water and energy cycles. ET_a and runoff account for 59% and 41% of land surface precipitation, respectively (Oki and Kanae 2006). And the solar radiation energy absorbed by land surface exceeds 50% is used for ET_a (Trenberth et al. 2009). ET_a can reflect the regional changes of land surface energy and hydrological budgets. Analyses of trends of ET_a are greatly significant for understanding climate change and its impacts at regional scales. Accurate simulation of ET_a is crucial for the management and planning of water resources, forestry, and agricultural irrigation (Maes et al. 2012; Farahani et al. 2007; Fisher et al. 2017).

Obtaining ET_a is a challenging task because of its complex interactions across the soil-plant-atmosphere continuum (Katul et al. 2012). ET_a can be accurately monitored by a wide variety of ground measurements such as lysimeters, energy balance Bowen ratio, and eddy covariance (Allen et al. 2011). However, estimation of large-scale, long-term ET_a remains difficult since these techniques typically cover short periods with limited spatial extent (Ma and Szilagyi 2019). And most ET_a methods require a significant number of soil and vegetation-related parameters as inputs (Masson et al. 2003), thus leading to data complexity and additional uncertainties.

There are several methods can estimate ET_a by using only routine meteorological observations data (Chen et al. 2020; Fan et al. 2018; McMahon et al. 2013). Among them, Bouchet (1963) proposed a complementary relationship (CR) which had been proven to be a feasible and efficient approach (Xu and Singh 2005; Nakamichi and Moroizumi 2015; Hobbins et al. 2001). The original complementary principle based a linear complementary relationship (CR) between ET_a , potential evapotranspiration (ET_p), and wet environment evapotranspiration (ET_w), in which ET_a and ET_p depart from ET_w in opposite directions when the land surface is drying from completely wet conditions with a constant energy input (Brutsaert 2015; Zhou et al. 2020). Several methods based on the CR had been proposed such as Advection-Aridity (Brutsaert and Strick 1979), CRAE (Morton 1983), and Granger-Gray (Granger and Gray 1989) methods. And they had been extensively used for obtaining long-term regional ET_a (Jian et al. 2018; Szilagyi et al. 2009).

However, in recent years, many studies had shown that it was difficult for ET_a and ET_p to satisfy the completely symmetrical complementary relationship. Brutsaert (2015) formulated a more general and nonlinear version of the complementary relationship which defined as "the generalized complementary relationship" by generalizing the CR to a

fourth-order polynomial function between ET_a/E_{pen} and ET_w/E_{pen} . Among them, E_{pen} is calculated by the Penman (1948) equation, which is the sum of radiation (E_{rad}) and aerodynamic (E_{aero}). Han et al. (2018) combining a sigmoid form of the generalized complementary function into the traditional AA method to represent the relationship between ET_a and ET_p by considering boundary conditions for extremely arid and completely wet environments. This method also developed minimum (x_{min}) and maximum (x_{max}) limits to E_{rad}/E_{pen} . Szilagyi et al. (2017) proposed a calibration-free nonlinear CR method with more appropriate physical constraints which built on the latest researches of the nonlinear formulation by Brutsaert (2015) and Crago et al. (2016). The most prominent advantage in the method is that it determines the parameter of the Priestley-Taylor coefficient (Priestley and Taylor 1972) from temperature and humidity data over wet areas. Therefore, the method avoids the complex parameter calibration requiring prior information of “ground-truth” ET_a which is often missing in developing countries, including China.

The Mekong River and the Salween River are two important international rivers in Southeast Asia. The Mekong River provides renewable energy and food security for a population of more than 60 million people in six countries: China, Myanmar, Lao PDR, Thailand, Vietnam, and Cambodia (Sabo et al. 2017). Their water fluctuation could not only affect the water availability, the ecological environment, and food security but also pose enormous challenges to transboundary water utilization and allocation (Fan and He 2015). Therefore, the research on trends of hydrological variables in the basins have attracted extensive attention. In addition, as the upper reaches of Mekong River and Salween River respectively, the Lancang River and Nu River have unique dry-hot valley with great slope and extremely complex terrain. Estimation of the ET_a change characteristics in the LCRB and NRB would provide certain technical support for water resources management and ecological environment protection in the Mekong River and Salween River basins.

A wide range of studies have investigated the spatiotemporal pattern of ET_a at regional scales (Gao et al. 2007; Liu et al. 2019; Xu et al. 2021; Yang et al. 2021). ET_a complementary methods have been greatly developed in recent years. However, there are relatively few studies on ET_a changes and evaluation of the developed CR methods in Mekong River and Salween River Basins. In this study, we aimed to (1) simulating ET_a by the corrected hydrologic budget balance method; (2) evaluating the accuracy of three developed CR methods in simulating monthly ET_a at regional scales of the two basins; (3) detecting trends of ET_a in the NRB and LCRB during the past six decades (1956-2018), and quantifying contribution of climate factors to regional ET_a changes.

2. Materials and Methods

2.1 Study Area

The Lancang River and Nu River are the upper reaches of the Mekong and Salween rivers which are located in southern Tibet, China. The Nu River basin (NRB) and Lancang River basin (LCRB) are characterized by its location in a deep V-shaped and valley area. In addition, there is a huge drop in water levels between the upper and lower reaches of the river. Because the drop is more than 4,600 m within the channel length about 2,000 km. Therefore, the time of runoff concentration of the basin is short and the velocity of streamflow is high. This would have a great impact on regional ET_a . The climate in the basins varied significantly from northwest to the southeast due to impacts of topography and latitude. The upstream region belongs to a plateau climate. The climate is cold with little precipitation. The runoff in the upper reaches of the river is mainly recharge by groundwater, accounting for more than 50% of the annual runoff, followed by recharge by rainwater and meltwater. The mid-stream and downstream regions are located in the subtropical and tropical climate zone. The rainfall is abundant affected by monsoon. The river runoff is mainly replenished by precipitation, which accounts for more than 60% of the annual runoff. The annual precipitation of LCRB is about 1000mm and the temperature is between $14^{\circ}C$ and $22^{\circ}C$. The annual precipitation of NRB is about 900mm and the annual temperature is between $17^{\circ}C$ to $29^{\circ}C$. About 85% of the precipitation is concentrated in the wet season between June and September. The mid-stream is the main rainstorm region in the basin. The mean annual ET_a in the NRB and LCRB are 350 mm and 480 mm whilst the mean annual ET_p are 950 mm and 1100 mm, respectively. The ratio of ET_a was 40% of ET_p in the basins. The wet season ET_a accounts for 85% of the annual ET_a .

Fig.1 Locations of the Nu River Basin and Lancang River Basin.

2.2 Data

(1) Observed meteorological data

Observed daily meteorological data for the period from 1956 to 2018 at 18 stations in and near the study area were obtained from the China Meteorological Administration (<http://data.cma.cn/>). The data includes precipitation, air temperature, wind speed, relative humidity, and sunshine hours. The monthly and annual series were calculated from the daily observed data

series. The area weight of each station was used to calculate the regional average value. The area weights were calculated based on the Tyson polygon method.

(2) Observed hydrological data

Observed runoff data series from six hydrological stations on the main stream of the Lancang River and Nu River were used in this study. Each hydrological station represents the upstream, mid-stream and downstream regions of the LCRB and NRB, respectively (Fig.1). The upstream, mid-stream and downstream regions of the LCRB are described as Changdu (LC-U), Changdu-Jiuzhou (LC-M), Jiuzhou-Yunjinghong (LC-D), respectively. The upstream, mid-stream and downstream regions of the NRB are described as Jiayuqiao (N-U), Jiayuqiao-Gongshan (N-M), Gongshan-Daojieba (N-D), respectively. All sites included monthly runoff data from 1956 to 2000. In addition, Jiayuqiao and Changdu stations also included monthly runoff data from 2007 to 2018. Data were obtained from the Tibet Autonomous Region Hydrology and Water Resources Survey and China Hydrological Yearbook.

2.3 Simulation of ET_a

2.3.1 Hydrological budget balance method

ET_a of the NRB and LCRB was simulated by the hydrological budget balance method at basin scales (Liu et al. 2014; 2019; Wan et al. 2015). In a basin, the hydrological budget balance equation could be expressed as:

$$ET_i^{WB} = P_i - R_i - \Delta W \quad (1)$$

where P and R are the basin-wide totals of precipitation (mm) and the net stream flow at the basin outlet (mm), respectively, ΔW is the change in terrestrial water storage including the surface, subsurface, and ground water changes (mm) at a monthly or annual scale.

At the simulation of monthly ET_a , ΔW is usually negligible in many studies, which assumes precipitation (evaporation) is the only source (loss) of water in the basin (Hobbins et al., 2001; Zhang et al., 2012). However, the hydrological budget balance may not close when ΔW is neglected under changing climate and anthropogenic interferences such as water diversion, reservoir regulation, and agricultural irrigation (Liu et al., 2016). In this study, we defined $(P-R)$ as the biased

ET_{biased}^{WB} relative to the reference ET^{WB} . The ET_{biased}^{WB} can be corrected based on ET^{WB} measured during the same period at the monthly scale through a two-step bias correction method (BCM, Li et al., 2014). Firstly, at each basin, the monthly ET^{WB} and ET_{biased}^{WB} series were fitted separately using a gamma distribution. This has been shown as an effective method for modeling the probability distribution of ET_a (Liu et al., 2016). Water-balance-derived ET_a was used for trends detection of ET_a in the NRB and LCRB during 1956- 2018 by Mann–Kendall test in seasonal and annual time series.

2.3.2 Nonlinear AA method

Brutsaert and Strick (1979) proposed the AA method,

$$ET_a^{AA} = 2ET_w - ET_p \quad (2)$$

Kahler and Brutsaert (2006) pointed out that the assumed symmetric nature of the CR becomes asymmetric when used with evaporation pan data. This meant that the change in the apparent potential evaporation, as the environment dries from an initially wet condition, will be larger than the corresponding change in ET_a . Therefore, the AA method had since evolved to adopt the asymmetric CR (Brutsaert and Parlange 1998; Szilagyi 2007).

$$ET_p - ET_w = b(ET_w - ET_a) \quad (3)$$

where b is another constant of proportionality. Rearrangement of (3) leads to

$$ET_a = \frac{1+b}{b}ET_w - \frac{1}{b}ET_p \quad (4)$$

In nonlinear AA method, ET_p and ET_w are denoted by the Penman (1948) equation (E_{Pen}) and the Priestley-Taylor (1972) equation, respectively.

$$ET_w = \alpha E_{rad} = \alpha \frac{\Delta}{\Delta + \gamma} (R_n - G) \quad (5)$$

$$E_{Pen} = E_{rad} + E_{aero} = \frac{\Delta}{\Delta + \gamma} (R_n - G) + \frac{\gamma}{\Delta + \gamma} f(u_z) (e_s - e_a) \quad (6)$$

Normalized by E_{Pen} , the nonlinear AA method can be expressed as a linear function (Han et al. 2008):

$$\frac{ET_a^{AA}}{E_{Pen}} = \left(1 + \frac{1}{b}\right) \alpha \frac{E_{rad}}{E_{Pen}} - \frac{1}{b} \quad (7)$$

where E_{rad} and E_{aero} are the radiation and aerodynamic terms for the Penman equation, respectively (mm/day); α is an empirical coefficient; Δ is the slope of the saturation vapor pressure curve at air temperature (hPa/°C); γ is the

psychrometric constant (hPa/°C); R_n is the net radiation near the surface (mm/day); G is the soil heat flux; $f(u_z)$ is the wind function, which is calculated by Penman's wind function (Penman, 1948), that is, $f(u_z) = 0.26(1 + 0.54u_z)$, where u_z is the wind speeds at 2 m heights (m/s); e_s is the vapor pressure of the air (hPa); and e_a is the saturation vapor pressure at air temperature (hPa). All these variables are calculated by the method recommended by the Food and Agriculture Organization (FAO) of the United Nations (Allen 2000).

2.3.3 B2015 method

Brutsaert (2015) generalized the CR to a fourth-order polynomial function between ET_a/E_{Pen} and ET_w/E_{Pen} , the application of which still requires specifying the methods of E_{Pen} and ET_w . Considering the relationship with nonlinear AA approach, this new polynomial function is regarded as the generalized nonlinear advection–aridity method (B2015) and has the same variables as the nonlinear AA function (Crago et al. 2016; Ma et al. 2019), that is:

$$\frac{ET_a^{B2015}}{E_{Pen}} = (2 - c)\alpha^2 \left(\frac{E_{rad}}{E_{Pen}}\right)^2 - (1 - 2c)\alpha^3 \left(\frac{E_{rad}}{E_{Pen}}\right)^3 - c\alpha^4 \left(\frac{E_{rad}}{E_{Pen}}\right)^4 \quad (8)$$

where c is thought to be zero under usual situations (Brutsaert, 2015). Thus, a fixed $c = 0$ and calibrated parameter α of the B2015 have been adopted for daily (Aieta., 2017; Brutsaert et al., 2017; Hu et al., 2018; Zhang et al., 2017), annual, and multi-year scales (Liu et al., 2016). The equation (8) could be represented as:

$$\frac{ET_a^{B2015}}{E_{Pen}} = 2\alpha^2 \left(\frac{E_{rad}}{E_{Pen}}\right)^2 - \alpha^3 \left(\frac{E_{rad}}{E_{Pen}}\right)^3 \quad (9)$$

2.3.4 H2018 method

Han et al. (2018) developed a nonlinear CR method (Han et al. 2012) by introducing minimum (x_{min}) and maximum (x_{max}) limits to E_{rad}/E_{Pen} (Han and Tian 2018). This sigmoid generalized complementary function (H2018) can be written as:

$$\frac{ET_a^{H2018}}{E_{Pen}} = \frac{1}{1 + m \left(\frac{x_{max} - x}{x - x_{min}}\right)^n} \quad (10)$$

where x_{min} and x_{max} corresponding to the minimum and maximum values of E_{rad}/E_{Pen} ; x is defined as the ratio of E_{rad} to E_{Pen} ; and m and n are constants. The H2018 exhibits a three-stage pattern, and ET_a/E_{Pen} increases

approximately linearly with E_{rad}/E_{pen} during the middle stage in environments that are neither too dry nor too wet. By making a first-order Taylor expansion of the H2018 at $ET_a/E_{pen} = 0.5$ equal to the linear nonlinear AA function, parameters m and n can be transferred from α and b^{-1} :

$$\begin{cases} n = \frac{4\alpha(1+b^{-1})(x_{0.5}-x_{min})(x_{max}-x_{0.5})}{(x_{max}-x_{min})} \\ m = \left(\frac{x_{0.5}-x_{min}}{x_{max}-x_{0.5}}\right)^n \end{cases} \quad (11)$$

where $x_{0.5} = (0.5 + b^{-1}) / (\alpha(1 + b^{-1}))$ is the value of E_{rad}/E_{pen} corresponding to $ET_a/E_{pen} = 0.5$. The linear nonlinear AA function can be regarded as a special case of the H2018 (Han and Tian 2018), for which $x_{min} = 0$ and $x_{max} = 1$ have been suggested for a daily scale because the function and simulated results are not sensitive to x_{min} and x_{max} .

2.4 Evaluation criteria

The performance of the nonlinear AA, B2015 and H2018 methods in simulating monthly ET_a in the NRB and LCRB was evaluated by water-balance-derived ET_a , in which the optimal model parameters α , and b^{-1} are also calibrated. The evaluation criteria included the Nash efficiency coefficient (NSE), the square-R (R^2), the normalized root mean square error (NRMSE), and the relative error between the modeled ET_a and the observed ET_a .

$$NSE = 1 - \frac{\sum_{i=1}^n (ET_a^{mol,i} - ET_a^{obs,i})^2}{\sum_{i=1}^n (ET_a^{obs,i} - \overline{ET_a^{obs,i}})^2} \quad (12)$$

$$NRMSE = \frac{\sqrt{\frac{1}{n} \sum_{i=1}^n (ET_a^{mol,i} - ET_a^{obs,i})^2}}{\sqrt{\frac{1}{n-1} \sum_{i=1}^n (ET_a^{mol,i} - \overline{ET_a^{mol,i}})^2}} \quad (13)$$

where i and n denote the time series and length of the time sequence, respectively; $ET_a^{mol,i}$ and $ET_a^{obs,i}$ are modeled and observed values, respectively.

2.5 Contribution of meteorological factors on ET_a

Meteorological factors with strongly physically correlation with ET_a were selected for analysis, including precipitation, air temperature, relative humidity, wind speed, and sunshine hours (Li et al. 2014; Valipour 2015). The contribution rate

of meteorological factors to ET_a was the sensitivity coefficient of a single meteorological factor multiplied by the multi-year relative change rate of this factor. It could be expressed as follows,

$$Con_{V_i} = S_{V_i} \times RC_{V_i} \quad (14)$$

where V_i is meteorological factor such as temperature, wind speed, relative humidity, and sunshine hours; Con_{V_i} is the contribution rate of V_i to the change in ET_a ; S_{V_i} is the sensitivity coefficient of V_i ; $RC_{V_i}(\%)$ is the multi-year relative change rate of V_i .

The dimensionless relative sensitivity coefficient proposed by McCuen (1974) was used to characterize the sensitivity coefficient of ET_a to climate factors. A simpler and more effective method was to calculate the approximate solution based on the finite difference expansion of Taylor series (Hupet and Vanclooster 2002):

$$S_{V_i} = \frac{\Delta ET}{\Delta V_i} \frac{|V_i|}{ET} \quad (15)$$

where ET and ΔET are the daily ET_a and daily variation, respectively; and V_i and ΔV_i are the daily meteorological factor values and daily variation, respectively. Under the condition that the variable of a single meteorological factor varies by $\pm 10\%$, the sensitivity coefficient of ET_a to each meteorological factor was calculated in turn.

The multi-year relative change rate of meteorological factor was calculated by the following formula,

$$RC_{V_i}(\%) = \frac{n \cdot Trend_{V_i}}{|aV_i|} \times 100 \quad (16)$$

where aV_i is the multi-year average value of V_i ; $Trend_{V_i}$ is the annual climate tendency rate of V_i .

3. Results

3.1 The performance of three developed CR methods in simulating monthly ET_a

In this study, the ranges of parameters α of the B2015 was [0.91, 1.13] with an average value of 1.03; the ranges of parameter α and b^{-1} for the nonlinear AA method were [0.89, 1.14] and [0.60, 1.51], respectively. For the H2018, the range of parameter α was [1.01, 1.14] with an average value of 1.05, and the ranges of parameter b^{-1} was [1.05, 1.78]. The performance of the nonlinear AA, B2015, and H2018 methods in simulating monthly ET_a in the NRB and LCRB were compared (Table 1). The discrepancies among the three developed methods for ET_a estimation was small. The

relative errors between the monthly ET_a simulated by the nonlinear AA, B2015, and H2018 methods and the water-balance-derived ET_a were 3.5%, 4.3%, and 3.5%, respectively. The NSE of three developed methods were 0.89, 0.83, and 0.91, respectively. The R-square were 0.90, 0.84, and 0.93, respectively. And the NRMSE were 0.35 mm, 0.37 mm, and 0.28 mm, respectively. Overall, the H2018 performed better than the B2015 and nonlinear AA methods.

The performance of three developed CR methods in simulating wet season ET_a was generally similar with that of annual ET_a . It showed a relatively poor performance in simulating dry season ET_a , with the NSE lower than 0.6 except for nonlinear AA method in LCRB. However, the relative errors were less than 10%, indicating that the methods were able to accurately simulate the average value.

In general, the developed CR methods were able to simulate ET_a with a high accuracy at the annual and wet season scales in the LCRB and NRB. The simulation accuracy of the LCRB was slightly higher than that of the NRB in terms of evaluation criteria.

Table 1. Evaluation results of three developed CR methods in simulating monthly ET_a .

		NSE			R ²			NRMSE (mm)			Relative error (%)		
		Annual	Dry	Wet	Annual	Dry	Wet	Annual	Dry	Wet	Annual	Dry	Wet
non-	NRB	0.90	0.60	0.83	0.90	0.72	0.87	0.39	0.32	0.25	3.7	3.3	4.0
AA	LCRB	0.88	0.54	0.87	0.90	0.67	0.89	0.32	0.35	0.15	3.2	3.5	3.1
B2015	NRB	0.82	0.53	0.78	0.82	0.60	0.85	0.40	0.57	0.35	5.1	5.2	4.8
	LCRB	0.85	0.52	0.84	0.86	0.64	0.86	0.34	0.55	0.28	3.4	3.4	3.5
H2018	NRB	0.90	0.56	0.89	0.91	0.67	0.90	0.29	0.52	0.20	3.8	4.0	3.6
	LCRB	0.92	0.57	0.91	0.94	0.70	0.93	0.28	0.52	0.15	3.2	3.6	2.8

Frequency distributions of the relative error for the nonlinear AA, B2015 and H2018 methods in simulating annual, wet and dry seasons ET_a were shown in Fig.2. In general, the frequency of the relative error of developed CR methods exhibited a normal distribution. In term of the frequency distribution of the H2018 method, more than 95.2% of the errors were between -25% and 25%. Among them, the error frequency between -5% and 5% was the highest, with the value of 30.1%. The frequency distribution of wet season was consistent with that of annual series. An 85.7% margin of error was between -25% and 25%. The error frequency was the highest between -5% and 5%, with the value of 30.6%.

The frequency distribution of the relative error of dry season ET_a was not consistent with that of wet season. More than 52.4% of errors were between -15% and 20%. Among them, the highest between 5% and 10% with the value of 9.5%.

The error frequency of 19.4% was greater than 50%, which was much higher than that of 2.4% in annual and rainy seasons. The relative error was slightly higher in dry season in terms of frequency distribution. The frequency distribution of the relative error for nonlinear AA and B2015 were basically the same as those of H2018. For example, more than 90% of the errors were between -25% and 25%, and the error frequency was the highest between -5% and 5% with the value of 33.3%. However, there were some inconsistencies. For example, the B2015 method had a better simulation effect in dry season. More than 71.4% of the errors distributed between -25% and 25%. The error frequency was the highest between -10% and -5% with the value of 14.3%.

Fig.2 Frequency distributions of the relative error for the nonlinear AA, B2015 and H2018 methods.

3.2 Trends of ET_a , precipitation, and runoff in the NRB and LCRB

Table 2 showed the trends of precipitation, runoff and ET_a in the NRB and LCRB. In terms of precipitation, the increasing magnitude of the annual precipitation in the NRB and LCRB was 30.5 mm/10a and 42.0 mm/10a, respectively. The wet season precipitation increased significantly in the LC-M, with the magnitude of 68.4 mm/10a. The magnitude of

increasing trend of dry season precipitation was lower. The contribution rate of increasing magnitude of precipitation in dry season to annual was 24.5% and 28.0%, respectively. In terms of annual and wet season precipitation series, the mid-stream region of the two basins showed the highest increasing magnitude, while the upstream region was lowest. The magnitude of increasing trend was 32.4 mm/10a and 68.4 mm/10a, respectively. The increasing trends of annual and wet season precipitation in the LCRB were significant. The significance level was even exceeded 0.01.

It showed an increasing trend for ET_a in the upstream region of the LCRB at three temporal scales (dry and wet seasons and annual series). The significant (significance level of 0.05, the same below) increasing trend was detected for wet season and annual series. The magnitude of increasing trend of three temporal scales was 5.9 mm/10a, 14.3 mm/10a, and 16.3 mm/10a, respectively. The highest increasing magnitude was wet season ET_a in the LC-D, with the value of 18.6mm/10a. On the whole, the annual and wet season ET_a in each region of the two basins showed an increasing trend. The average magnitude of increasing trend was 13.5 mm/10a and 15.1 mm/10a, respectively. The increasing magnitude of ET_a in NRB was downstream region > upstream region > mid-stream region, with the value of 15.2 mm/10a, 9.9 mm/10a, and 9.8 mm/10a, respectively. There was little difference between the upstream, mid-stream and downstream regions of LCRB. The increasing magnitude of annual ET_a in LCRB was 39.4 % higher than that in NRB. In addition, the dry season ET_a in the N-U and N-M both exhibited decreasing trends, with the value of -3.1 mm/10a and -1.5 mm/10a, respectively. The variation difference between dry season ET_a and wet season ET_a was the most significant in N-M. The increasing magnitude of wet season ET_a was 7.1 times that of dry season. This is because dry season ET_a accounted for only 13% of the annual ET_a . Dry season ET_a accounted for the highest proportion of annual increasing magnitude in LC-D, with the value of 52.3%. In addition, precipitation was the main factor that caused ET_a change. The increasing magnitude of ET_a accounted for 44.8% of the precipitation increment.

Runoff in the NRB showed increasing trends at three temporal scales. The increasing magnitude of annual series for the whole basin was 29.3 mm/10a. The highest and the lowest increasing magnitude of annual series were in the mid-stream and upstream regions, with the value of 38.0 mm/10a and 23.5 mm/10a, respectively. This was consistent with the magnitude of precipitation, indicating the changes of runoff were mainly caused by that of precipitation in the NRB. The highest increasing magnitude of wet season series was 35.4 mm/10a in the mid-stream region, which was consistent with that of annual series. The significant increasing trends of dry season runoff in the NRB and wet season runoff in the N-D

were detected. The significance level was even exceeded 0.01. In addition, the difference between the increasing magnitude of precipitation and runoff in the N-U was lower than that of ET_a . This indicated that there was glacial melt water in this region to replenish the ET_a .

Runoff in the LCRB except for the LC-U also exhibited increasing trends at three temporal scales, with the magnitude of annual series for the whole basin was 15.8 mm/10a. The significant increasing trends of dry and wet seasons, and annual runoff were also detected in the mid-stream region. The magnitude was 13.4 mm/10a, 49.8 mm/10a, and 56.5 mm/10a, respectively. The decreasing trends of runoff were detected in the LC-U. The annual magnitude was -13.8 mm/10a. In other words, according to the hydrological budget balance, the increasing precipitation cannot meet the increasing water consumption by ET_a . This might be the reason for the decreasing runoff.

Table 2. Trends of precipitation, ET_a and runoff in the NRB and LCRB during 1956-2018.

Slope (mm/10a)		NRB			NRB	LCRB			LCRB
		N-U	N-M	N-D		LC-U	LC-M	LC-D	
Precipitation (P)	Dry season	3.3	4.9	15.8	7.5	5.5	8.2	20.9	11.8
	Wet season	16.3	31.8	37.3	28.3	16	65.8**	30.5	34.3
	Annual	19.4	32.4	40.9	30.5	25.7	68.4**	40	42
ET_a	Dry season	-3.1	-1.5	6	0.1	5.9	5.6	7.7	6.5
	Wet season	10.2	10.6	13.1	11.2	14.3**	13.9	18.6	15.7
	Annual	9.9	9.8	15.2	11.4	16.3**	18.8	21.3	18.8
Runoff (R)	Dry season	8.7**	8.2**	3.4**	7	-1.1	13.4**	2.7	4.1
	Wet season	19.4	35.4	19.9**	25.7	-13.4	49.8**	16	13.7
	Annual	23.5	38	24.1	29.3	-13.8	56.5**	17.2	15.8

* and ** represent the significance level of 0.05 and 0.01 respectively.

Since H2018 had a best simulation effect, the simulation results of ET_a distribution in the NRB and LCRB from 1958 to 2018 were selected to replace the years in which the data of hydrological budget balance method were missing (Fig.3). Annual precipitation increased from northwest to southeast. The precipitation of most stations (13/18) in the two basins showed an increasing trend, with an increasing magnitude of 2.4- 124.4 mm/10a. The precipitation at three stations increased significantly (85.2- 144.1 mm/10a). While the precipitation at five stations showed a decreasing trend, with the value of -50.6- -17.3 mm/10a. Most of stations showed an increasing trend in the dry season. Only five stations showed a decreasing trend, and mainly located in the mid-stream region (3/5). The decreasing magnitude of them between -56.3- -0.6 mm/10a. The trend of dry season precipitation in the mid-stream region was opposite to that of the whole basin, which

was consistent with the above results (Table 2). The trend of wet season precipitation was basically consistent with that of annual precipitation. And more stations showed an increasing trend (15/18).

The spatial distribution of ET_a was highly consistent with precipitation. The ET_a in NRB and LCRB were downstream region > upstream region > mid-stream region. In the LCRB, for example, the annual ET_a in the downstream region (650.4 mm) was three times that in the upstream region (217.6 mm). In addition, ET_a at most stations (16/18) showed an increasing trend in recent 60 years. The increasing magnitude of NRB and LCRB was 17.0 mm/10a and 27.1 mm/10a, respectively. A few downstream stations (2/18) had a decreasing trend, with the decreasing magnitude between -4.8 and -1.9 mm/10a. ET_a decreased more in dry season than in annual (4/18). From the trend of annual increasing ET_a , the decreasing magnitude in dry season was less than the increasing magnitude in wet season.

Fig.3 Annual and seasonal trends of precipitation and ET_a at each station from 1956 to 2018 simulated by H2018 method (Yellow/Green triangles represent increase trends, and blue triangles are decreasing trends. Large symbols indicate the significance level of 0.05).

3.3 Contribution of meteorological factors on ET_a

Precipitation, temperature and humidity increased from south to north in NRB and LCRB (Fig.4), which was consistent with the spatial distribution of ET_a . On the contrary, wind speed decreased in this direction. The sunshine hours were the shortest in the mid-stream region, which was especially significant in wet season. In other words, latitude and topography affected the regional climate, and the geographical characteristics of different meteorological factors were bound to have different influences on ET_a .

Air temperature in the basins exhibited significant increasing trends at all temporal scales (dry and wet seasons and annual series) during the past 60 years. On the contrary, wind speed showed significant decreasing trends. There was little difference for trends of air temperature between annual and dry season series at observed stations. It only showed a decreasing trend at one station located at the mid-stream region of the NRB. But decreasing trends were detected at four stations, which were located in the upstream region of the LCRB and the mid-stream of two basins, for air temperature of wet seasons. The variation characteristics of relative humidity also showed a high consistency among three temporal scales at observed stations. But it showed regional variations. The increasing humidity was detected at the upstream and mid-stream regions. While most downstream sites showed a decreasing trend. The number of decreasing humidity in the dry season (7/18) was more than that in the wet season (4/18).

Sunshine hours in the LCRB exhibited significant decreasing trends at all temporal scales (7/9). It only showed an increasing trend at two stations located at the boundary of the downstream region. However, there was a seasonal and regional differences in the NRB. The decreasing sunshine hours were detected at the upstream and mid-stream regions. While downstream sites increased slightly. Compared with the dry season sunshine hours, the wet season hours showed an increasing trend with four more observed stations in the upstream and mid-stream regions. The spatial and temporal distribution and variation trend of different meteorological factors would have different effects on regional ET_a .

Fig.4 Annual and seasonal trends of major meteorological variables in the NRB and LCRB during the past 60 years

(Green triangles represent increasing trends, and blue triangles are decreasing trends. Large symbols indicate the significance level of 0.05).

The contribution rate of meteorological factors to ET_a was shown in Fig.5. The contribution rates of increasing air temperature to the increasing ET_a in the NRB and LCRB were 23.3% and 23.7%, respectively. Relative humidity, wind speed and sunshine hours all had negative contributions to ET_a . Among them, the contribution rates of increasing humidity were -12.5% and -9.2%, the contribution rates of decreasing wind speed were -10.8% and -9.6%, and the contribution rates of decreasing sunshine hours were -6.5% and -4.1% in the NRB and LCRB, respectively. The impacts of meteorological factors on ET_a in the basins were basically consistent in the dry and wet seasons except for the N-U and N-M. Contributions of annual and dry season meteorological factors were mainly different in the regions. The positive contribution of dry season humidity, wind speed, and sunshine to the total was 13.3% and 13.4% in the N-U and N-M, respectively. While the wet season total contributions were -8.8% and -25.7%, and annual total contributions were -24.8% and -21.7%, respectively. In addition, the performance of the wet season sunshine hours in the N-D was completely opposite to that in other areas. The increasing wet season sunshine hours contributed 9.0% to the increasing ET_a in the N-D. The two basins mainly relied on the positive contribution of air temperature, which was the dominant factor leading to the increase of ET_a . Humidity and wind speed were also very important meteorological impact factors. The changes of meteorological factors in different regions and seasons caused spatiotemporal variation of ET_a , and provided positive/negative contributions to the regional ET_a .

Fig.5 The contribution of meteorological factors on ET_a .

The correlation coefficients between meteorological factors and ET_a in the NRB and LCRB were shown in Fig.6. There was a positive correlation between ET_a and precipitation, temperature, wind and sunshine hours. The correlation between ET_a and precipitation in wet season was higher than that in dry season. There was little difference among seasonal correlation coefficients for other meteorological factors. The correlation between ET_a and precipitation and temperature in the LC-M was the highest, reaching 0.81 and 0.68, respectively. In mid-stream region of the NRB, ET_a was with the strongest correlation with wind speed, and the correlation coefficient was higher than 0.80. The correlation between ET_a and sunshine hours in the wet season in up-stream region of the LCRB reached 0.73. There was a negative correlation between ET_a and relative humidity in the whole basin. The negative correlation was particularly strong in the N-M, LC-U and LC-M. The correlation coefficients were all greater than -0.65.

Fig.6 The correlations between meteorological factors and ET_a.

4. Discussions

The parameter α is related to the natural characteristics. Researches pointed out that the parameter α in the Priestly-Taylor formula had a wider range of value with roughly 0.6-1.5 (DeBruin 1983; McMahon et al. 2013), which represented the combined effects of the land-atmosphere coupling relationship and underlying vegetation, soil and water conditions on the complementary relationship of ET_a. In this study, the value of the parameter α was negatively correlated with the regional aridity index (AI= ET/P) in the basins (Fig.7), which was consistent with Liu et al. (2016).

Fig.7 Negative correlation between AI and α value.

Gao et al. (2018) and Zhou et al. (2020) respectively estimated the ET_a distribution in the upstream region of Huaihe river basin and the Loess Plateau based on the generalized complementary principle (B2015 and H2018). The results showed that the simulation accuracy of H2018 was higher than that of B2015 in the Huaihe River basin and the Loess Plateau, and the results are consistent with that in the LCRB and NRB. Gao et al. (2018) pointed out that when $\alpha = 1.25$, the relative error of the method was within $\pm 5\%$. Zhou et al. (2020) showed that H2018 and B2015 had the best performance when $\alpha = 1.05$ and 1.14 , respectively. The α value in the basins studied in this paper was relatively low. It is possible that the LCRB and NRB have higher aridity index which is related to the local climatic conditions and vegetation coverage. The developed CR methods after parameter adjustment has good performance in different regions, which provides more references and possibilities for the study of regional ET_a .

ET_a is directly sourced from soil water, open water, and indirectly from water by vegetation (Balugani et al. 2016). Precipitation affects ET_a through soil moisture constraints, especially in arid regions. For example, with high precipitation, ET_a is less limited to soil moisture, and the ET_a might be the same as the potential evapotranspiration (Liu et al. 2012). However, in arid environments with limited precipitation, the soil water content is insufficient, and ET_a tends to be largely dependent on available soil water. The arid environment places a strong constraint on ET_a , causing the ET_a to be much lower than potential evapotranspiration. High temperature accelerates ET_a by providing more energy. And the longer sunshine hours mean that more solar radiation energy is provided. Therefore, ET_a is sensitive to both

temperature and sunshine (Li et al. 2017). Wind speed, another meteorological factor positively related to ET_a , is responsible for transporting water heat and carbon dioxide. Wind is in some cases dominating radiation (Liu and Zhang 2013). There is a negative correlation between the relative humidity and ET_a . With an increase in humidity, the moisture content in the air is higher and moisture evaporated into the air decreases (Moratiel et al. 2010). As demonstrated in this study meteorological factors had different effects on ET_a at different time scales in different regions. The quantitative relationship between regional ET_a and climate and soil-plant-atmosphere continuum should be considered in the future.

5. Conclusions

Monthly ET_a in the LCRB and NRB were simulated by the hydrological budget balance method based on the observed hydrological and meteorological data from 1956 to 2018. The nonlinear AA and two generalized complementary functions, B2015 and H2018 were evaluated by monthly water-balance-derived values. Impacts of major meteorological factors on ET_a were also assessed. The conclusions were as follows,

- (1) All three developed CR methods were able to accurately simulate monthly ET_a series. The NSE between the monthly ET_a simulated by the nonlinear AA, B2015, and H2018 methods and the water-balance-derived values were 0.89, 0.83, and 0.91, respectively. The R-square were 0.90, 0.84, and 0.93, respectively. The difference between NSE and R-square was highest in dry season ET_a , with an average of 0.55 and 0.67, respectively. Overall, the H2018 method showed the relatively best performance. The parameter α had a negative correlation with the regional aridity index.
- (2) Annual ET_a and precipitation showed significant increasing trends during 1956-2018 in the basins at all temporal scales (dry and wet seasons and annual series). Runoff also exhibited an increasing trend in each sub-basin, except for the downstream region of the LCRB. The increasing magnitude was downstream region > mid-stream region > upstream region. The increasing magnitudes of wet reason precipitation and runoff in the mid-stream region was the highest, with the value of 73.7 mm/10a and 44.9 mm/10a, respectively. The ET_a increased dramatically in the downstream region, the magnitude reached 25.9 mm/10a. Precipitation was the main factor leading to ET_a change. The increasing magnitude of ET_a accounted for 42.4% of the precipitation increment.

(3) The contribution rate of air temperature to ET_a was the highest, reaching 23.5%, which showed a significant positive correlation. The second was wind speed, whose contribution rate was -10.2% on average, and even reached -14.1% in the upstream region of the NRB. The correlation coefficient between ET_a and wind speed was highest in mid-stream region of the NRB, which was greater than 0.80. The contribution rates of increasing humidity to ET_a were -12.5% and -9.2% in the NRB and LCRB, respectively. ET_a was negatively correlated with humidity. The negative correlation was especially strong in the mid-stream region, with coefficients were greater than -0.65. The sunshine hours had the least effect on ET_a , and the contribution rates were -6.5% and -4.1%, respectively.

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References

- Allen RG (2000) Using the FAO-56 dual crop coefficient method over an irrigated region as part of an evapotranspiration intercomparison study. *J Hydrol* 229:27-41. [http://doi.org/10.1016/S0022-1694\(99\)00194-8](http://doi.org/10.1016/S0022-1694(99)00194-8)
- Allen R, Irmak A, Trezza R, Hendrickx JMH, Bastiaanssen W, Kjaersgaard J (2011) Satellite-based ET estimation in agriculture using SEBAL and METRIC. *Hydrol Process* 25:4011-4027. <http://doi.org/10.1002/hyp.8408>
- Balugani E, Lubczynski MW, Metselaar K (2016) A framework for sourcing of evaporation between saturated and unsaturated zone in bare soil condition. *Hydrol Sci J* 61:1981-1995. <http://doi.org/10.1080/02626667.2014.966718>
- Bouchet RJ (1963) Evapotranspiration réelle et potentielle, signification climatique. *IAHS Publ* 62:134-142
- Brutsaert W (2015) A generalized complementary principle with physical constraints for land surface evaporation. *Water Resour Res* 51:8087-8093. <http://doi.org/10.1002/2015WR017720>
- Brutsaert W, Parlange MB (1998) Hydrologic cycle explains the evaporation paradox. *Nature* 396:30. <http://doi.org/10.1038/23845>

- Brutsaert W, Cheng L, Zhang L (2020) Spatial distribution of global landscape evaporation in the early twenty first century by means of a generalized complementary approach. *J Hydrometeorol* 21:287-298. <http://doi.org/10.1175/JHM-D-19-0208.1>
- Brutsaert W, Li W, Takahashi A, Hiyama T, Zhang L, Liu W (2017) Nonlinear advection-aridity method for landscape evaporation and its application during the growing season in the southern Loess Plateau of the Yellow River basin. *Water Resour Res* 53:270-282. <http://doi.org/10.1002/2016WR019472>
- Chen ZJ, Zhu ZC, Jiang H, Sun SJ (2020) Estimating daily reference evapotranspiration based on limited meteorological data using deep learning and classical machine learning methods. *J Hydrol* 591:125286. <http://doi.org/10.1016/j.jhydrol.2020.125286>
- Crago R, Szilagyi J, Qualls R (2016) Rescaling the complementary relationship for land surface evaporation. *Water Resour Res* 52:8461-8471. <http://doi.org/10.1002/2016WR019753>
- DeBruin HAR (1983) A model method for the Priestley-Taylor parameter α . *J Clim Appl Meteorol* 22:572-578. [https://doi.org/10.1175/1520-0450\(1983\)022<0572:AMFTPT>2.0.CO;2](https://doi.org/10.1175/1520-0450(1983)022<0572:AMFTPT>2.0.CO;2)
- Fan H, He DM (2015) Temperature and precipitation variability and its effects on streamflow in the upstream regions of the Lancang-Mekong and Nu-Salween Rivers. *J Hydrometeorol* 16:2248-2263. <https://doi.org/10.1175/JHM-D-14-0238.1>
- Fan JL, Yue WJ, Wu LF, Zhang FC, Cai HJ, Wang XK, Lu XH, Xiang YZ (2018) Evaluation of SVM, ELM and four tree-based ensemble models for predicting daily reference evapotranspiration using limited meteorological data in different climates of China. *Agr Forest Meteorol* 263:225-241. <https://doi.org/10.1016/j.agrformet.2018.08.019>
- Farahani HJ, Howell TA, Shuttleworth WJ, Bausch WC (2007) Evapotranspiration: Progress in measurement and modeling in agriculture. *Trans ASABE* 50:1627-1638
- Fisher JB, Melton F, Middleton E, Hain C, Anderson M, Allen R, Wood EF (2017) The future of evapotranspiration: Global requirements for ecosystem functioning, carbon and climate feedbacks, agricultural management, and water resources. *Water Resour Res* 53:2618-2626. <https://doi.org/10.1002/2016WR020175>
- Gao G, Chen DL, Xu CY, Simelton E (2007) Trend of estimated actual evapotranspiration over China during 1960-2002. *J Geophys Res Atmos* 112:D11120. <https://doi.org/10.1029/2006JD008010>

- Gao JQ, Qiao M, Qiu XF, Zeng Y, Hua HH, Ye XZ, Adamu M (2018) Estimation of actual evapotranspiration distribution in the Huaihe River upstream basin based on the generalized complementary principle. *Adv Meteorol* 2018:2158168. <https://doi.org/10.1155/2018/2158168>
- Granger RJ, Gray DM (1989) Evaporation from natural nonsaturated surfaces. *J Hydrol* 111:21-29. [https://doi.org/10.1016/0022-1694\(89\)90249-7](https://doi.org/10.1016/0022-1694(89)90249-7)
- Han SJ, Tian FQ (2018) Derivation of a sigmoid generalized complementary function for evaporation with physical constraints. *Water Resour Res* 54:5050-5068. <https://doi.org/10.1029/2017WR021755>
- Han SJ, Hu H, Tian FQ (2008) Evaluating the advection-aridity model of evaporation using data from field-sized surfaces of HEIFE. *International Symposium on Flood Forecasting and Water Resource Assessment for IAHS-PUB*.
- Hobbins MT, Ramirez JA, Brown TC, Claessens, LHJM (2001) The complementary relationship in estimation of regional evapotranspiration: The complementary relationship areal evapotranspiration and advection-aridity models. *Water Resour Res* 37:1367-1387. <https://doi.org/10.1029/2000WR900358>
- Hupet F, Vanclooster M (2002) Effect of the sampling frequency of meteorological variables on the estimation of the reference evapotranspiration. *J Hydrol* 243:192-204. [https://doi.org/10.1016/S0022-1694\(00\)00413-3](https://doi.org/10.1016/S0022-1694(00)00413-3)
- Jian DN, Li XC, Sun HM, Tao H, Jiang T, Su BD, Hartmann H (2020) Estimation of actual evapotranspiration by the complementary theory-based advection-aridity model in the Tarim River basin, China. *J Hydrometeorol* 19:289-303. <https://doi.org/10.1175/JHM-D-16-0189.1>
- Katul GG, Oren R, Manzoni S, Higgins C, Parlange MB (2012) Evapotranspiration: A process driving mass transport and energy exchange in the soil-plant-atmosphere-climate system. *Rev Geophys* 50:RG3002. <https://doi.org/10.1029/2011RG000366>
- Li B, Chen F, Liu XM (2017) Sensitivity of the Penman-Monteith reference evapotranspiration to sunshine duration in the upper Mekong River basin. *Hydrol Sci J* 62:830-842. <https://doi.org/10.1080/02626667.2016.1243286>
- Li XP, Wang L, Chen DL, Yang K, Wang AH (2014) Seasonal evapotranspiration changes (1983–2006) of four large basins on the Tibetan Plateau. *J Geophys Res* 119:13079-13095. <https://doi.org/10.1002/2014JD022380>
- Liu Z, Yao Z, Huang H, Wu S, Liu G (2014) Land use and climate changes and their impacts on runoff in the Yarlung Zangbo River basin, China. *Land Degrad Dev* 25:203-215. <https://doi.org/10.1002/ldr.1159>

504 Liu M, Bardossy A, Li J (2012) Physically-based modeling of topographic effects on spatial evapotranspiration and soil
505 moisture patterns through radiation and wind. *Hydrol Earth Syst Sci* 16:357-373. [https://doi.org/10.5194/hess-16-](https://doi.org/10.5194/hess-16-357-2012)
506 357-2012

507 Liu WB, Wang L, Zhou J, Li YZ, Sun FB, Fu GB, Li XP, Sang YF (2016) A worldwide evaluation of basin-scale
508 evapotranspiration estimates against the water balance method. *J Hydrol* 538:82-95.
509 <https://doi.org/10.1016/j.jhydrol.2016.04.006>

510 Liu XM, Zhang D (2013) Trend analysis of reference evapotranspiration in Northwest China: The roles of changing wind
511 speed and surface air temperature. *Hydrol Process* 27:3941-3948. <https://doi.org/10.1002/hyp.9527>

512 Liu XM, Liu CM, Brutsaert W (2016) Regional evaporation estimates in the eastern monsoon region of China: Assessment
513 of a nonlinear formulation of the complementary principle. *Water Resour Res* 52:9511-9521.
514 <https://doi.org/10.1002/2016WR019340>

515 Liu Z, Yao Z, Wang R (2019) Simulation and evaluation of actual evapotranspiration based on inverse hydrological
516 modeling at a basin scale. *Catena* 180:160-168. <https://doi.org/10.1016/j.catena.2019.03.039>

517 Li Z, Chen YN, Yang J, Wang Y (2014) Potential evapotranspiration and its attribution over the past 50 years in the arid
518 region of Northwest China. *Hydrol Process* 28:1025-1031. <https://doi.org/10.1016/10.1002/hyp.9643>

519 Ma N, Szilagyi J (2019) The CR of evaporation: A calibration-free diagnostic and benchmarking tool for large-scale
520 terrestrial evapotranspiration modeling. *Water Resour Res* 55:7246-7274. <https://doi.org/10.1029/2019WR024867>

521 Maes WH, Steppe K (2012) Estimating evapotranspiration and drought stress with ground-based thermal remote sensing
522 in agriculture: a review. *J Exp Bot* 63:4671-4712. <https://doi.org/10.1093/jxb/ers165>

523 Masson V, Champeaux JL, Chauvin F, Meriguet C, Lacaze R (2003) A global database of land surface parameters at 1-
524 km resolution in meteorological and climate models. *J Clim* 9:1261-1282. [https://doi.org/10.1175/1520-0442-](https://doi.org/10.1175/1520-0442-16.9.1261)
525 16.9.1261

526 McCuen RH (1974) A sensitivity and error analysis of procedures used for estimating evaporation. *J AM Water Resour*
527 *Assoc* 10:486-497. <https://doi.org/10.1111/j.1752-1688.1974.tb00590.x>

528 McMahon TA, Peel MC, Lowe L, Srikanthan R, McVicar TR (2013) Estimating actual, potential, reference crop and pan
 529 evaporation using standard meteorological data: A pragmatic synthesis, *Hydrol Earth Syst Sci* 17:1331-1363.
 530 <https://doi.org/10.5194/hess-17-4503-2013>
 531 Moratiel R, Duran JM, Snyder RL (2010) Responses of reference evapotranspiration to changes in atmospheric humidity
 532 and air temperature in Spain. *Clim Res* 44:27-40. <https://doi.org/10.3354/cr00919>
 533 Morton FI (1983) Operational estimates of areal evapotranspiration and their significance to the science and practice of
 534 hydrology. *J Hydrol* 66:1-76. [https://doi.org/10.1016/0022-1694\(83\)90177-4](https://doi.org/10.1016/0022-1694(83)90177-4)
 535 Nakamichi T, Moroizumi T (2015) Applicability of three complementary relationship models for estimating actual
 536 evapotranspiration in urban area. *J Hydrol Hydromechanics* 63:117-123. <https://doi.org/10.1515/johh-2015-0011>
 537 Oki T, Kanae S (2006) Global hydrological cycles and world water resources. *Science* 313:1068-1072.
 538 <https://doi.org/10.1126/science.1128845>
 539 Penman HL (1948) Natural evaporation from open water, bare soil and grass. *Proc R Soc Lond A Math Phys Sci* 193:120-
 540 145. <https://doi.org/10.1098/rspa.1948.0037>
 541 Priestley CHB, Taylor RJ (1972) On the assessment of surface heat flux and evaporation using large-scale parameters.
 542 *Mon Weather Rev* 100:81-92. [https://doi.org/10.1175/1520-0493\(1972\)100<2.CO;2](https://doi.org/10.1175/1520-0493(1972)100<2.CO;2)
 543 Sabo JL, Ruhi A, Holtgrieve GW, Elliott V, Arias ME, Ngor PB, Rasanen TA, Nam S (2017) Designing river flows to
 544 improve food security futures in the Lower Mekong Basin. *Science* 358: eaao1053.
 545 <https://doi.org/10.1126/science.aao1053>
 546 Szilagyi J (2007) On the inherent asymmetric nature of the complementary relationship of evaporation. *Geophys Res Lett*
 547 34:L02405. <https://doi.org/10.1029/2006GL028708>
 548 Szilagyi J, Crago R, Qualls R (2017) A calibration-free formulation of the complementary relationship of evaporation for
 549 continental-scale hydrology. *J Geophys Res* 122:264-278. <https://doi.org/10.1002/2016JD025611>
 550 Szilagyi J, Hobbins MT, Jozsa J (2009) Modified advection-aridity model of evapotranspiration. *J Hydrol Eng* 14:569-
 551 574. [https://doi.org/10.1061/\(ASCE\)HE.1943-5584.0000026](https://doi.org/10.1061/(ASCE)HE.1943-5584.0000026)
 552 Trenberth KE, Fasullo JT, Kiehl J (2009) Earth's global energy budget. *Bull AM Meteorol Soc* 90:311-323.
 553 <https://doi.org/10.1175/2008BAMS2634.1>

- Valipour M (2015) Importance of solar radiation, temperature, relative humidity, and wind speed for calculation of reference evapotranspiration. *Arch Agron Soil Sci* 61:239-255. <https://doi.org/10.1080/03650340.2014.925107>
- Wan ZM, Zhang K, Xue XW, Hong Z, Hong Y, Gourley JJ (2015) Water balance based actual evapotranspiration reconstruction from ground and satellite observations over the Conterminous United States. *Water Resour Res* 51:6485-6499. <https://doi.org/10.1002/2015WR017311>
- Xu CY, Singh VP (2005) Evaluation of three complementary relationship evapotranspiration models by water balance approach to estimate actual regional evapotranspiration in different climatic regions. *J Hydrol* 308:104-121. <https://doi.org/10.1016/j.jhydrol.2004.10.024>
- Xu RR, Gao P, Mu XM, Gu CJ (2021) Spatial-temporal change of actual evapotranspiration and the causes based on the advection-aridity model in the Weihe River basin, China. *Water* 13:303. <https://doi.org/10.3390/w13030303>
- Yang JH, Wang W, Hua TT, Peng M (2021) Spatiotemporal variation of actual evapotranspiration and its response to changes of major meteorological factors over China using multi-source data. *J Water Clim Change* 12:325-338. <https://doi.org/10.2166/wcc.2020.221>
- Zhang L, Cheng L, Brutsaert W (2017) Estimation of land surface evaporation using a generalized nonlinear complementary relationship. *J Geophys Res* 122:1475-1487. <https://doi.org/10.1002/2016JD025936>
- Zhang YQ, Leuning R, Chiew FHS, Wang EL, Zhang L, Liu CM, Sun FB, Peel MC, Shen YJ, Jung M (2012) Decadal trends in evaporation from global energy and water balances. *J Hydrometeorol* 13:379-391. <https://doi.org/10.1175/JHM-D-11-012.1>
- Zhou HX, Han SJ, Liu WZ (2020) Evaluation of two generalized complementary functions for annual evaporation estimation on the Loess Plateau, China. *J Hydrol* 587:124980. <https://doi.org/10.1016/j.jhydrol.2020.124980>