Simulation of Actual Evapotranspiration and Evaluation of Three Complementary Relationships in Three Parallel River Basins

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Abstract

Based on observed precipitation and runoff data, the monthly actual evapotranspiration (ETa) was calculated using the hydrological budget balance method in three parallel river basins. The performance of three complementary relationship methods, namely, the nonlinear advection-aridity (non-AA) method, generalized complementary relationship method (B2015), and sigmoid generalized complementary function (H2018), for simulating ETa was evaluated. The evaluation results showed that the three methods could accurately simulate monthly ETa series. The Nash–Sutcliffe efficiency coefficients between the monthly ETa simulated by the non-AA, B2015, and H2018 methods and the water balance-derived ETa were 0.74, 0.78, and 0.79, respectively. The correlation coefficients were 0.84, 0.89, and 0.90, and the root mean square errors were 10.76 mm mon−1, 10.01 mm mon−1, and 9.78 mm mon−1, respectively. ETa increased spatially from the upstream region to the downstream region at the catchment scale. Annual ETa simulated by the non-AA, B2015, and H2018 models showed significant increasing trends during the years 1956–2018 in the basins, with the increasing magnitudes of 1.53 mm/a, 1.66 mm/a, and 1.47 mm/a, respectively. Research on the influence of meteorological factors and ETa showed a positive correlation between ETa and precipitation, temperature, wind, and hours of sunshine, with average correlation coefficients of 0.40, 0.64, 0.63, and 0.72, respectively. The value between ETa and relative humidity was −0.38. ETa in the basins was highly sensitive to temperature, wind speed, and hours of sunshine, with average sensitivity coefficients of 0.26, 0.21, and 0.27, respectively. Moreover, it was moderately sensitive to relative humidity, with a sensitivity of −0.18.

Keywords Generalized complementary relationship · Hydrological budget balance · Actual evapotranspiration · Climate change

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# 1 Introduction

Actual evapotranspiration ($ET_a$) accounts for 59% of land surface precipitation (Oki and Kanae 2006). Solar radiation energy absorbed by land surfaces exceeding 50% is used for $ET_a$ (Trenberth et al. 2009). $ET_a$ reflects regional changes in land surface energy and hydrological budget. $ET_a$ analysis is crucial for the management and planning of water resources, forestry, and agricultural irrigation (Maes and Steppe 2012).

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 using a wide variety of ground measurements, such as lysimeters, energy balance Bowen ratio (da Costa Faria Martins 2022), and eddy covariance. However, in situ measurements provide only point- or field-scale measurements. Large-scale and long-term $ET_a$ monitoring relies on the water balance method, complementary relationship models, and energy balance models.

Several methods can estimate $ET_a$ using only routine meteorological observational data (Chen et al. 2020; Fan et al. 2018). Bouchet (1963) proposed a complementary relationship (CR), which has proven to be a feasible and efficient approach. The original complementary principle is based on a linear 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 (Zhou et al. 2020). Several methods based on CR have been proposed, such as Advection-Aridity (Brutsaert and Stricker 1979), CRAE (Morton 1983), and Granger-Gray (Granger and Gray 1989) methods. They have been extensively used to obtain long-term regional $ET_a$ (Jian et al. 2018; Szilagyi et al. 2009).

However, many studies have shown that it is difficult for $ET_a$ and $ET_p$ to achieve completely symmetrical CR. Brutsaert (2015) formulated a more general and nonlinear version of CR, which was defined as "the generalized complementary relationship" by generalizing the CR to a fourth-order polynomial function between $ET_a/ET_p$ and $ET_w/ET_p$. Han and Tian (2018) used a sigmoid form of the generalized complementary function in the traditional Advection-Aridity method to represent the relationship between $ET_a$ and $ET_p$ by considering boundary conditions for extremely arid and completely wet environments.

Many studies have focused on the spatiotemporal pattern of $ET_a$ on a global or regional scale (Liu et al. 2019; Yang et al. 2021). There are relatively few studies on $ET_a$ changes in three parallel river basins, which are characterized as unique dry-hot valleys. The Nu and Lancang Rivers, which are located in basins, are the upper reaches of the international Salween River and Mekong River, respectively. This includes semi-arid, semi-humid, and humid regions. Investigation of spatial patterns and temporal changes in $ET_a$ of this region is of great interest (Sabo et al. 2017). The evaluation of CR models improves the application of $ET_a$ in ecological environment protection, agricultural irrigation, and watershed water resource management. It also has scientific significance for improving the accuracy of CR models.

In this study, a water balance-based ET (WB_ET) series was used to evaluate the accuracy of CR-based ET (CR_ET) in three parallel river basins. In addition, WB_ET and CR_ET data were used to investigate the spatial and temporal variations in $ET_a$, respectively. The objectives of this study were to (1) simulate $ET_a$ using the corrected hydrologic budget balance method, (2) evaluate the accuracy of the three developed CR methods in simulating monthly $ET_a$, and (3) detect trends of $ET_a$ at the catchment and site scales in three parallel river basins.
2 Material and Methods

2.1 Study Area

The three parallel river basins include a series of parallel north-south mountain ranges in southwest China, with an area of approximately 538,000 km². The study area includes the Nu (NRB), Lancang (LCRB), and Jinsha (JSRB) River basins above the Daojieba, Yunjinghong, and Shigu stations, respectively. The Nu and Lancang rivers are upstream of the Salween and Mekong rivers, respectively. The terrain of this region is complex and changeable, characterized by a deep V-shaped valley with a high velocity of surface and subsurface runoff. The upstream region has a plateau climate of semi-arid regions with low temperatures and little precipitation. The midstream and downstream regions are located in subtropical and tropical climate zones of semi-humid and humid regions, respectively. In general, the mean annual precipitation in the three parallel river basins ranges from 150–1500 mm/a, and heavy rains are concentrated during the wet season (May to October). The annual air temperature is between 10 °C and 30 °C. The annual ET ranges from 50 mm/a in the north to 1500 mm/a in the south. Wet season ET accounts for 85% of the annual ET.

2.2 Data

Daily meteorological data for 1956–2018 from 35 stations in the study area were obtained from the China Meteorological Administration (http://data.cma.cn/). The data included precipitation (mm), air temperature (°C) at a height of 2 m, wind speed (m/s) at a height of 10 m, relative humidity (%), and hours of sunshine (h). The monthly and annual series were additions from the daily observed data series. The area weight of each site was calculated using the Thiessen polygon method.

Runoff data from nine hydrological stations for 1956–2018 in the mainstream of the basins were used in this study. Each hydrological station represented the main stream control stations of the upstream, midstream, and downstream regions of the Nu, Lancang, and Jinsha Rivers, respectively (Fig. 1). The information on the nine hydrological sites is presented in Table 1. Data were obtained from the China Hydrological Yearbook.

2.3 Simulation of ET\textsubscript{a}

2.3.1 Hydrological Budget Balance Method

ET\textsubscript{a} was simulated using the hydrological budget balance method at the basin scale (Liu et al. 2014, 2019). In a basin, the hydrological budget balance equation can be expressed as:

\[ ET_i^{WH} = P_i - R_i - \Delta W \]  

(1)

where \( i \) is the sequential range, \( P \) and \( R \) are the precipitation (mm) and runoff at the basin outlet (mm), respectively, and \( \Delta W \) is the change in terrestrial water storage, including the surface, subsurface, and ground water changes (mm).

In the simulation of monthly ET\textsubscript{a}, \( \Delta W \) is usually negligible in many studies, which assumes precipitation is the only source of water in the basin, with evaporation being
the only way to lose water (Zhang et al. 2012). In this study, we defined \((P-R)\) as the biased \(ET^{WB}_{biased}\) relative to the reference \(ET^{WB}\). The \(ET^{WB}_{biased}\) 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. 2014a, b). For each basin, the monthly \(ET^{WB}\) and \(ET^{WB}_{biased}\) series were fitted separately using a gamma distribution. This has been shown to be an effective method for modeling the probability distribution of \(ET_a\) (Liu et al. 2016a, b).
2.3.2 Nonlinear AA Method

Brutsaert and Stricker (1979) proposed the AA method,

\[ ET_{a}^{AA} - ET_{w} = ET_{w} - ET_{p} \]  \tag{2} 

The AA method has since evolved to adopt an asymmetric CR (Brutsaert and Parlange 1998; Szilagyi et al. 2017).

\[ ET_{p} - ET_{w} = b (ET_{w} - ET_{a}) \]  \tag{3} 

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

\[ ET_{a} = \frac{1 + b}{b} ET_{w} - \frac{1}{b} ET_{p} \]  \tag{4} 

In non-AA method, \( ET_{p} \) and \( ET_{w} \) are denoted by the Penman equation (Penman 1948) and Priestley-Taylor equation (Priestley and Taylor 1972), respectively.

\[ ET_{w} = \alpha ET_{rad} = \alpha \frac{\Delta}{\Delta + \gamma} (R_{n} - G) \]  \tag{5} 

\[ ET_{p} = ET_{rad} + ET_{aero} = \frac{\Delta}{\Delta + \gamma} (R_{n} - G) + \frac{\gamma}{\Delta + \gamma} f(u_{2})(e_{s} - e_{a}) \]  \tag{6} 

where \( ET_{rad} \) and \( ET_{aero} \) are the radiation and aerodynamic terms, respectively (mm/day), \( \alpha \) is an empirical coefficient, \( \Delta \) is the slope of the saturation vapor pressure curve at air temperature (hPa/°C), \( \gamma \) is the psychrometric constant (hPa/°C), \( R_{n} \) is the net radiation near the surface (mm/day), \( G \) is the soil heat flux, \( f(u_{2}) \) is the wind function (Penman 1948) [i.e., \( f(u_{2}) = 0.26(1 + 0.54u_{2}) \), where \( u_{2} \) is the wind speed at 2 m height (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).

| Hydrological station | Longitude (°) | Latitude (°) | Catchment area (km²) | Temporal coverage |
|----------------------|--------------|--------------|----------------------|------------------|
| NRB                  | Jiayuqiao    | 96.24        | 30.87                | 68,384           |
|                      | Gongshan     | 98.68        | 27.73                | 101,146          |
|                      | Daojieba     | 98.88        | 24.98                | 110,224          |
| LCRB                 | Changdu      | 97.17        | 31.15                | 53,800           |
|                      | Jiuzhou      | 99.22        | 25.79                | 88,051           |
|                      | Yuninghong   | 100.78       | 22.03                | 115,894          |
| JSRB                 | Zimenda      | 97.22        | 33.03                | 137,704          |
|                      | Batang       | 99.02        | 29.83                | 187,873          |
|                      | Shigu        | 99.93        | 26.9                 | 214,184          |

Table 1 Observed runoff data from nine hydrological stations
2.3.3 B2015 Method

Brutsaert (2015) generalized CR to a fourth-order polynomial function. Considering the relationship with the non-AA approach, the new polynomial function is regarded as the generalized nonlinear advection-aridity method (B2015) and has the same variables as the non-AA function (Crago et al. 2016; Ma and Szilagyi 2019):

\[
ET_{a}^{B2015} = \left( \frac{ET_w}{ET_p} \right)^2 \left[ (2-c)ET_p - (1-2c)ET_w - c\frac{ET^2_w}{ET_p} \right]
\]

(7)

where \( c \) is considered to be zero under typical situations (Brutsaert 2015). Thus, a fixed \( c=0 \) and calibrated parameter \( \alpha \) of B2015 have been adopted for daily (Hu et al. 2018; Zhang et al. 2017), annual, and multi-year scales (Liu et al. 2016a, b). The Eq. (8) could be represented as:

\[
ET_a = \left( \frac{ET_w}{ET_p} \right)^2 (2ET_p - ET_w)
\]

(8)

2.3.4 H2018 Method

Han and Tian (2018) developed a sigmoid generalized complementary function (H2018) as follows:

\[
\frac{ET_{H2018}}{EPen} = \frac{1}{1 + m\left(\frac{x_{\text{max}} - x}{x_{\text{max}} - x_{\text{min}}}\right)^n}
\]

(9)

where \( x_{\text{min}} \) and \( x_{\text{max}} \) correspond to the minimum and maximum values of \( ET_{\text{rad}}/ET_p \). \( x \) is defined as the ratio of \( ET_{\text{rad}} \) to \( ET_p \), and \( m \) and \( n \) are constants. The H2018 exhibits a three-stage pattern, and \( ET_a/ET_p \) increases approximately linearly with \( ET_{\text{rad}}/ET_p \) 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 \( ET_a/ET_p = 0.5 \) equal to the linear AA function, parameters \( m \) and \( n \) can be transferred from \( \alpha \) and \( b^{-1} \):

\[
\begin{align*}
\left\{ \begin{array}{l}
n = \frac{4a(1+b^{-1})(x_{0.5} - x_{\text{min}})(x_{\text{max}} - x_{0.5})}{(x_{0.5} - x_{\text{min}})^2} \\
m = \frac{(x_{\text{max}} - x_{\text{min}})}{x_{0.5} - x_{\text{min}}} \end{array} \right.
\end{align*}
\]

(10)

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

The performance of the monthly ET datasets was evaluated using WB_ET. The evaluation criteria included the relative error (RE), Pearson correlation coefficient (cc), root mean square error (RMSE), and Nash–Sutcliffe efficiency (NSE).

\[
RE = \frac{x(i) - y(i)}{y(i)} \times 100
\]  

\[
cc = \frac{\sum_{i=1}^{n} [x(i) - \bar{x}] [y(i) - \bar{y}]}{\sqrt{\sum_{i=1}^{n} [x(i) - \bar{x}]^2} \sqrt{\sum_{i=1}^{n} [y(i) - \bar{y}]^2}}
\]  

\[
RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (x(i) - y(i))^2}
\]  

\[
NSE = 1 - \frac{\sum_{i=1}^{n} [x(i) - y(i)]^2}{\sum_{i=1}^{n} [y(i) - \bar{y}]^2}
\]

where \(x(i)\) and \(y(i)\) are the model and observed variables at \(i\)-time step, respectively, \(\bar{x}\) and \(\bar{y}\) are the model and observed mean, respectively, \(n\) is the total number of observation.

2.5 Influence of Meteorological Factors on \(ET_a\)

Meteorological factors with strong physical correlations with \(ET_a\) were selected for analysis, including precipitation, air temperature, relative humidity, wind speed, and hours of sunshine (Li et al. 2014a, b; Valipour 2015). The correlation and sensitivity coefficients were chosen as the indicators. The sensitivity coefficient (McCuen 1974) of the meteorological factors for \(ET_a\) can be expressed as follows:

\[
S_{V_i} = \frac{\Delta ET \cdot V_i}{\Delta V_i \cdot ET}
\]

where \(ET\) and \(\Delta ET\) are the daily \(ET_a\) and daily variation, respectively, and \(V_i\) and \(\Delta V_i\) 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.

3 Results

3.1 Performance of Three Developed CR Methods in Simulating Monthly \(ET_a\)

The ranges of \(\alpha\) and \(b^{-1}\) for the non-AA method were [0.89, 1.14] and [0.16, 0.77], respectively. The range of parameter \(\alpha\) of the B2015 was [0.94, 1.13], with an average
value of 1.03. For the H2018, the range of parameter $\alpha$ was [1.01, 1.14], with an average value of 1.05, and the range of parameter $b^{-1}$ was [0.18, 1.08].

The performances of the three developed CR methods in simulating monthly $\text{ET}_a$ in the three parallel river basins were compared (Table 2). The RE between the monthly $\text{ET}_a$ simulated by the non-AA, B2015, and H2018 methods and WB$_{\text{ET}}$ was 3.8%, 2.3%, and 2.4%, respectively. The NSE values were 0.74, 0.78, and 0.79, respectively. The R-square values were 0.84, 0.89, and 0.90, respectively, and the RMSE values were 10.76 mm mon$^{-1}$, 10.01 mm mon$^{-1}$, and 9.78 mm mon$^{-1}$, respectively. Overall, H2018 performed better than the B2015 and non-AA methods. In general, the developed CR methods could simulate $\text{ET}_a$ with high accuracy during the wet season. The $\text{ET}_a$ in the dry season was less than or equal to zero, resulting in a large discrepancy between the actual situation and the model calculation. The $\text{ET}_a$ in the wet season contributed 70–90% of the annual total, with
The frequency distributions of RE for the non-AA, B2015, and H2018 methods in simulating ETa are shown in Fig. 2. In general, the RE frequencies of the developed CR methods exhibit a normal distribution. For the H2018 method, more than 95.2% of the errors were between −25% and 25%. The error frequency between −5% and 5% was the highest, with a value of 30.1%. The frequency distribution of the wet season was consistent with that of the annual series. An 85.7% margin of error was between −25% and 25%. The error frequency was the highest between −5% and 5%, with a value of 30.6%. For dry season ETa, more than 52.4% of the errors were between −15% and 20%, the highest between 5 and 10%, with a value of 9.5%. The frequency distribution of RE for the three CR models was slightly higher during the dry season. More than 90% of the errors were between −25% and 25%, and the error frequency was the highest between −5% and 5%, with a value of 33.3%.

3.2 Trends of ETa, Precipitation, and Runoff in the Three Parallel River Basins

The spatial pattern of the annual WB_ET in the three parallel river basins increased spatially from the upstream region (143 mm/a) to the downstream region (707 mm/a) at the catchment scale (Fig. 3). The wet season ET accounts for 70–90% of the annual ET.

The spatial trend of CR_ET showed a notably lower value at the northern site and a higher value at the southern site at the three temporal scales, which was similar to the findings for WB_ET. The simulation results of the H2018 model show that the ETa was the lowest in the upstream region of the JSRB, with a multi-year average ETa of 205 mm/a, and the highest value in the downstream region of the LCRB, with an ETa of 1385 mm/a.
WB_ET exhibited an increasing trend during the years 1960–2018 in the NRB, LCRB, and JSRB, with the magnitude being 1.41 mm/a, 0.60 mm/a, and 1.37 mm/a, respectively. It showed a decreasing trend in the upstream region and a significant increasing trend (significance level of 0.05, the same below) in the downstream region. Trends in ET\textsubscript{a} in the dry and wet seasons (not shown) were similar to those at the annual scale. The dry season ET\textsubscript{a} decreased significantly in LCU and JSU, whereas the wet season ET\textsubscript{a} decreased significantly in NU (Fig. 4).

The CR_ET trends at the site scale were generally consistent with those derived by WB_ET at the catchment scale (Fig. 5). ET exhibited an increasing trend in the NRB, LCRB, and JSRB, with the magnitude being 1.53 mm/a, 0.66 mm/a, and 1.47 mm/a, respectively. A decreasing trend was observed in the upstream region. An increasing trend in the annual CR_ET was observed in half of the sites (17/35), which were concentrated in the downstream region. The trends of the dry season and wet season CR_ET (not shown) were consistent with those of the annual CR_ET series. The trend type for CR_ET showed a non-significant decrease (14/35), followed by a non-significant increase (11/35). The dry- and wet-season ET series were consistent with the annual ET series.

**Fig. 3** a Annual, b dry season, and c wet season evapotranspiration in the three parallel river region basins

**Fig. 4** Variation trend of ET\textsubscript{a} of a interannual, b dry season, and c wet season in the three parallel river region basins. * represents significance level of 0.05, and ** represents significance level of 0.01
Table 3 shows the trends of precipitation and runoff in the three parallel river basins. In terms of precipitation, the increasing magnitude of the precipitation at three temporal scales was 3.2 mm/a, 1.1 mm/a, and 2.6 mm/a, respectively. Runoff also exhibited increasing trends with the magnitude being 2.2 mm/a, 1.2 mm/a, and 1.4 mm/a, respectively.
Therefore, the difference between the precipitation variable and the runoff variable on the three temporal scales was 1.0 mm/a, –0.1 mm/a, and 1.2 mm/a, respectively. Moreover, upon synthesizing the inter-annual growth trend of \( \text{ET}_a \) (1.4 mm/a), it could be inferred that the difference between the precipitation and runoff variables (1.0 mm/a) contributed 71.4% of the \( \text{ET}_a \) change.

In addition, the average increasing magnitudes of precipitation in the NRB, LCRB, and JSRB were 4.0 mm/a, 3.6 mm/a, and 2.1 mm/a, respectively, and those of runoff were 3.0 mm/a, 2.2 mm/a, and 1.4 mm/a, respectively. The difference between them was 1.0 mm/a, 1.4 mm/a, and 0.7 mm/a, respectively. Based on the \( \text{ET}_a \) in the NRB (1.41 mm/a), LCRB (1.60 mm/a), and JSRB (1.17 mm/a) in the analysis of the long-term variation trend of the \( \text{ET}_a \) in the basin, the ratios of the interannual precipitation and runoff variables to the \( \text{ET}_a \) variables were 0.73, 0.89, and 0.57, respectively. Therefore, according to the theoretical equation of hydrological balance, the precipitation, runoff, and \( \text{ET}_a \) in the NRB and LCRB can meet the water closure condition on a long-term scale.

### 3.3 Influence of Meteorological Factors on \( \text{ET}_a \)

Precipitation, temperature, and humidity increased from south to north in three parallel river basins (Fig. 6). By contrast, the wind speed decreased. The hours of sunshine, among all the regions, were the shortest in the mid-stream region, and this difference was especially significant during the wet season. The precipitation at most stations (25/34) showed an increasing trend, with an average increase in magnitude of 2.4 mm/a. The air temperature exhibited significant increasing trends on all temporal scales (dry and wet seasons, and annual series). In contrast, the wind speed showed a significant decreasing trend. The variation characteristics of the relative humidity also showed high consistency among the three temporal scales. In addition, the precipitation, air temperature, relative humidity, and hours of sunshine in the basin were relatively higher during the wet season, whereas the wind speed was higher in the dry season.

| Table 3  | Trends of precipitation and runoff in the NRB and LCRB during 1956–2018 |
|----------|-----------------------------------------------------------------------|
| Basin    | Precipitation (mm)                                                   | Runoff (mm) |
|          | Annual | Dry | Wet | Annual | Dry | Wet |
| NRB      | NU     | 2.2 | 0.7 | 1.5    | 3.5  | 2.2  | 2.7  |
|          | NM     | 2.9 | 0.7 | 2.8    | 3.2  | 1.1  | 2.6  |
|          | ND     | 6.9 | 2.8 | 5.3    | 2.2  | 1.6  | 0.9  |
|          | Mean   | 4.0 | 1.4 | 3.2    | 3.0  | 1.6  | 2.1  |
| LCRB     | LCU    | 1.5 | 0.5 | 1.2    | 1.8  | 1.0  | 1.4  |
|          | LCM    | 4.0 | 1.2 | 2.9    | 1.5  | 0.4  | 1.2  |
|          | LCD    | 5.3 | 2.3 | 4.5    | 3.2  | 1.2  | 2.1  |
|          | Mean   | 3.6 | 1.3 | 2.9    | 2.2  | 0.9  | 1.6  |
| JSRB     | JSU    | 1.0 | 0.3 | 0.8    | 1.6  | 1.3  | 0.7  |
|          | JSM    | 2.2 | 0.9 | 1.5    | 1.5  | 1.1  | 0.9  |
|          | JSD    | 3.1 | 1.3 | 2.1    | 1.2  | 1.2  | 0.8  |
|          | Mean   | 2.1 | 0.8 | 1.5    | 1.4  | 1.2  | 0.8  |
The correlation coefficients (cc) between the meteorological factors and ET\textsubscript{a} in the three parallel river basins are shown in Figs. 7 and 8. There was a positive correlation between ET\textsubscript{a} and precipitation, temperature, wind, and hours of sunshine, with average cc values of 0.40, 0.64, 0.63, and 0.72, respectively. A negative correlation was observed between ET\textsubscript{a} and relative humidity, with the average cc of –0.38. The cc values for each meteorological factor in the different basins were slightly different. Among them, the temperature and wind speed in the NRB had the strongest correlation with the ET\textsubscript{a}, and the average cc values were 0.66 and 0.65, respectively. The average cc of precipitation, temperature, wind speed, and hours of sunshine in the LCRB and ET\textsubscript{a} were higher than 0.60, of which precipitation had the strongest correlation, with an average cc of 0.66. Hours of sunshine in the JSRB had the highest correlation with ET\textsubscript{a}, with an average cc being as high as 0.72.

In addition, the correlation between each meteorological factor and ET\textsubscript{a} varied seasonally to a certain extent. The average cc between the dry season precipitation and ET\textsubscript{a} was 0.45, which was 0.18 lower than the average cc in the wet season. In contrast, the correlation between wind speed and ET\textsubscript{a} was relatively high during the dry season. The average cc of each basin was 0.74, which was 0.19 higher than the average value of the cc in the wet season.

The sensitivity coefficients of the meteorological factors to ET\textsubscript{a} are shown in Table 4. The ET\textsubscript{a} in the basins was highly sensitive to temperature, wind speed, and hours of sunshine, as well as moderately sensitive to relative humidity. Among them, the NRB had the highest sensitivity coefficient of hours of sunshine, with an average sensitivity coefficient of 0.32, whereas the ET\textsubscript{a} in the LCRB was more sensitive to temperature changes, with a sensitivity coefficient of 0.29. The temperature, relative humidity, wind speed, and hours of sunshine in the JSRB showed strong sensitivity, and the absolute average sensitivity coefficient fluctuated around 0.25. Moreover, ET\textsubscript{a} was more sensitive to relative humidity and wind speed in the upstream region. The average values of the sensitivity coefficients of relative humidity and wind speed in the upstream region were –0.23 and 0.26, respectively.

The sensitivity coefficients between the ET\textsubscript{a} and meteorological factors showed seasonal differences. The differences between the dry season and wet season sensitivity coefficients for ET\textsubscript{a} and air temperature, relative humidity, and hours of sunshine ranged from 0.03 to 0.06. Among them, the difference between the wind speed in the dry and wet seasons was the most significant in each basin, with an average sensitivity coefficient of 0.24 in the dry season and 0.18 in the wet season. In addition, the sensitivity of temperature and hours of sunshine in wet season was higher than that in dry season, with the average values of 0.29 and 0.25, respectively.

4 Discussion

The parameter α is related to the natural characteristics. Studies revealed that the parameter α in the Priestly-Taylor formula had a wider range of value with roughly 0.6–1.5 (De Bruin 1983), which represented the combined effects of the land–atmosphere coupling relationship and underlying vegetation, soil, and water conditions on the CR of ET\textsubscript{a}. In this study, the value of the parameter α was negatively correlated with the regional aridity index (AI = ET/P), which was consistent with results presented by Liu et al. (2016a, b).
Gao et al. (2018) and Zhou et al. (2020) estimated the ET$_a$ distribution in the upstream region of the Huaihe River Basin and Loess Plateau based on B2015 and H2018. Their results showed that the simulation accuracy of H2018 was higher than that of B2015, and the results were consistent with those of the LCRB and NRB. Gao et al. (2018) indicated that when $\alpha = 1.25$, the RE 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 $\alpha$ values of the basins in this study were relatively low. It is possible that the LCRB and NRB have a higher aridity index, which is related to the local climatic conditions and vegetation coverage. The CR methods developed after parameter adjustment provide more references and possibilities for the study of regional ET$_a$.

ET$_a$ is directly sourced from soil water and open water and indirectly from water supplied by vegetation (Balugani et al. 2016). Precipitation affects ET$_a$ through soil moisture constraints, particularly in arid regions. For example, with high precipitation, ET$_a$ is less limited to soil moisture, and ET$_a$ might be the same as ET$_p$ (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 the available soil water. The arid environment places a strong constraint on ET$_a$, causing it to be much lower than ET$_p$. High temperatures accelerate the ET$_a$ by providing more energy. Longer hours of sunshine indicate that more solar radiation energy is provided. Therefore, ET$_a$ is sensitive to both temperature and sunlight (Li et al. 2017). Wind speed, another meteorological factor positively related to ET$_a$, is responsible for transporting water heat and carbon dioxide. In some cases, wind dominates the radiation (Liu and Zhang 2013). With an increase in humidity, the moisture content in the air is higher, and the moisture evaporated into the air decreases (Moratiel et al. 2010). As demonstrated in this study, meteorological factors had different effects on ET$_a$. The quantitative relationship between regional ET$_a$ and climate and the soil–plant-atmosphere continuum should be considered in the future.

Many interpolation methods can be used to calculate precipitation in a study area with complex topography. These interpolation methods are helpful in investigating the spatial distribution characteristics of precipitation. However, the interpolation results may vary significantly with different methods. In other words, it is difficult to ensure the accuracy of the interpolation results for the study area. There are 35 meteorological observation stations covering the present study area of $5.4 \times 10^5$ km$^2$. In this study, the area weight was calculated using the Tyson polygon method. The advantage of this method is that it can make full use of the precipitation characteristics of the adjacent areas represented by each station. The effects of topographic factors on precipitation were not considered in this study. This would have introduced some uncertainties in the areal precipitation results. Actual evapotranspiration can be further studied for more climatic types and topographical features using the interpolation method of McVicar et al. (2007) and Thomas (2008), which might reduce uncertainties.

The ET$_a$ sequence at the basin and site scales can be reasonably simulated using hydrological budget balance and developed CR models. Long-term ET$_a$ series can be established based on hydrometeorological data, especially for remote areas and insufficient observational data. There is a need to conduct research on watersheds with different climate types and topographic features, optimize the developed CR models, and analyze the uncertainties and methods for improvement. This is of great significance for the ecological protection, management planning, and development, as well as utilization, of water resources in the basin.
Fig. 7 Correlation coefficients between meteorological factors and ET$_a$

Fig. 8 Correlation coefficients between meteorological factors and ET$_a$ at the basin scale

Table 4 Sensitivity coefficients of meteorological factors on ET$_a$

| Basin | NRB | LCRB | JSRB |
|-------|-----|------|------|
|       | NU  | NM   | ND   | LCU | LCM | LCD | JSU | JSM | JSD |
| Temperature (°C) | Annual | 0.14 | 0.26 | 0.25 | 0.29 | 0.33 | 0.26 | 0.26 | 0.23 | 0.33 |
| Dry | 0.04 | 0.18 | 0.23 | 0.25 | 0.26 | 0.28 | 0.22 | 0.18 | 0.27 |
| Wet | 0.24 | 0.34 | 0.27 | 0.33 | 0.40 | 0.24 | 0.30 | 0.28 | 0.29 |
| Mean | 0.14 | 0.26 | 0.25 | 0.29 | 0.33 | 0.26 | 0.26 | 0.23 | 0.30 |
| Relative humidity (%) | Annual | −0.23 | −0.14 | −0.11 | −0.18 | −0.15 | −0.19 | −0.27 | −0.20 | −0.18 |
| Dry | −0.25 | −0.13 | −0.16 | −0.23 | −0.18 | −0.22 | −0.24 | −0.28 | −0.14 |
| Wet | −0.21 | −0.15 | −0.06 | −0.13 | −0.12 | −0.16 | −0.30 | −0.12 | −0.22 |
| Mean | −0.23 | −0.14 | −0.11 | −0.18 | −0.15 | −0.19 | −0.27 | −0.20 | −0.18 |
| Wind speed (m/s) | Annual | 0.21 | 0.18 | 0.14 | 0.18 | 0.14 | 0.17 | 0.39 | 0.35 | 0.14 |
| Dry | 0.24 | 0.24 | 0.19 | 0.27 | 0.24 | 0.22 | 0.30 | 0.29 | 0.18 |
| Wet | 0.18 | 0.12 | 0.09 | 0.09 | 0.09 | 0.12 | 0.48 | 0.41 | 0.10 |
| Mean | 0.21 | 0.18 | 0.14 | 0.18 | 0.14 | 0.17 | 0.39 | 0.35 | 0.14 |
| Sunshine hours (h) | Annual | 0.30 | 0.34 | 0.32 | 0.26 | 0.28 | 0.14 | 0.31 | 0.24 | 0.20 |
| Dry | 0.35 | 0.30 | 0.26 | 0.31 | 0.26 | 0.18 | 0.29 | 0.27 | 0.28 |
| Wet | 0.25 | 0.38 | 0.38 | 0.21 | 0.30 | 0.10 | 0.33 | 0.21 | 0.12 |
| Mean | 0.30 | 0.34 | 0.32 | 0.26 | 0.28 | 0.14 | 0.31 | 0.24 | 0.20 |
5 Conclusions

The monthly $ET_a$ in the three parallel river basins was simulated using the hydrological budget balance method, based on observed hydrological and meteorological data from years 1956–2018. Three generalized complementary methods, namely, non-AA, B2015, and H2018, were evaluated using monthly water balance-derived values. The impacts of major meteorological factors on $ET_a$ were also assessed. The conclusions are as follows:

1. All three developed CR methods were able to accurately simulate the monthly $ET_a$ series. The relative errors of the monthly $ET_a$ series simulated by the three models were fitted to a normal distribution, and the peaks were concentrated in −5%–5%. The NSE between the monthly $ET_a$ simulated by the non-AA, B2015, and H2018 methods and the water balance-derived values were 0.74, 0.78, and 0.79, respectively. The R-square values were 0.84, 0.89, and 0.90, respectively, and the RMSE values were 10.76 mm mon$^{-1}$, 10.01 mm mon$^{-1}$, and 9.78 mm mon$^{-1}$, respectively.

2. $ET_a$ increased spatially from the upstream region to the downstream region at the catchment scale. The $ET_a$ in the three parallel river basins simulated by the non-AA, B2015, and H2018 models showed an upward trend on all temporal scales (dry and wet seasons, and annual series), with increasing magnitudes of 1.53 mm/a, 1.66 mm/a, and 1.47 mm/a, respectively. Precipitation, runoff, and $ET_a$ in the basin met the water closure conditions on a long-term scale.

3. There was a positive correlation between $ET_a$ and precipitation, temperature, wind, and hours of sunshine, with average cc values of 0.40, 0.64, 0.63, and 0.72, respectively. There was a negative correlation between $ET_a$ and relative humidity throughout the basin, with an average cc of −0.38. $ET_a$ in the basins was highly sensitive to temperature, wind speed, and hours of sunshine, with average sensitivity coefficients of 0.26, 0.21, and 0.27, respectively. Moreover, it was moderately sensitive to relative humidity, with a sensitivity coefficient of −0.18.

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Author Contribution All the authors contributed to the conception and design of the study. The first draft of the manuscript was written by Yongshan Jiang, and all the authors commented on the previous versions of the manuscript. All authors have read and approved the final manuscript.

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Availability of Data and Materials The data and materials used in this study will be made available upon request.

Declarations

Ethics Approval Not applicable.

Consent to Participate Not applicable.
Consent to Publish  Written informed consent for publication was obtained from all participants.

Competing Interests  We declare that we do not have any commercial or associative interests that represent a conflict of interest in connection with the submitted work.

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