Evaluation of Evapotranspiration Partitioning Methods for Water Accounting: A Case of the Heihe River Basin in the Arid-semi-arid Region

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1. Introduction

The enormous pressures on water resources and the uncertainty of future water availability will result in complex management and planning decisions. Therefore, it is important to collect high-quality information within a standard framework in water resources planning and management. To achieve this goal, the concept of water accounting has been introduced in water resources management. Water accounting is an important process to enhance water management and support sustainable water use, which involves all components of the natural water cycle and is closely related to human activities on the water cycle. To help people understand the complex interactions between human activities and the water cycle. The blue-green water concept are introduced in the water accounting, which can expand the scope of traditional water resources and provide a more comprehensive and realistic understanding of water resources. According to the difference of water sources, the actual evapotranspiration (ET) could be partitioned into green water ET (GWET, from green water) and blue water ET (BWET, from blue water), which are key parameters in water accounting. However, current ET remote sensing products generally only provide total ET and lack GWET and BWET information, which limits their application in water accounting. In recent years, there have been various methods proposed for partitioning ET into GWET and BWET. These methods typically rely on different sets of data and assumptions, and can lead to different estimates of blue and green water contributions. Therefore, it becomes particularly important to systematically evaluate and compare the differences between the different methods. The objective of this study on the Heihe River Basin is to compare and evaluate different methods to partition total actual ET into GWET and BWET.

2. Method

2.1 Precipitation deficit method

The precipitation deficit method estimates GWET and BWET as the differences between spatially distributed monthly effective precipitation (P_e) and actual ET (ET_a). when ET_a minus P_e is negative, the GWET is equal to the ET_a and the BWET is zero. it means that P_e will meet ET_a. Conversely, when ET_a minus P_e is positive, GWET is P_e and BWET equals ET_a minus P_e:

$$GWET = ET_a,\ BWET = 0 \qquad \text{if } ET_a - P_e <= 0 \tag{1}$$

$$GWET = P_e,\ BWET = ET_a - P_e \qquad \text{if } ET_a - P_e > 0 \tag{2}$$

2.2 Budyko model

The Budyko hypothesis (BH) proposed that long-term average annual evapotranspiration from a catchment is governed by precipitation and available energy. This study applies the extended Budyko framework derived by Zhang et al (2008) (Eq. 3):

$$\frac{Y_t}{W_t} = 1 + \frac{Y_{0,t}}{W_t} - \left[1 + \left(\frac{Y_{0,t}}{W_t}\right)^{\beta}\right]^{\frac{1}{\beta}} \tag{3}$$

where Y_t is evapotranspiration opportunity, mm/month. The demand limit for Y_t can be considered as the sum of potential evapotranspiration ($E_{0,t}$,mm/month) and soil water storage capacity (SM_{max}) and is denoted as $Y_{0,t}$, mm/month. β is a model parameter, representing evapotranspiration efficiency. W_t is available water, mm/month. The specific calculation is as follows:

$$W_t = X_t + SM_{t-1} \tag{4}$$

$$Y_{0,t} = ET_{0,t} + SM_{max} \tag{5}$$

$$SM_{max} = \theta_{sat} * R_d \tag{6}$$

$$\beta = \frac{ET_{a,t}}{ET_{0,t}} \tag{7}$$

where X_t is called catchment rainfall retention (mm/month) and is the amount of rainfall retained by the catchment for ET_a, change in soil-moisture storage SM_t - SM_{t-1} and recharge R_t (Eq. 8). SM_{t-1} is soil moisture in time step t-1, mm/month. θ_{sat} is saturated soil moisture content ($cm^3\ cm^{-3}$). R_d is root depth, mm. The catchment rainfall retention X_t can be calculated as:

$$\frac{X_t}{P_t} = 1 + \frac{X_{0,t}}{P_t} - \left[1 + \left(\frac{X_{0,t}}{P_t}\right)^{\omega}\right]^{\frac{1}{\omega}} \tag{8}$$

$$X_{0,t} = ET_{0,t} + SM_{max} - SM_{t-1} \tag{9}$$

where $X_{0,t}$ is the demand limit for X_t, which is the sum of available storage capacity ($SM_{max} – SM_{t-1}$) and potential evapotranspiration ($E_{0,t}$). P_t is precipitation, mm/month. ω is a model parameter with range (1,∞) that describes the shape of the Budyko curve, which shows the integrated catchment characteristic. the X_t (the amount of rainfall is retained by the catchment) is far from enough to meet the crop water demand for irrigation agriculture, so the X_t is consumed by crop ET. Hence, according to the concept of GWET and X_t (the amount of rainfall retained by the catchment), the X_t is actually equal to the GWET for irrigation agriculture (Eq.10). For other land use types, since the X_t has not been completely consumed by ET, it needs to further partition the BWET and GWET by calculating Y_t according to the extended Budyko framework (Eq.3). By combining ET_a from satellite-derived data, BWET and GWET can be partitioned by Eq.11 and Eq.12:

For irrigation agriculture:

$$GWET_t = X_t,\ BWET_t = ET_{a,t} - X_t \tag{10}$$

For other land cover/use:

$$GWET_t = ET_t,\ BWET_t = 0 \qquad if\ \ Y_t - ET_{a,t} \geq 0 \tag{11}$$

$$GWET_t = Y_t,\ BWET_t = ET_{a,t} - Y_t \qquad if\ \ Y_t - ET_{a,t} < 0 \tag{12}$$

2.3 Soil water balance model

The soil water balance model is a pixel-based monthly water balance model. According to monthly water balance equation, the soil moisture available for ET ($SM_{green,t}$. mm/month) can be estimated indirectly (Eq.13):

$$SM_{green,t} = SM_{t-1} + P_t - I_t - Q_{green,t} - Q_{prec,\,reen,t} \tag{13}$$

where SM_{t-1} is the soil moisture storage at the end of the previous timestep, mm/month. P_t is actual precipitation, mm/month. I_t is interception of precipitation, mm/month. $Q_{rain,t}$ is surface runoff, mm/month. $Q_{prec,green,t}$ is percolation, mm/month. The surface runoff ($Q_{green,t}$) is calculated using an adjusted version of the Soil Conservation Service runoff method. Then $Q_{prec,green,t}$ is calculated as exponential function of the soil moisture:

$$Q_{perc,\,green,t} = SM_{t-1} \times e^{-\frac{fperc}{SM_{t-1}}} \tag{14}$$

To partition ET into the GWET and BWET, ET_a from satellite-derived data is subtracted driven by satellite data with $SM_{green,t}$ (Eq.13). when $SM_{green,t}$ is sufficient for ET_a, the GWET is equal to ET_a. When $SM_{green,t}$ is insufficient for ET_a, it means that ET_a is replenished by surface water or groundwater. The GWET becomes the amount of $SM_{green,t}$ (soil moisture supplied by precipitation). And BWET is the differences between ET_a and $SM_{green,t}$:

$$GWET_t = ET,\ BWET_t = 0 \qquad if\ \ SM_{green,t} > ET \tag{15}$$

$$GWET_t = SM_{green,t},\ BWET_t = ET - GWET_t \qquad if\ \ SM_{green,t} < ET \tag{16}$$

3. Results and discussions

The model needs accurate input data for partitioning ET into GWET and BWET. To assess the accuracy of precipitation (P) and ET from satellite-derived data, we compared satellite-derived data with the in situ measurements of precipitation and ET from 2012 to 2021 in the upstream, midstream, and downstream of the Heihe River Basin (**Fig. 1** and **Fig. 2**). Three different methods were adopted to partition the GWET and BWET of the vegetation ecosystem in the Heihe River Basin from 2001-2018, and the percentage of annual GWET and BWET maps are shown in **Fig. 3**. There are wide differences in the GWET and BWET among different land cover/use in the Heihe River Basin (**Fig. 4**). The annual average GWET and BWET of the three methods were calculated and showed that the GWET and BWET in the same vegetation ecosystem were significantly different, among which the agricultural (irrigated) ecosystem was the most typical (**Fig. 5**). The inter-annual fluctuation of GWET was relatively large, and BWET was relatively stable in the Heihe River Basin from 2001 to 2018. But there aren't the trend of increase or decrease significantly for GWET and BWET (**Fig. 6**).

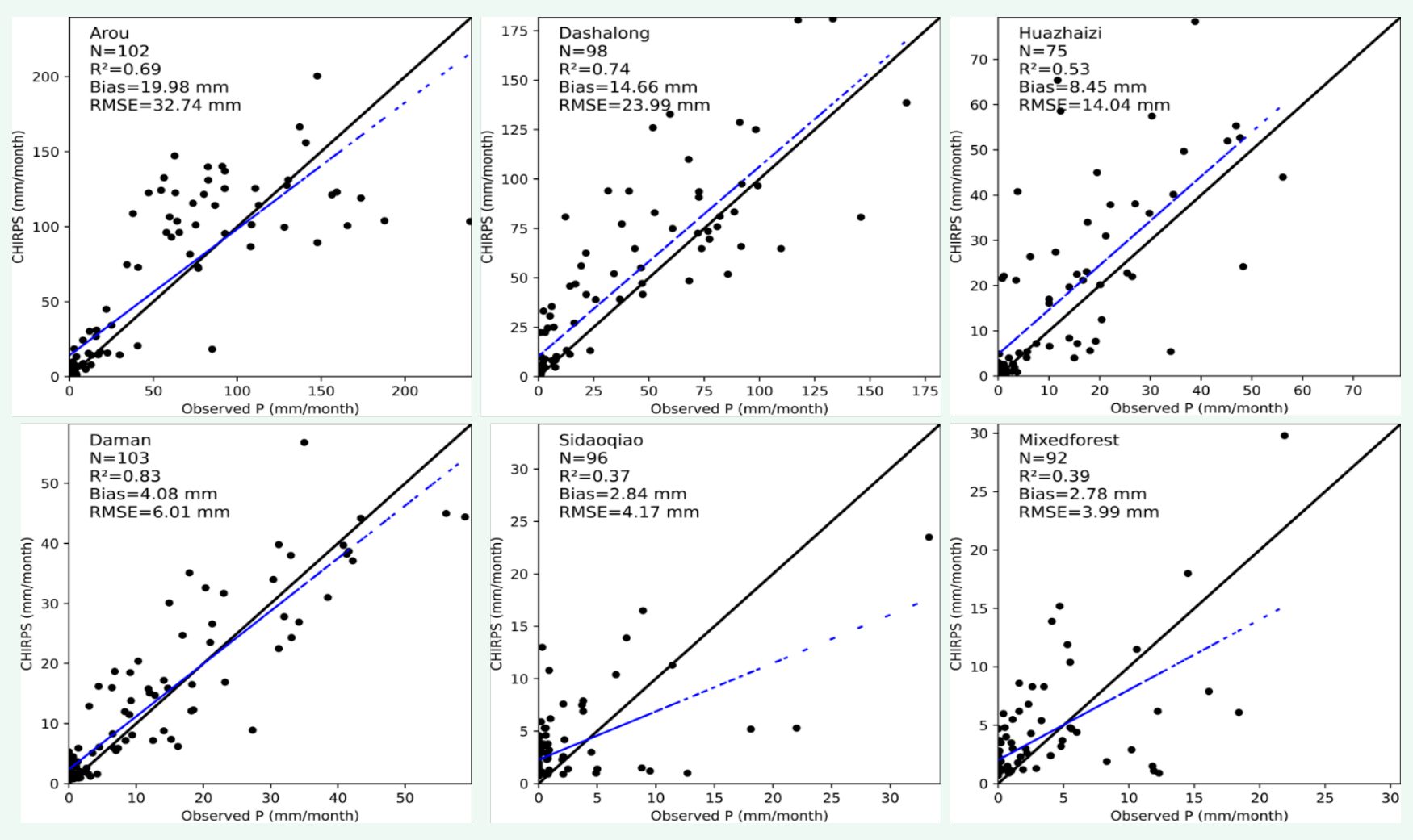

Fig.1. Validation of CHIRPS data using data collected over 2013–2021 from 6 in situ sites in the Heihe River Basin).

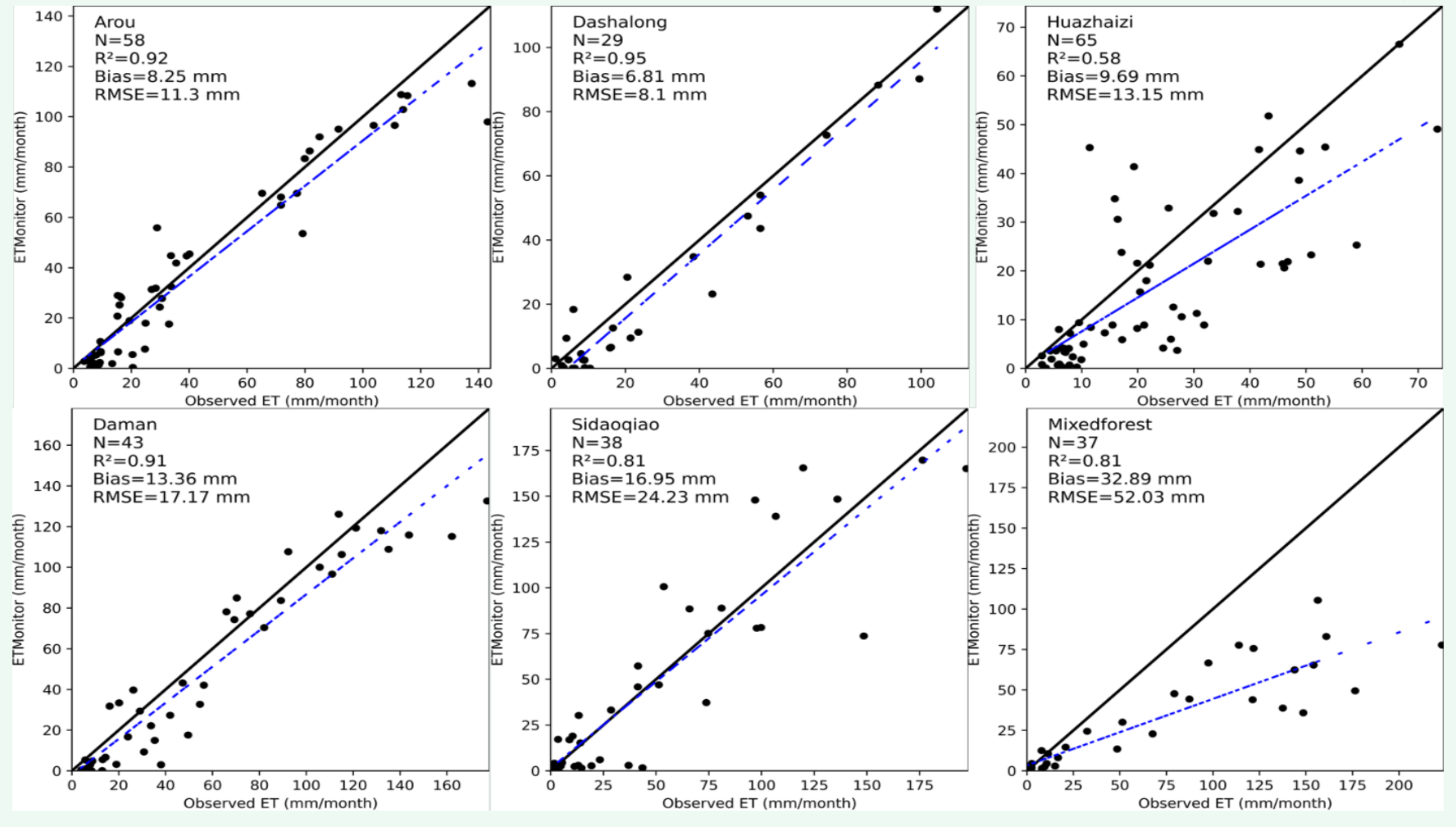

Fig.2. Validation of ETMonitor data using data collected over 2013–2021 from 6 in situ sites in the Heihe River Basin.

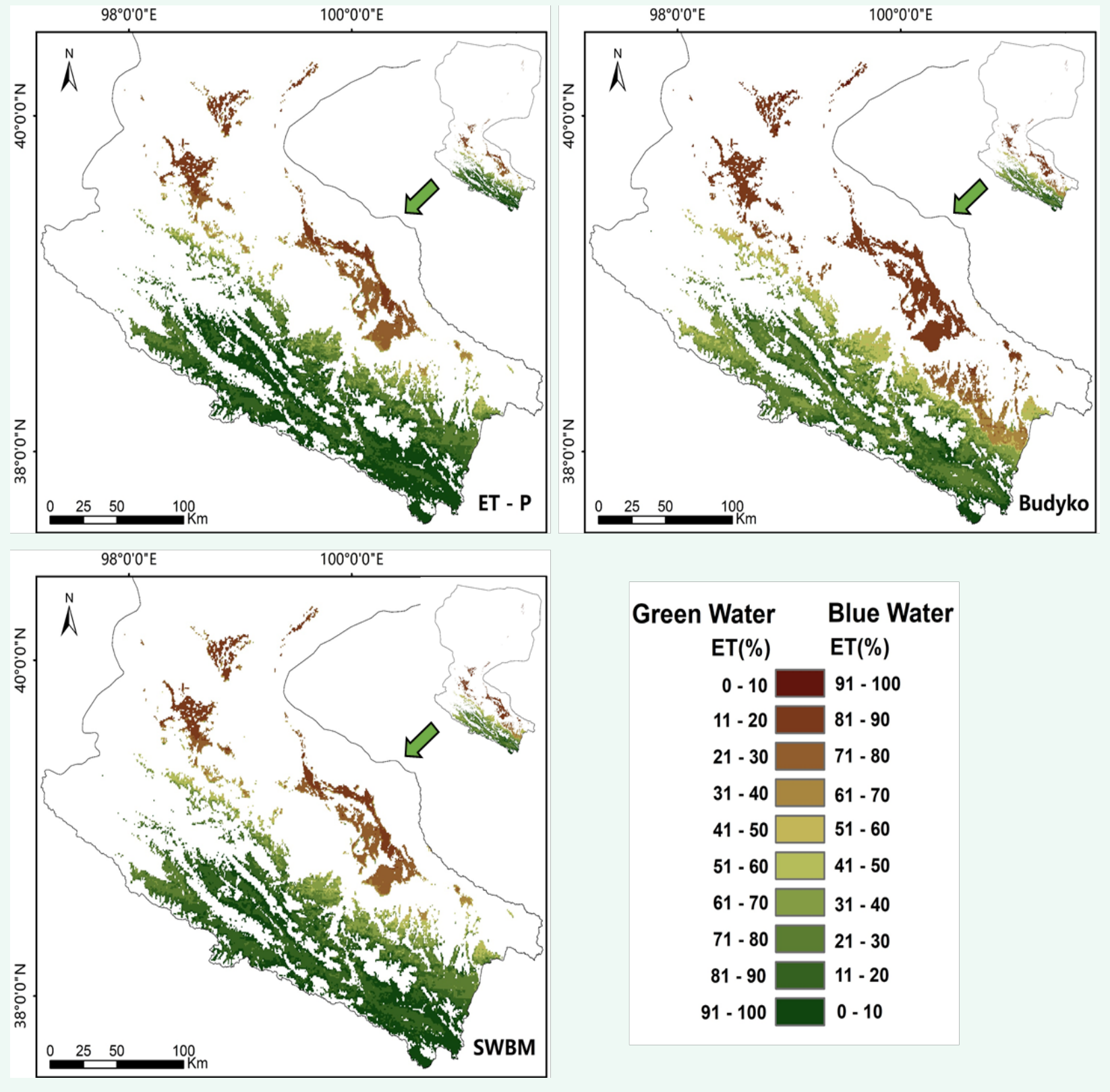

Fig.3. the percentage maps of annual ETgreen and ETblue contributions to the total ET by three methods in the Heihe River Basin from 2001 to 2018.

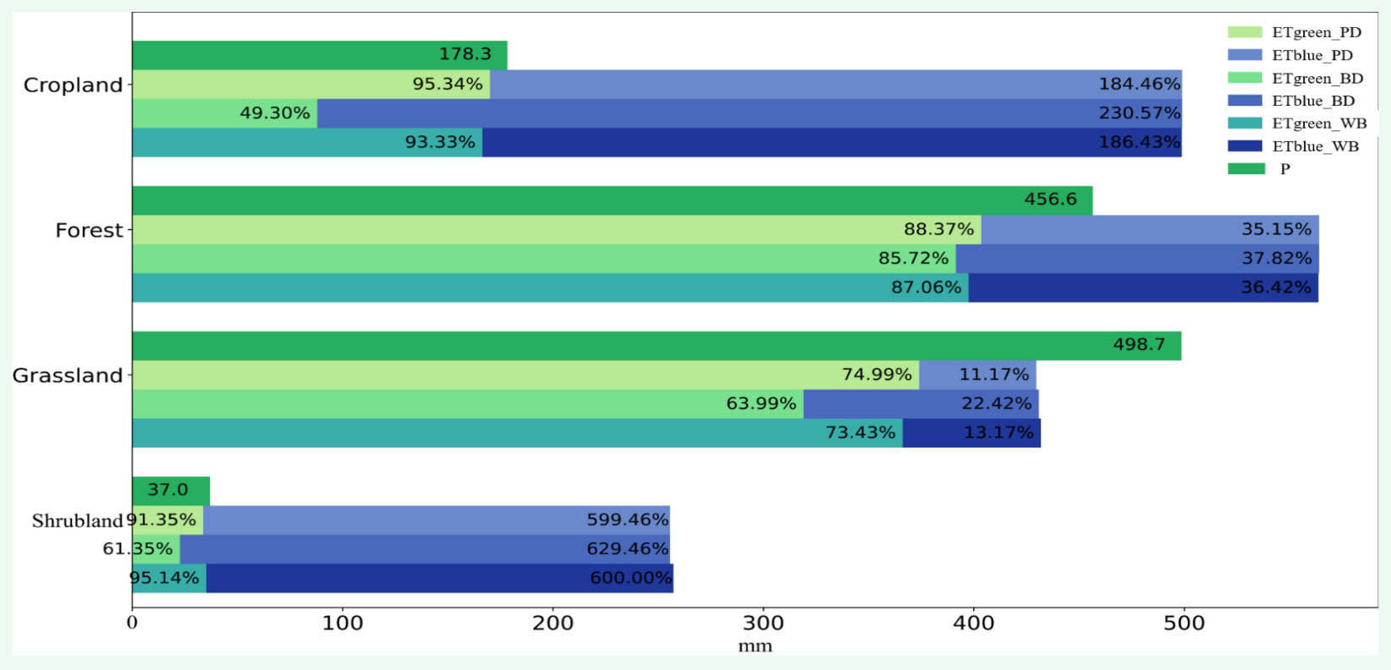

Fig.4. Sources of ET for different land cover in the Heihe River Basin from 2001-2018.

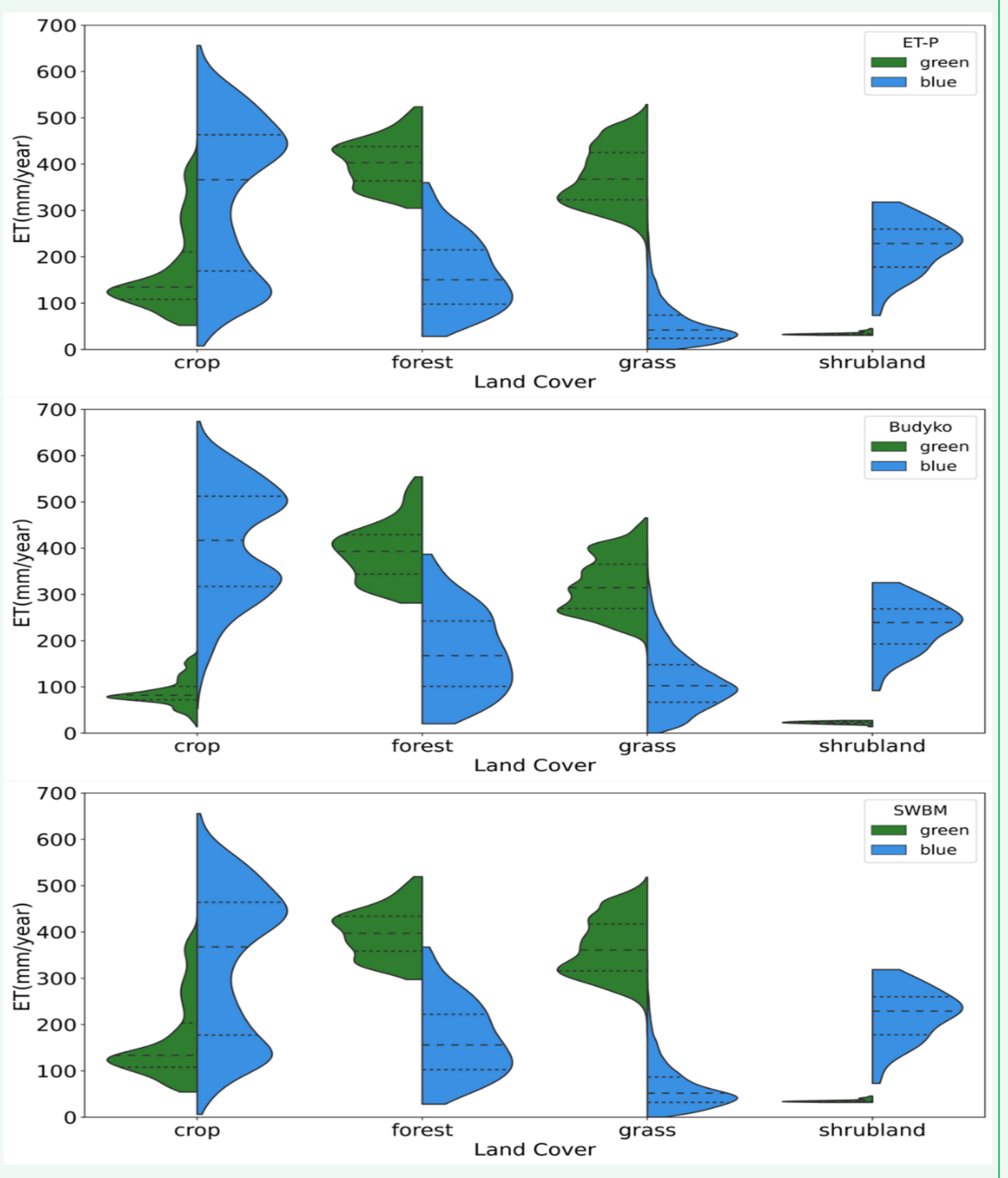

Fig.5. The performance metrics with 95% confidence intervals for SM retrievals at validation sites

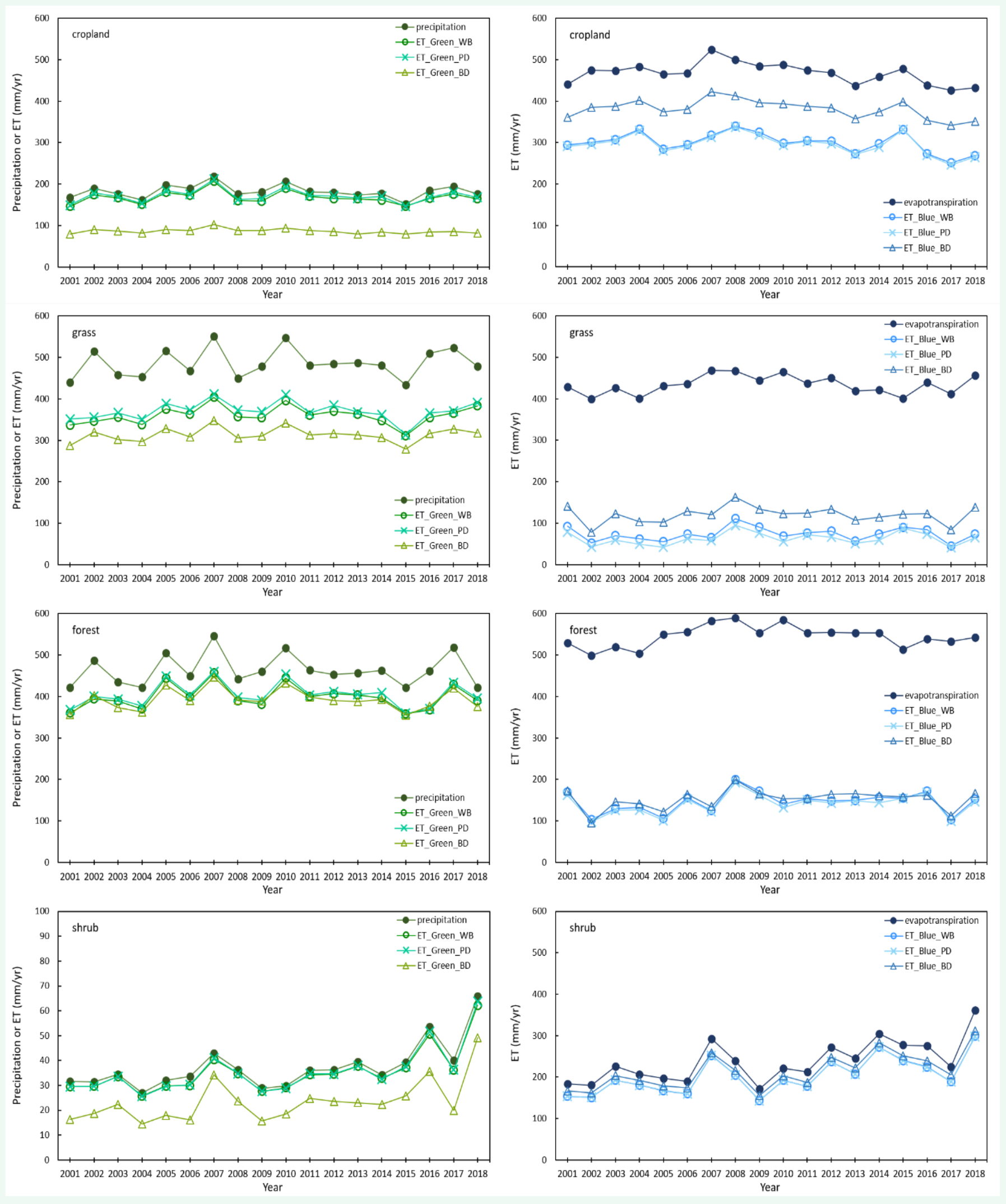

Fig.6. Figure 9. Changes of ETgreen and ETblue of land cover in the Heihe River Basin from 2001-2018.

4. outlook

In this study, we compared three methods for estimating GWET and BWET in the Heihe River Basin over the period 2001–2018. The three methods give the similar spatial distributions of GWET and BWET, but their relative contribution to total ET varies based on the method used. The PD method and the WB method show similar results, while it is different from the other two methods according to BD method. The study found that the WB method was realistic results for all ecosystems. BD method gave too low GWET for the grass and agricultural (irrigated) ecosystem. The PD method showed higher GWET in Heihe River Basin, because the PD method without considering the runoff flow when ET is greater than P. The irrigated districts in the middle reaches of the Heihe River, BWET (average 357.5 mm) was much larger than GWET (average 141.4 mm), and the average of its three method results accounted for 71.65% of the total ET. Moreover, BWET was larger than precipitation (178.3 mm), which indicats that irrigation plays an important role in maintaining agroecosystems in this region. This study can help improve the comprehensive water resources and land use management capabilities of the basin.

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