



Revisiting the White method for estimating groundwater evapotranspiration: a consideration of sunset and sunrise timings

Tian-Ye Wang^{1,2} · Ping Wang¹ · Jing-Jie Yu^{1,2} · Sergey P. Pozdniakov³ · Chao-Yang Du¹ · Yi-Chi Zhang¹

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Abstract

The well-known White method (A method of estimating ground-water supplies based on discharge by plants and evaporation from soil: Results of investigation in Escalante Valley, Utah. Washington D.C, US Geological Survey. Water Supply Paper 659-A United States Department of the Interior, 1932) based on diurnal water table observations has been widely applied to estimate groundwater evapotranspiration (ET_G) from phreatophyte vegetation. One of the limitations of this method is its large uncertainties in quantifying the daily groundwater recovery rate (r), which is assumed to be equal to the average rate of groundwater level rise between midnight (i.e., 00:00 h) and 04:00 h. Recent studies pointed out that ET_G is highly dependent on the shape and duration of the diurnal clear-sky solar radiation curve and that using the groundwater recovery rate over a short interval of nighttime hours to represent the daily r may lead to large uncertainties in ET_G estimates. In this study, we analysed the dependence of the estimated daily r on the sunset and sunrise timings. Numerical experiment results showed that the estimated r is highly sensitive to the duration between sunset and sunrise, which varies seasonally. Instead of using fixed time spans (TSs), e.g., from midnight to 04:00 h, we recommend a more universal method for determining the TS, which is associated with the sunset and/or sunrise timings and used to estimate the daily r . This dynamic TS approach was tested at a *Tamarix ramosissima*-dominated riparian site with a hyper-arid climate (precipitation of 35 mm a⁻¹) in northwestern China. Compared with the observed evapotranspiration (ET), our approach showed better performance and less subjectivity in estimating ET_G than the traditional White approach.

Keywords Groundwater recharge rate · Groundwater evapotranspiration · Water table fluctuations · Phreatophytes

White method: problem revisited

The idea of using diurnal water table monitoring data to estimate groundwater evapotranspiration (ET_G) from phreatophyte vegetation was proposed by White (1932). During a

field investigation in Escalante Valley, Utah, United States, he observed that the groundwater level began to drop at the same hour every morning and started to rise at approximately the same hour every night. Such diurnal fluctuations in groundwater level are associated with two predominant processes (Wang et al. 2014): the lateral groundwater flow recharge throughout the day and the vertical groundwater withdrawal by phreatophyte vegetation during the daytime (Meinzer 1927; White 1932). Based on the assumption that the abovementioned lateral and vertical processes are independent, White (1932) proposed an analytical solution for estimating daily ET_G [$L T^{-1}$]:

$$ET_G = S_y(24r + s), \quad (1)$$

where S_y is the specific yield (dimensionless), r is the average hourly groundwater recovery rate throughout the entire day [$L T^{-1}$] and s is the net rise or fall of the groundwater level for the same period [$L T^{-1}$].

✉ Ping Wang
wangping@igsnr.ac.cn

✉ Jing-Jie Yu
yuji@igsnr.ac.cn

¹ Key Laboratory of Water Cycle and Related Land Surface Processes, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, 11A, Datun Road, Chaoyang District, Beijing 100101, People's Republic of China

² University of Chinese Academy of Sciences, Beijing 100049, China

³ Department of Hydrogeology, Lomonosov Moscow State University, GSP-1, Leninskie Gory, Moscow 119899, Russia

Initially, White (1932) assumed that evapotranspiration (ET) by phreatophyte vegetation ceased from midnight to 04:00 h and that r was equal to the average rate of groundwater level rise between midnight and 04:00 h. Recent studies have indicated that ET_G is closely associated with the shape and duration of the clear-sky solar radiation curve (Soylu et al. 2012; Wang and Pozdniakov 2014). As the sunshine duration (i.e., the sunset and sunrise timings) generally has a seasonal change, the shape and distribution of the clear-sky solar radiation curve and the phenology of vegetation may vary synchronously (Yue et al. 2016). Therefore, using the groundwater recovery rate during a constant interval of nighttime hours from midnight to 04:00 h for representing daily r may lead to significant uncertainties in ET_G estimates (e.g., Martinet et al. 2009; Soylu et al. 2012; Wang and Pozdniakov 2014).

In practical applications, different optimal time spans (TSs) have been proposed recently to estimate the daily r in Eq. (1) (e.g., Miller et al. 2010; Zhang et al. 2016). Fahle and Dietrich (2014) suggested that using longer TSs would improve the daily r estimation and that the result could be further enhanced by including two-night averages. However, these studies still used fixed TS approaches and neglected seasonal changes in the duration between sunset and sunrise. In addition, the selection of the optimal TS is still somewhat subjective.

The objective of this study is to introduce a flexible TS approach for estimating daily r , which is associated with dynamic sunset and sunrise timings. The applicability of the proposed approach is evaluated in a synthetic example, and its performance (i.e., the estimated ET_G) is further tested at a field site through comparisons with the traditional White method and two refined methods, which have been proposed by Gribovszki et al. (2008) and Loheide (2008) (hereafter referred to as the Gribovszki method and the Loheide method, respectively).

Theoretical background

Relationship between lateral groundwater flow and vertical ET_G

The groundwater table dynamics directly reflect the storage changes in groundwater. According to Wang et al. (2014), the relationship between groundwater table dynamics and predominant recharge/discharge processes can be expressed as follows:

$$H(t) = H_0 + \int_0^t (r(t) - ET_G(t)/S_y) dt, \quad (2)$$

where $H(t)$ [L] is the water head at time t and H_0 [L] is the initial water head.

Given that the groundwater recovery rate is determined by the groundwater hydraulic gradient between the background (H_b) (i.e., where diurnal fluctuations are not apparent) and the riparian zone (H), the value of r can be expressed as follows:

$$r(t) = \alpha(H_b(t) - H(t)) \quad (3)$$

The parameter α [$L L^{-1} T^{-1}$] reflects the hydraulic resistance of the aquifer from the background to the riparian zone.

Similar to Liu et al. (2005), we assume that the diurnal ET_G is zero before sunrise and after sunset and follows a sinusoidal form during daylight times, which is also one of the fundamental assumptions of the White method. Therefore, the instantaneous ET_G can be calculated as follows:

$$ET_G(t_s) = \frac{\pi}{2DL} \sin\left(\pi \frac{t_s}{DL}\right) ET_d, \quad (4)$$

where $ET_G(t_s)$ is the instantaneous ET_G rate at time t_s [T], DL is the sunshine duration [–], t_s is the number of hours since sunrise [–] and ET_d [$L T^{-1}$] is the daily ET_G during a day.

Assuming $r(t)$ does not change at each time step Δt , Eq. (2) can be expressed as follows:

$$H(t) = H(t - \Delta t) + [r(t - \Delta t) - ET_G(t - \Delta t)/S_y] \times \Delta t \quad (5)$$

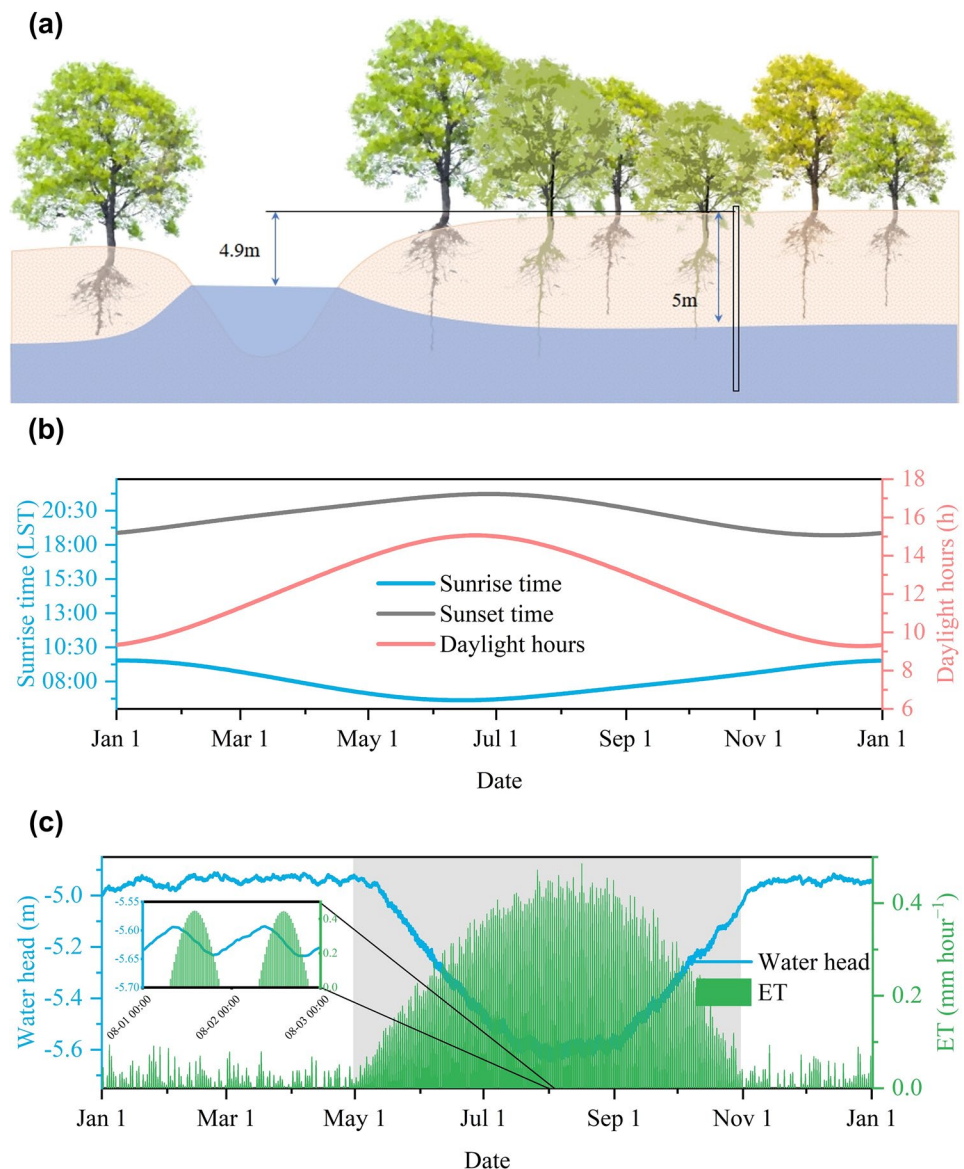
Equation (5) provides an analytical solution for estimating ET_G during each time step Δt , and it is similar to the approach provided by Yin et al. (2013).

Synthetic examples

Based on previous studies estimating ET_G at phreatophyte-dominated sites in hyper-arid areas (Wang et al. 2018; Zhang et al. 2016), we tested the impacts of the seasonal change in sunshine duration and different TSs on the recharge rate estimated by the traditional White (1932) method. We assumed a riparian zone with a constant river water level of 4.9 m below the reference surface. The initial water table depth at the groundwater evapotranspiration site was 5 m, and the specific yield was 0.038 (Zhang et al. 2016) (Fig. 1a). The parameter α was manually adjusted to 0.006 day^{-1} , which ensured that the yearly groundwater recharge and discharge were normally equal.

For simplicity, the sunrise and sunset timings are set to be consistent with those for the field site at $87^\circ 54' E$ and $40^\circ 27' N$, which is the location of the study site in "Field applications". As shown in Fig. 1b, the sunrise and sunset timings, which were obtained using the program provided by the NOAA (National Oceanic and Atmospheric Administration, <https://www.esrl.noaa.gov/gmd>), show notable seasonal variations. To make the sunrise and sunset timings coincide with the sampling frequency (30-min interval), the sunrise

Fig. 1 Conceptual scheme (a), annual sunrise and sunset times (b), and modelled half-hourly water head and ET_G (c) of the synthetic example. The inserted figure in c represents the diurnal fluctuations in the water table and ET_G from 1 August to 2 August



and sunset times used for estimating daily r are rounded down to the time at the hour or half-hour. For example, the sunrise time of 06:41 h on 30 June is set to 06:30 h, and the sunrise time of 07:04 h on 31 July is set to 07:00 h.

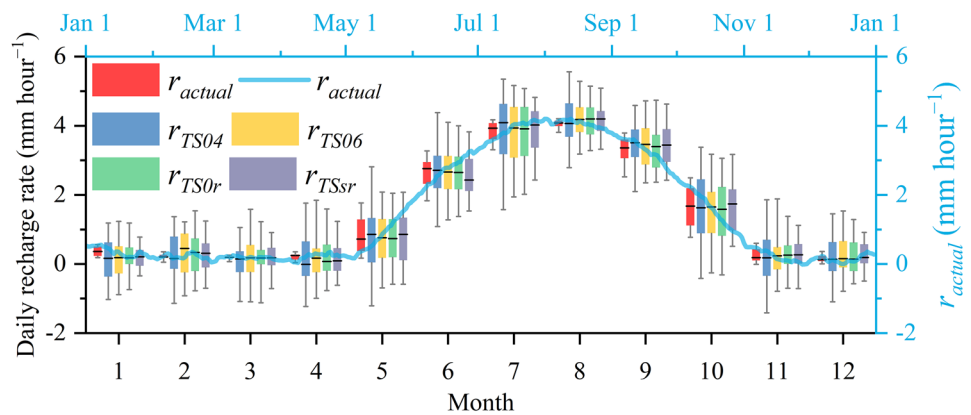
The growing season for the local phreatophytic vegetation is from 1 May to 31 October, and the annual ET_G is set to 500 mm. The seasonal allocation of the ET_G follows a sinusoidal form similar to that of the diurnal ET_G variation during the growing season but with a random error, which is normally distributed with a mean value of 5% of the maximum ET_d in the growing season and added to each day (Fig. 1c). Based on these preconditions, the annual half-hourly ET_G and water table dynamics as shown in Fig. 1c are generated using Eqs. (4) and (5).

The groundwater table exhibits notable fluctuations at both seasonal and diurnal scales because the vegetation

induces periodic consumption of groundwater (Fig. 1c); that is, the water table becomes deeper when the ET_G increases and vice versa. In addition, the amplitude of the water table fluctuations is positively correlated with the intensity of the ET_G .

Next, we use the hydrograph to derive daily r values, which are estimated for different TSs (i.e., 00:00–04:00 h, 00:00–06:00 h, 00:00–sunrise, and previous sunset–sunrise) and then compared with the actual daily mean r (Fig. 2, r_{actual}). The temporal variations in r_{actual} are determined by the changes in the hydraulic gradient between the recharge boundary and the ET_G estimation site. Generally, during the growing season, the ET_G causes an increase in the hydraulic gradient and further leads to an increasing recharge inflow. Such processes also happen at the daily

Fig. 2 Monthly statistical characteristics (box plot) of the estimated and actual daily recharge rate (r_{actual}) on the left axis and the line plot of the actual daily recharge on the right axis. The subscripts TS04, TS06, TS0r, and TSsr represent the r values estimated with the time spans of 00:00–04:00 h, 00:00–06:00 h, 00:00–sunrise, and previous sunset–sunrise, respectively



scale, i.e., an increasing recharge rate can be observed when the phreatophytes start to take up groundwater.

The estimated monthly recovery rates using different TSs are close to the r_{actual} , although the amplitudes of their variations are quite different. The monthly variances of the estimated daily recharge rates (as indicated by the whiskers in Fig. 2) generally decrease in order from r_{TS04} to r_{TS06} to r_{TS0r} to r_{TSsr} . This result means that the uncertainties are reduced in such an order. This decrease provides evidence for the viewpoint that using longer TSs could improve the estimation of the daily recharge rates (Fahle and Dietrich 2014; Loheide 2008). Compared with fixed TSs, varying TSs generally have a better performance. Furthermore, because the recharge rate is derived from the hydrograph for the previous night, the recharge rate tends to be underestimated in the period when the hydraulic gradient is increasing (e.g., June) and overestimated in the period when the hydraulic gradient is decreasing (e.g., September).

The ET_{G} s estimated by different TSs using the traditional White method are compared with the actual ET_{G} as shown in Fig. 3a–d. Clearly, the points are scattering increasingly close to the 1:1 line as the adopted TS changes from TS04 to TS06 to TS0r to TSsr. Quantitatively, the explained variance (R^2) and the Nash–Sutcliffe efficiency coefficient (NSE) increase in this order while the root mean square error (RMSE) decreases in this order. These results mean that the accuracies of the estimated ET_{G} are significantly improved using the sunrise- and/or sunset-related TSs.

Note that Wang and Pozdniakov (2014) provided a statistical approach to estimating ET_{G} , which also considered the duration of daylight time; see Table 1 in Wang and Pozdniakov (2014) for the Liu et al. (2005) model. Using this approach, we estimate the daily ET_{G} by considering the daylight time between sunrise and sunset. As shown in Fig. 3e, this approach performs even better for ET_{G} estimation than the abovementioned White method with different TSs. However, if we take the average duration of daylight time over the growing season but neglect its temporal variations, then the estimated ET_{G} becomes worse. In this respect,

the consideration of the daylight time between sunrise and sunset is equally important in different approaches for estimating ET_{G} , which are generally based on the diurnal water table fluctuations.

Field applications

Study site and field observations

As an application example, the proposed dynamic TS approach was tested using monitoring data from a *Tamarix ramosissima*-dominated riparian site (87°54'E, 40°27'N) along the lower Tarim River, northwestern China. The climate in this region is hyper-arid, with an annual precipitation of less 35 mm and potential evaporation of approximately 1340 mm a⁻¹ (Wang et al. 2018; Yuan et al. 2014). The study site is far away from human activities, and the soil is predominately silt loam, with an approximately 20-cm dry sandy surface layer (Zhang et al. 2016). The dominant vegetation at the study site includes *Tamarix ramosissima*, *Tamarix hispida*, and *Tamarix elongate*, which rely heavily on shallow phreatic groundwater rather than shallow-layer soil moisture (Wang et al. 2019; Yuan et al. 2014).

The instrumentation included an eddy covariance (EC) system placed 1.8 m above the vegetation canopy, a 20-m shallow groundwater monitoring well with an automatic water level logger (CTD-Diver, Eijkelcamp, EM Giesbeek, The Netherlands), and a 5-m soil profile with nine frequency domain capacity (FDC) sensors (FDS100, Unism, Beijing, China). All measurements were recorded at 30-min intervals, and the daily evapotranspiration was determined from the sum of the 30-min EC measurements. More detailed information regarding this site and the field measurements can be found in Yuan et al. (2014, 2015). According to Wang et al. (2018) and Yuan et al. (2014), due to the deep groundwater depth (> 5 m) and low precipitation, soil evaporation is weak and negligible at the selected site. Therefore, as pointed by Zhang et al.

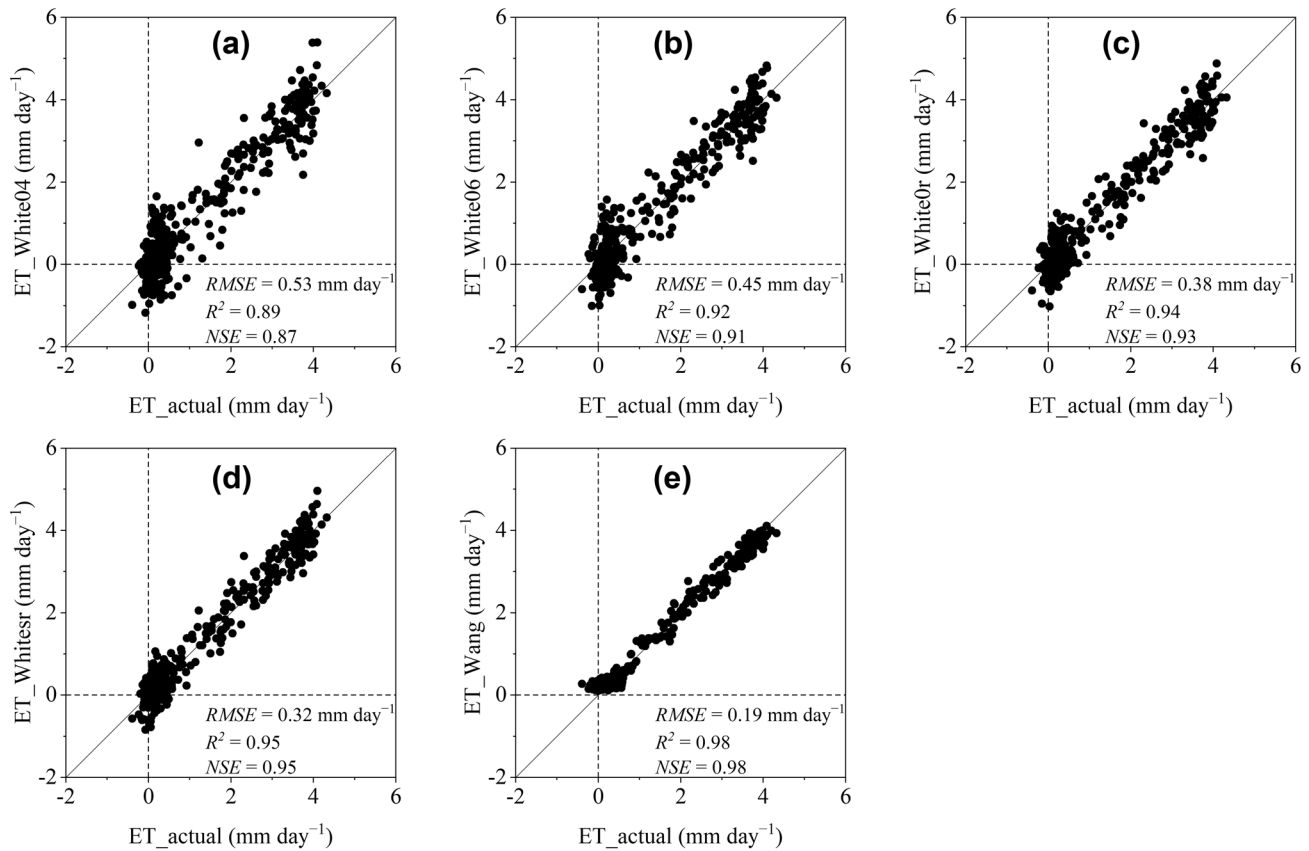


Fig. 3 Comparisons between the estimated ET_G s and the synthetic actual ET_G

(2016) and Wang et al. (2019), the ET derived from the EC system during the growing season is approximately equal to the ET_G .

Methodology

Previously, Zhang et al. (2016) evaluated the performance of the White method at this site using different daily r values, which were determined by different water table recovery time periods. This study concluded that the TS of 00:00 h to 06:00 h for r estimation with the White method performed better than other TSs (i.e., 00:00–04:00 h, 18:00–06:00 h, 22:00–07:00 h). To evaluate the performance of the proposed approaches, the ET_G during the growing season (from 1 May to 31 October 2013) was estimated with the dynamic TS. The specific yield used for calculation was set to 0.038, which was determined by Zhang et al. (2016). The estimated ET_G would be compared with the ET observed by EC measurements and obtained with three traditional methods (i.e., White (1932), Gribovszki et al. (2008) and Loheide (2008) methods) with a fixed TS (00:00–06:00 h).

Comparison of the dynamic time span approach with traditional approaches

As shown in Fig. 4, the ET_G calculated with the White, Loheide, and Gribovszki methods using the fixed TS (00:00–06:00 h) is consistent with the measured ET_G as indicated by the high R^2 (Fig. 3a–c). The RMSE is quite close between the Loheide and Gribovszki methods (0.61 and 0.62 mm day^{-1} , respectively), while the RMSE is slightly higher with the White method (0.71 mm day^{-1}). The NSE achieves the highest value (0.80) with the Loheide and Gribovszki methods and is 0.76 with the White method, which means that the two former methods are more efficient than the White method. Briefly, when the 00:00–06:00 h TS is used for estimating the recharge rate, the Loheide method performs best and the White method performs worst.

The actual daily transpiration start time may dynamically change with the sunrise time. Then, the optimal TS used for estimating the daily recharge rate may change with the sunrise time (Loheide 2008). This assumption is confirmed by Fig. 4d. When the 00:00–sunrise TS is employed, compared with the fixed TS, the RMSE decreases from 0.71 to 0.66 mm day^{-1} and the R^2 and

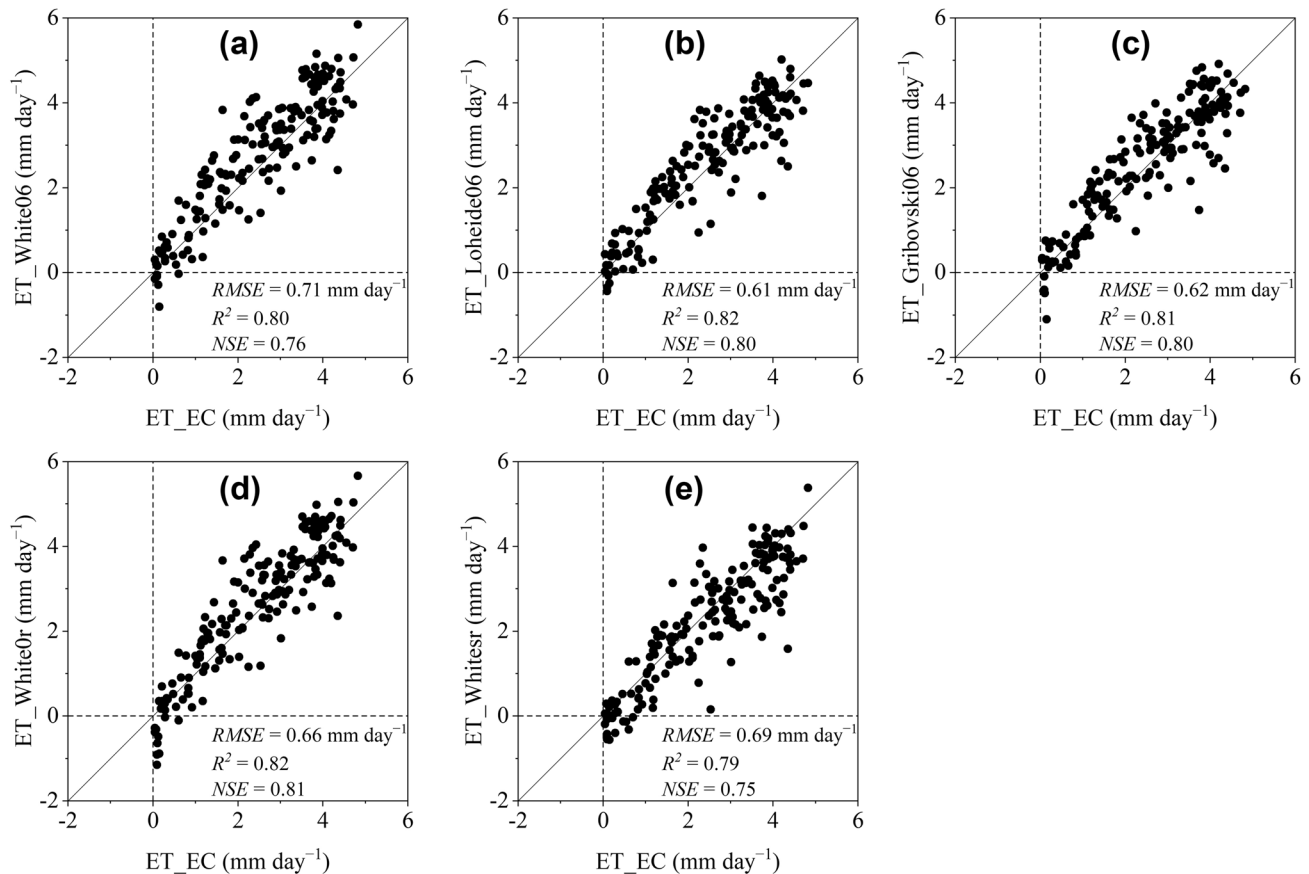


Fig. 4 Comparisons of the ET observed by eddy covariance (ET_EC) and the estimated ET_G based on diurnal groundwater fluctuations from 1 May to 31 October in 2013. The text behind the short under-

line indicate the calculation methods and the time span used; i.e., 06 denotes the 00:00–06:00 h TS, 0r denotes the 00:00 h–sunrise TS, and sr denotes the previous sunset–sunrise TS

NSE increase from 0.80 to 0.82 and from 0.76 to 0.81, respectively. The overall accuracy is basically equal to that achieved with the Loheide method and the Gribovzki method. However, compared with the synthetic example, when the previous sunset–sunrise TS is employed, the resulting estimated ET_G is not improved (Fig. 4e). This outcome may be attributed to the fact that the plant's groundwater uptake does not immediately cease after sunset [which has been pointed out by Loheide (2008)] because the water status of the plant has been depleted during the day and the roots may continue to replenish water for several hours. In addition, Loheide (2008) emphasized that the hours immediately after sunset should not be used to estimate the recharge rate.

Overall, using a dynamically changed TS to estimate the recharge rate can achieve a better ground water recharge rate estimate for all three methods (the results using the dynamic TS for the Loheide method and the Gribovzki method are not shown here), especially for the White method. Then, this result also implies that the White method is more sensitive to the TS chosen for recharge rate estimation.

Discussion and conclusions

The daily groundwater recharge rate is an important variable needed for estimating ET_G using the diurnal water table fluctuation approach. However, the determination of this recharge rate is highly sensitive to the selected TS, which is somewhat subjective (Loheide 2008) for the traditional White (1932) approach (Fahle and Dietrich 2014; Loheide 2008; Zhang et al. 2016). This sensitivity is partly due to the influence of the shape and duration of the diurnal clear-sky solar radiation curve on the diurnal groundwater recharge rate (Soylu et al. 2012). Here, we propose a more robust approach that uses a dynamically changing TS, which is determined from the sunrise and/or sunset time and used to estimate the daily r . Numerical experiments and field implications both showed improved performances for such an approach in comparison with other traditional approaches. Additionally, a statistical approach to estimate ET_G (Wang and Pozdniakov 2014) that considered the duration of daylight time also showed a better performance than the approach that neglected the seasonal dynamics of

sunrise and sunset times. A simple improvement in the TS for the White method could reduce the uncertainties in the estimated daily r and achieve an estimated accuracy for the daily ET_G that is basically equivalent to those for some other sophisticated refined methods. Moreover, compared with the traditional White (1932)-based methods, the proposed sunrise (sunset)-dependent TS for estimating the recharge rate can reduce subjectivity in TS selection.

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