Performance of the White method for estimating groundwater evapotranspiration under conditions of deep and fluctuating groundwater

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Abstract:

The White method is a simple but the most frequently applied approach to estimate groundwater evapotranspiration (ET_g) from groundwater level diurnal signals. Because of a lack of direct measurements of ET_g , it is difficult to evaluate the performance of the White method, particularly in field environments with variable groundwater fluctuations. A 2-year field observation in a hyper-arid riparian tamarisk (*Tamarix* spp.) stand with deep groundwater depth in the lower Tarim River basin of China was conducted to measure the surface evapotranspiration (ET_s) and groundwater table. The performance of the White method and the influences of the variable groundwater fluctuations on the determinations of the specific yield (S_y) and recharge rate of groundwater (r) in the White method were investigated. The results showed that the readily available S_y determined by Lohende's method was feasible but must be finely determined based on the soil textures in the layers in which the groundwater level fluctuated. A constant S_y value for a defined porous medium could be assumed regardless of the discharge or recharge processes of groundwater. The time span of 0000 h to 0600 h for r estimation for the White method worked best than other time spans. A 2-day moving average of r values further enhance ET_g estimation. Slight effects of environmental or anthropogenic disturbances on the diurnal fluctuations of groundwater level did not influence the ET_g estimations by the White method. Our results provide valuable references to the application of the White method for estimating daily ET_g in desert riparian forests with deep groundwater depth. Copyright © 2015 John Wiley & Sons, Ltd.

KEY WORDS groundwater evapotranspiration; the White method; specific yield; recharge rate of groundwater; desert riparian forest; deep groundwater depth

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INTRODUCTION

In arid and semiarid climates, groundwater is the main and most reliable source of water for ecosystems, particularly for ecosystems dominated by phreatophytes (Orellana *et al.*, 2012). Groundwater evapotranspiration (ET_g) is a critical resource management issue, and its estimation has been studied extensively (Lubczynski, 2009). ET_g refers to water losses from groundwater in both forms of evapotranspiration: (1) direct water uptake through roots from groundwater or the capillary fringe and (2) direct evaporation of water from the water table, which is then transported through the unsaturated zone to the land surface in the vapour phase (Ridolfi *et al.*, 2008; Vervoort and van der Zee, 2009; Orellana *et al.*, 2012).

Many studies have attempted to quantify ET_g based on the groundwater level diurnal variations. Among these methods, the White method (White, 1932) is one of the most common approaches for quantifying ET_g because of its simplicity (Martinet *et al.*, 2009; Yin *et al.*, 2013). The White method is expressed by the following equation:

$$ET_g = (24r \pm s) \times S_y \quad (1)$$

The daily ET_g is equal to the sum of the storage change (s , mm d^{-1}) plus groundwater recharge (r , mm h^{-1}). The former is represented by the variation of the groundwater table, while the latter is derived from the water level behaviour at night. Both quantities are multiplied by the specific yield (S_y , $\text{cm}^3 \text{cm}^{-3}$), which serves as a conversion factor (Fahle and Dietrich, 2014). The White method estimates daily ET_g using hourly or more frequent data on groundwater levels from a monitoring well. Moreover, the White method provides the basis for all subsequent ET_g estimation algorithms from the

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groundwater level diurnal signals. Most of these methods are based on the same fundamental principle and encompass three components: specific yield, recharge rate, and storage change (Dolan *et al.*, 1984; Gribovszki *et al.*, 2008; Loheide, 2008; Hatler and Hart, 2009).

S_y is of crucial importance because errors in S_y estimation directly translate to the ET_g estimates (Loheide *et al.*, 2005; Lautz, 2008; Mould *et al.*, 2010; Cheng *et al.*, 2013). However, there are many difficulties in estimating S_y because this parameter is not constant with time; it depends upon the water table depth and the soil hydraulic properties. It is also influenced by hysteresis and differs if the water table is in discharge or recharge (Alley *et al.*, 2002; Scanlon *et al.*, 2002; Nachabe *et al.*, 2005). S_y is often calculated for water table drainage only, but for a rising water table condition, the encapsulated air is likely to reduce the value of S_y , that is, less water volume is needed to provide a positive water table fluctuation (water table rise) than a negative fluctuation (water table drop) (Nachabe *et al.*, 2005). In addition, the basic assumption of the White method about the recharge rate (r), namely, that the average rate of groundwater level rise between midnight and 0400 h is equal to the average groundwater recharge rate over the entire day, is not appropriate for variable groundwater fluctuations. The recharge rate is often a function of the head difference between the observation well and the recharge source (Loheide, 2008). The transient recharge rate would change with time. The replacement of the daily average recharge rate with that determined during a certain time span induces errors in the estimation of ET_g (Fahle and Dietrich, 2014). Consequently, the White method is usually modified with regard to the time period used for recharge estimation (Rushton, 1996; Loheide, 2008; Miller *et al.*, 2010). Some other methods even avoid using the variable r (Soylu *et al.*, 2012; Wang and Pozdniakov, 2014).

The variables S_y and r in the White method are time-dependent, and the time dependence of S_y and r usually results from the variable water level fluctuations with time, as mentioned earlier. In field environments, climate variability, plant growth, river level changes, and anthropogenic disturbance might influence the temporal processes of shallow groundwater level fluctuations, which would reduce the ET_g estimation precision of the White method (Zhu *et al.*, 2011). Because of the difficulty in directly measuring ET_g , it is difficult to evaluate the influences of the S_y and r estimations on the performance of the White method in field environments. Some evaluations have been conducted based on groundwater flow modelling (Loheide *et al.*, 2005; Yin *et al.*, 2013). Recently, from direct measurements of ET_g and r obtained with a lysimeter, Fahle and Dietrich (2014) compared six methods of estimating ET_g using diurnal

groundwater level fluctuations and evaluated the role and influences of S_y and r in these methods. However, his experiment was conducted over a grassland site with a shallow groundwater table. The conclusions about the different methods could be notably different for a deeper groundwater table (Fahle and Dietrich, 2014), which is common across riparian forests in arid regions. Moreover, the seasonal processes of ET_g under variable water level fluctuations due to complex environmental changes could not be reproduced in a lysimeter-based experiment. Therefore, an evaluation of the White method under conditions with deep groundwater level and different water level fluctuations in the field and natural environment is necessary.

The Tarim Basin is located in a hyper-arid hinterland area of the Eurasian continent. The Tarim River, which crosses the basin, is an inland river with a length of 1321 km. A narrow desert riparian forests ecosystem develops along the river. Tamarisk (*Tamarix* spp.) is one of two constructive species in the riparian ecosystem. It is a typical phreatophytic and groundwater-dependent species in this area (Xu and Li, 2006). The surface evapotranspiration (ET_s) over the tamarisk stands in this area is due almost completely to the groundwater discharge (Yuan *et al.*, 2014). Hence, the temporal and, in particular, seasonal processes between ET_s and ET_g would be relatively consistent. In addition, an artificial water conveyance project that draws water from the Daxihaizi Reservoir to the lower river channel every year (Tao *et al.*, 2008) has been implemented to improve the lower riparian ecological systems of the Tarim River (Chen *et al.*, 2008). These anthropogenic disturbances, in association with plant growth and weather changes, have altered the normal groundwater regimes and produced variable groundwater level fluctuations in the riparian forest zone. These changes provide ideal field conditions for evaluating the White method for estimating ET_g under variable water level fluctuations by comparing the calculated ET_g with the measured ET_s .

We conducted a 2-year field experiment in a typical tamarisk stand in the lower reach of the Tarim River from 2012 to 2013. At this site, precipitation is scarce, and the groundwater level fluctuates at a depth of around 6 m. The ET_s was measured by the eddy covariance (EC) method, and the groundwater table was automatically measured concurrently every half hour. Because of the combined impacts of weather change, plant growth, and variable surface water levels in the Tarim River channel, the day-to-day groundwater level fluctuations were variable during the entire growing seasons. In this study, we focused on the White method expressed by equation (1) and did not consider other modified methods for estimating ET_g based on the diurnal groundwater fluctuations. We evaluated the performance of the White

method for estimating ET_g under variable water level fluctuations in a riparian tamarisk stand with deep groundwater depth. The influences of the variable water level fluctuations on the S_y and r temporal processes were explored. Some suggestions to improve the White method for desert riparian forests are presented.

MATERIALS AND METHODS

Site descriptions

The field experiment was conducted throughout a well-growing riparian tamarisk stand in the lower reach of the Tarim River, which is located in the arid northwestern region of China. One of the distinctive features of the study area is the hyper-arid climate. According to the meteorological records of the Tieganklik Weather Station, which is located in the lower Tarim River basin, the mean annual precipitation was 33.7 mm from 1957 to 2012. The observed maximal annual precipitation was 75.7 mm in 1974, and the minimal annual precipitation was 3.4 mm in 2001. However, the annual potential evapotranspiration can reach more than 2000 mm (Chen *et al.*, 2006). Precipitation generally occurs in June, July, and August and is scarcely observed in the remaining months. The lower reach of the Tarim River is located between the Taklamagan Desert and the Kuluk Desert, from the Daxihaizi Reservoir to the terminal Taitmar Lake. Water resources in the lower reach of the Tarim River are under strict artificial controls, and water in the Daxihaizi Reservoir is drawn off, contributing to flows in the lower river channel every year (Tao *et al.*, 2008). As a result of this artificial water management in the lower reach of the Tarim River, most plants can gain water from groundwater supplied by lateral seepage of the river rather than rare flooding events (Ye *et al.*, 2009).

The well-growing tamarisk stand selected for observation covers a uniform area of approximately 200×300 m. This area is flat and located at $87^\circ 54' E$, $40^\circ 27' N$, with an altitude of 846 m. The tamarisk stand is one of the best-growing tamarisk stands in the lower reach of the Tarim River, with an average height of approximately 2 m. It is also the dominant species in the stand. Under the shrubs, a small amount of herbs (mainly are *Alhagi sparsifolia* and *Glycyrrhiza inflata*) grow. Our survey of the vegetation in the vibrant growing season in July 2013 showed that the Simpson diversity index of the observation site was 0.71; the maximal vegetation cover was 0.65, and the leaf area index measured by LAI-2250 (Li-cor, NE, USA) was 1.15.

Field measurements and data processing

Surface evapotranspiration. An EC system was placed 1.8 m above the vegetation canopy in the tamarisk stand

to measure the stand evapotranspiration. The core flux instrumentation consisted of a high-frequency (10 Hz sampling with a 30-min integration period) sonic anemometer (CSAT3), and an open-path infrared H_2O/CO_2 gas analyser (EC150, Campbell Scientific, USA) to measure momentum, heat, vapour, and CO_2 flux. A thermocouple (HMP155A-L, VAISALA Co, Finland) was installed 1.5 m above the canopy to measure air temperature and humidity. For the energy balance test, a CNR4 net radiometer (Kipp and Zonen, The Netherlands) was placed 1.5 m above the canopy and projected 3 m horizontally from the tower to measure the net radiation (R_n). Two heat flux plates (HFP01-L, Campbell Scientific, USA) were buried 0.08 m below the surface to measure the ground heat flux. Four thermocouple temperature sensors (109, Campbell Scientific, USA) were buried in different locations in the upper 0.02 and 0.06 m of soil among and beneath the bushes to measure soil temperature. The soil thermal storage was calculated using the integration method of soil temperature gradient analysis (Mayocchi and Bristow, 1995). An automatic rain gauge (52203, RM Young Inc., USA) was placed at an empty plot south of the flux tower to record precipitation. A data-logger (CR3000-NB, Campbell Scientific, USA) was used for raw data collection and online flux data preliminary processing. The meteorological and radiation elements were measured every 30 min.

The post-processing of the EC data involved spectral correction and a two-angle coordinate rotation of the wind-velocity components to reorient the x -axis parallel to the local main wind direction. The density correction was also applied to the flux calculations. The half-hourly turbulent fluxes and meteorological variables were again screened to remove abnormal data points caused by sensor malfunction, rain events, and sensor maintenance.

The energy balance was analysed for the EC data. The net radiation (R_n), latent heat (LE), and sensible heat (H) were obtained from the EC data, and the ground heat flux (G) was calculated from the average of the two soil heat flux plate measurements and the storage of energy in the 8 cm of soil above the heat flux plates. The canopy storage heat and photosynthetic energy consumption were ignored because of the sparse, low canopy. The slope of the relationship between the half hourly data of net radiation minus ground heat flux ($R_n - G$), and the half hourly data for total turbulent flux ($H + LE$) indicated that the EC underestimates turbulent fluxes by 16% for both the whole measurement period (slope = 0.84, $R^2 = 0.93$) and the daytime of the growing seasons (slope = 0.84, $R^2 = 0.90$). The energy balance was forced to close according to the Bowen ratio (Wohlfahrt *et al.*, 2009). Small gaps (i.e. <2 h) in the data were filled by linear interpolation.

The hourly ET_s (mm h^{-1}) of the riparian tamarisk stands was calculated based on the observed hourly LE value. The daily ET_s (mm d^{-1}) was the sum of the hourly ET_s for 1 day; when the calculated hourly ET_s was negative, it was set to zero.

Groundwater level. Only one groundwater level observational well was installed near the flux tower but monitored over 2 years for the repetitions. The distance of the observational well to the Tarim River channel was 320 m. An automated pressure groundwater level logger (CTD-Diver, Eijkelcamp, The Netherlands) was used to record the groundwater level below the surface at 30-min intervals. The groundwater table was corrected by air pressure measured by the EC system (Gribovszki *et al.*, 2013). A five point moving average was used to smoothen the groundwater data to prevent noise of various origins from impacting the pressure measurements (Loheide *et al.*, 2005). The data were also frequently calibrated in the field with manual measurements of depth to groundwater.

Methodology for the evaluation of White method

Assumptions. At our observation site, surface evapotranspiration could result from four water sources: (1) groundwater, (2) overflowing flood, (3) precipitation, and (4) antecedent soil water in the root layer. Therefore, the total riparian stand daily ET_s could be defined as follows:

$$ET_s = ET_g + ET_f + ET_p + ET_r \quad (2)$$

where ET_g , ET_f , ET_p , and ET_r are the daily evapotranspiration from groundwater, flood water, precipitation, and the existing soil water in the root layer, respectively.

Because no flood occurred at our study site during the observation period, ET_f could be neglected. Because of the scarce precipitation, ET_p could also be neglected most of the time. In addition, according to our observation results, the soil water contents in the shallow layers in the study site did not exhibit any obvious temporal change (Yuan *et al.*, 2014), which indicated that the soil water was stable even though it might participate in the root water uptake and ET processes. Thus, ET_r could also be neglected, and ET_g was approximately equal to ET_s at

our observation site. Tamarisk is a typical phreatophyte species. Its fine roots largely develop near the water source (Gary, 1963; Qong *et al.*, 2002; Xu *et al.*, 2011). In hyper-arid regions, groundwater is commonly the singular water source (Yuan *et al.*, 2015). Therefore, the temporal processes of ET_g were also approximately consistent with those of ET_s , particularly for a longer period, such as a season.

Here, we assumed the water movement from groundwater to surface evapotranspiration in the groundwater–soil–plant–atmosphere system in the observed tamarisk stand is in a steady state under the hyper-arid climate. Based on this assumption, we can evaluate the performance of the White method by comparing the ET_s course and ET_g course by measuring the daily and seasonal surface evapotranspiration courses.

Determination of specific yield. S_y is defined as the water volume released from storage per unit drop in the water table height per unit land area (Hillel, 2004). A simulation analysis demonstrated that the S_y estimation was only weakly dependent on the magnitude of the diurnal fluctuations (Loheide *et al.*, 2005). In this study, a readily available S_y (Loheide *et al.*, 2005) was selected. The S_y value was determined solely from the soil texture at the depth of the groundwater table. When the soil texture in the layer of the water level fluctuation magnitude does not change, S_y is constant, but if the soil texture changes, S_y changes.

Based on the observed fluctuation depths of the groundwater level in the 2012 and 2013 growing seasons (see detail in the section on Groundwater hydrographs), we took soil samples at a depth of 5.5–5.8 m and a depth of 6.0–6.3 m, respectively. The soil textures were obtained using the hydrometer method (Birkeland, 1984). The S_y value was finely determined based on the soil textures using the method presented by Loheide *et al.* (2005) (Table I). Because the soil textures differed in the layer of the water level that fluctuated in magnitude between the 2012 growing season and the 2013 growing season, the S_y values were also different between the 2 years (Table I).

Calculations of groundwater recharge rate and storage. In the classical White method, the daily mean r is calculated from the slope of the best fit line, which is

Table I. The soil textures at two different depths corresponding to the groundwater fluctuation depths during the two growing seasons of 2012 and 2013 and the readily available specific yield (S_y) values during the two growing seasons

Sampling depth (m)	Clay (%)	Silt (%)	Sandy (%)	S_y^a ($\text{m}^3 \text{m}^{-3}$)	Year of S_y applied
5.5–5.8	5.60	75.50	18.90	0.038	2013
6.0–6.3	5.54	65.78	28.68	0.065	2012

^a S_y was determined using the method presented by Loheide *et al.* (2005).

[Correction added on 11 September 2015, after first online publication on 29 July 2015: The initial header of Table I, third column was ‘Sand (%)’ and in the fourth column was ‘Silt (%)’. These has been replaced with ‘Silt (%)’ and ‘Sandy (%)’ respectively].

obtained from the least square method, to the hydrograph between midnight and 0400 h. It is assumed that this time span is the time period when groundwater evapotranspiration has ceased, and the daily recharge rate is equal to the average groundwater recharge rate over the entire day. Some methods have employed different time spans to fit the slope (Table II). For instance, Miller *et al.* (2010) derived r by employing the period from 2200 h at night to 0700 h the next morning. Obviously, the slope values (r values) fitted from different time spans are different (Figure 1). When S_y is constant, the change in the r values determines the temporal processes of the calculated ET_g . Thus, the calculation method for r is particularly important for the estimation of ET_g temporal processes. In this paper, we employed four time spans to estimate the recharge rate (Table II). The four time spans were: (1) 0000 h to 0400 h, which is the recommended period in the classical White method, (2) 0000 h to 0600 h, which is the lengthened time period employed by Loheide (2008), (3) 1800 h to 0600 h, which is a representative period of rising water levels during the night employed by Rushton (1996), and (4) 2200 h to 0700 h, another period of rising water levels during the night employed by Miller *et al.* (2010). All times in this paper refer to local time. Table II lists the r estimation approaches using different time spans that were included in our investigation and their abbreviations, which were named following the researchers' name.

Moreover, we investigated the impacts of averaging the r values over several days, including 2, 3, 5, and 7 days. Two-day averaging refers to averaging the calculated recharge rates of the previous night and the subsequent night; 3-day averaging refers to averaging the calculated

Figure 1. Illustration of the estimation methods for daily recharge rate (r) and storage change (s) of groundwater using the White method based on groundwater level diurnal fluctuation. Four different r estimation approaches based on different time spans are illustrated by the coloured lines

rates of the previous night, that night, and the subsequent night; 5-day averaging refers to averaging the calculated rates of the previous two nights, that night, and the subsequent two nights; 7-day averaging refers to averaging the calculated rates of the previous three nights, that night, and the subsequent two nights.

The value s is the net fall or rise of the water table in the 24-h period. In this paper, s was determined from the difference between the two water levels at 0000 h, today and the subsequent day (Figure 1).

Statistical analysis. The performance of the White method was evaluated by comparing the ET_g with the observed ET_s measured by the EC system using the root mean square error (RMSE) and Nash–Sutcliffe efficiency (NSE). The RMSE was calculated as equation (3):

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (ET_{s,i} - ET_{g,i})^2}{n}} \quad (3)$$

The NSE was calculated as equation (4):

$$NSE = 1 - \frac{\sum_{i=1}^n (ET_{g,i} - ET_{s,i})^2}{\sum_{i=1}^n (ET_{s,i} - \overline{ET_s})^2} \quad (4)$$

where ET_s is the daily surface evapotranspiration observed by the EC method, ET_g is the daily groundwater evapotranspiration estimated by the White method or its modified versions, and $\overline{ET_s}$ is the mean daily ET_s value over the interval of interest.

Table II. Four recharge rate estimation approaches using different time spans and their abbreviation and annotation in this paper

Time span	Abbreviation	Annotation
0000 h–0400 h	r_{White}	The recommended period in the classical White method
0000 h–0600 h	r_{Loheide}	Lengthened time period employed by Loheide (2008)
1800 h*–0600 h	r_{Rushton}	Water level ascending time period during the night employed by Rushton (1996)
2200 h*–0700 h	r_{Miller}	Another chosen water level ascending time period during the night employed by Miller <i>et al.</i> (2010)

*Times marked with an asterisk refer to the previous day.

The RMSE value indicates the degree of dispersion of the estimated ET_g relative to the observed ET_s (Willmott *et al.*, 1985). A higher RMSE value indicates a greater variation in the magnitude of the estimated ET_g . The NSE value indicates how well the observed ET_s values and estimated ET_g values fit the 1 : 1 line, and the values range from $-\infty$ to 1, with higher values indicating better agreement (Legates and McCabe, 1999).

Because precipitation will invalidate the assumption discussed in the section on Assumptions, the data from the corresponding time period of precipitation were removed in the statistical analysis.

RESULTS

Groundwater hydrographs

The groundwater depth varied between 4.95 and 6.46 m during the observation period from 1 January 2012 to 9 November 2013, and a general upward trend of the groundwater level was observed during the 2-year period (Figure 2). The oblique line area in Figure 2 corresponds to the growing seasons. In the non-growing seasons, the groundwater level usually moved upward slowly over time and relatively stable, but in the growing seasons, the groundwater level exhibited V-shaped seasonal variations. The groundwater level often began to decline continuously after the onset of the growing season (Figure 2), suggesting groundwater consumption due to plant water uptake. Around mid-August, the groundwater level suddenly rose, which indicated that the plant water uptake was less than the lateral seepage. The groundwater level rising was not due to a decrease in plant water consumption (Yuan *et al.*, 2014) but was the result of an increase in lateral seepage resulting from the artificial water conveyance from the Daxihaizi reservoir to the lower reach of the Tarim River at this time every year (Ye *et al.*, 2009). The V-shaped seasonal variations of the ground-

water level indicated that both plant water uptake and the artificial water conveyance controlled the seasonal variation of the groundwater level at our study site, which led to variable water level fluctuations. The variability of the water level fluctuations was mainly apparent in the following aspects.

First, because of the artificial water conveyance to the river channel of the lower reach of the Tarim River in August every year, the groundwater level in our observation site exhibited a downward trend in the first half and an upward trend in the second half of a growing season. The V-shaped seasonal variations formed two opposite long-term fluctuation trends of groundwater level, corresponding to the discharge process and recharge processes of groundwater, respectively.

Second, because of the differences in plant water consumption in different phenological stages, the groundwater evapotranspiration rates usually exhibited differences at different phenological stages of the plant, resulting in differing magnitudes of diurnal fluctuations of the groundwater level in different growing seasons. The diurnal fluctuation was particularly obvious in the vibrant growing seasons (Figures 3b and c) but weak in the early and late portions of the growing season (Figures 3a and d). Weak diurnal fluctuations can cause larger uncertainty in the recharge rate determination, as illustrated in Figures 3a and d. Groundwater level fluctuations were usually highly irregular during the low ET season, with low recharge rates (Figure 3d) and even negative correlation with time (Figure 3a).

Third, daily variations of weather can influence the surface evapotranspiration and, consequently, the groundwater evapotranspiration. For example, a cloudy day or precipitation can reduce groundwater consumption, and thus, a general downward groundwater level trend becomes a transient upward level trend (inset in Figure 2). These fluctuations were particularly obvious in June and July of 2013. This transient opposing fluctuation trend

Figure 2. Groundwater table hydrograph during the observation period from 1 January 2012, to 9 November 2013. The oblique line areas correspond to the growing seasons of the observed tamarisk stand

Figure 3. Four examples of diurnal fluctuations in different stages of a growing season. The solid lines illustrate the daily recharge rate estimation approaches. (a) An example in the early stage of the growing season; (b) an example in the first half of the vibrant growing season; (c) an example in the second half of the vibrant growing season; and (d) an example in the late stage of the growing season

increased the complexity of the groundwater level fluctuations in our experiments.

Fourth, the depths of the groundwater level fluctuations differed between the 2012 and 2013 growing seasons. The groundwater depth fluctuated from 5.63 to 6.46 m in the 2012 growing season and from 5.09 to 5.86 m in the 2013 growing season, resulting in different S_y values between the 2 years due to the different soil textures at different depths.

These complex groundwater level fluctuations in our experiments provided ideal conditions to evaluate the performance of the White method under variable groundwater level fluctuations in field environments with deep groundwater levels.

Seasonal variations of ET_g and ET_s

The groundwater evapotranspiration was very weak in non-growing seasons. Thus, the estimation of ET_g in the non-growing seasons using the White method would be not meaningful in our study area. Here, we selected only

the growing seasons of the observed tamarisk stand to explore the performance of the White method. In the calculations of ET_g in this section, we chose the r_{Loheide} approach to estimate the r value because the r_{Loheide} method was validated to be the best r estimation method among the four employed r estimation approaches, as will be discussed in the next section.

Comparisons of the temporal courses of the daily ET_g and the daily ET_s in 2012 and 2013 revealed that the seasonal variations in the estimated ET_g and the observed ET_s coincided ($R^2=0.67$), which not only confirmed that our assumptions on the relationship between ET_g and ET_s in the study area were reasonable but also indicated that the White method could adequately capture the seasonal variations of ET_g . However, we also observed that the range of the day-to-day fluctuations in ET_g was usually larger than that of ET_s (Figure 4).

In the calculations of the White method, because S_y was set to a constant value for an entire growing season (Table I), the estimation of the seasonal variation of ET_g was determined by the estimation of the variables r and s . Figure 4 also shows the seasonal variations of r and s in 2012 and 2013. The variations of the s value were determined by the difference in the day-to-day fluctuations in groundwater level. In the first half of the growing season, during which a downward trend of groundwater level occurred (Figure 2), most s values were positive (Figure 4), and in the second half of the growing season, most s values were negative (Figure 4) because of the upward trend of groundwater level (Figure 2). The seasonal courses of s did not coincide with those of ET_g ($R^2=0.16$), indicating that the fluctuating seasonal trend of groundwater level did not substantially influence the estimations of the seasonal variations of ET_g based on the White method. By contrast, the seasonal courses of r approximately coincided with those of ET_g ($R^2=0.68$) (Figure 4), revealing the critical role of the r value in the estimations of the seasonal variations of ET_g . Sensitivity analysis of equation (1) also revealed that the impact of the r values on the ET_g values was more significant than that of the s values. As variables r and s increase from 10% to 20%, the estimated ET_g values increase from approximately 1.3% to 2.5% for s and from approximately 11.3% to 22.5% for r , indicating that a slight error in r could cause a larger deviation in ET_g estimates.

Although the seasonal variations in the estimated ET_g and observed ET_s coincided, some obvious differences between ET_s and ET_g occurred during an entire growing season. Generally, these differences mainly occurred under two conditions. One condition was the time period of the early or late portion of the growing season, when the daily fluctuation range of groundwater levels was still small. The estimated ET_g often deviated from the observed ET_s in these periods. A negative or abnormal

Figure 4. Seasonal variations of the estimated groundwater evapotranspiration (ET_g), the observed surface evapotranspiration (ET_s), corresponding daily recharge rate (r) and storage change (s) of groundwater, and precipitations in (a) the 2012 growing season and (b) the 2013 growing season.

value of ET_g was occasionally obtained during these periods (Figure 4). Comparison with the corresponding values of r and s (Figure 4) revealed that the weak and irregular diurnal fluctuation of groundwater level in these periods (Figures 3a and d) caused these abnormal values of r and s . Another condition was precipitation events. After obvious precipitation events, the estimated ET_g was usually significantly less than the observed ET_s (Figure 4). In our observation area with a deep groundwater depth and a hyper-arid climate, precipitation increases the soil moisture in the surface layer, which subsequently increases surface evapotranspiration because of the increasing soil evaporation, while the transpiration of a phreatophytic plant such as tamarisk and the associated groundwater consumption would not increase. As a result, ET_g would be less than ET_s after a precipitation event. This phenomenon was particularly obvious after large precipitation events during the 2 years of growing seasons (Figure 4). Therefore, the differences between ET_g and ET_s after obvious precipitation events further support the validity of the ET_g estimation using the White method.

Comparisons of ET_g based on different r estimation approaches

The fitted r values differed based on different time spans. The estimated ET_g values using r estimation from four time spans, which were (1) 0000 h to 0400 h, (2) 0000 h to 0600 h, (3) 1800 h to 0600 h, and (4) 2200 h to 0700 h (Table II), exhibited obvious differences. Statistically comparing ET_g with ET_s allowed the performance of the four different time spans of r estimation to be examined (Figure 5). Here, a lower RMSE and a higher NSE indicate best fit between ET_g and ET_s .

In general, the performances of the ET_g estimations in 2013 (Figure 5b) were better than those in 2012 (Figure 5a), and the performances of the four approaches of r estimations exhibited similar differences in the 2 years of growing seasons. In 2012, the highest NSE (0.57) was achieved when employing the r_{Loheide} approach. In 2013, the highest NSE (0.73) was achieved when employing the r_{Miller} approach, while the NSE value obtained by employing the r_{Loheide} approach was 0.72, indicating that the r_{Loheide} approach performed as well

Figure 5. Comparisons of the observed surface evapotranspiration (ET_s) and the estimated groundwater evapotranspiration (ET_g) based on four different recharge rate estimation approaches in (a) the 2012 growing season and (b) the 2013 growing season. A one-to-one line is shown in each plot. Root mean square errors (RMSE) are in millimetre per day, Nash-Sutcliffe efficiencies (NSE) are dimensionless

as the r_{Miller} approach in 2013. The lowest NSE values in both years were obtained when employing the $r_{Rushton}$ approach. The estimated ET_g values were substantially less than the observed ET_s values based on the $r_{Rushton}$ approach, which was due to the lower r values obtained using the $r_{Rushton}$ approach. The classical White method employing the time span of midnight to 0400 h performed worse than the $r_{Loheide}$ and r_{Miller} approaches, but the estimated ET_g values based on the r_{White} approach generally did not substantially deviate from the observed ET_s values, in contrast to the $r_{Rushton}$ approach.

With respect to the RMSE values, the order from low to high was $r_{Rushton}$, r_{Miller} , $r_{Loheide}$, and r_{White} (Figure 5), indicating that the use of longer time span to fit the r value reduced the magnitude of the day-to-day fluctuations of the estimated ET_g . Thus, the use of a shorter time span to fit the r value produced larger temporal fluctuations of the r estimation, and lengthening the time span decreased the day-to-day fluctuations of the r values. However, for the $r_{Rushton}$ approach, lower overall r values were observed for the longest time period.

In summary, the approach employing the time period of midnight to 0600 h produced the best estimation of ET_g . The approach employing the time period of 1800 h to 0600 h substantially underestimated the ET_g value. The classical White method employing the time period of midnight to 0400 h yielded the largest day-to-day fluctuations of ET_g . The performance of the approach employing the time period of 2200 h to 0700 h was not consistent between the growing seasons of 2012 and 2013 but was superior to that of the classical White method.

Comparisons of ET_g based on different averaged r values

Figure 6 shows the ET_g seasonal variations based on four different averaged (2 or more days) r values and their comparisons with the ET_g determined from the non-averaged (1 day) r values and observed ET_s . Here, the r values were estimated by the $r_{Loheide}$ approach. None of the ET_g temporal courses based on the different averaged r values exhibited significant differences ($R^2 > 0.93$), and the seasonal trends were approximately consistent with that of the observed ET_s (Figure 6). However, as shown in Figure 6, the daily fluctuation of ET_g based on non-averaged r values was obviously larger than that based on averaged r values. The statistical parameters, including the RMSE in Table III, further emphasized these differences. For the four approaches for r estimation, all of the RMSE values based on the non-averaged r values were substantially larger than those based on the averaged r values in both 2012 and 2013 (Table III), indicating that averaging r for that day and neighbouring days could smooth the fluctuation of the r value and consequently lessen the daily fluctuation of the ET_g values. In addition, the NSE values based on the non-averaged r values were all substantially less than those based on the averaged r values (Table III), further indicating that averaging r for that day and neighbouring days could substantially improve the ET_g estimations.

However, the RMSE values did not substantially decrease and the NSE values did not substantially increase when the days for averaging r increased from 2 to 7 days for all four approaches of r estimation in both 2012 and 2013 (Table III), indicating that 3 to 7 days for

Figure 6. Seasonal variations of estimated groundwater evapotranspiration (ET_g) based on different averaged recharge rate (r) values and their comparisons with the ET_g obtained from the non-averaged r values and the observed surface evapotranspiration (ET_s) during (a) the 2012 growing season and (b) the 2013 growing season. The r refers to non-averaged, $2r$ refers to 2-day averaging, $3r$ refers to 3-day averaging, $5r$ refers to 5-day averaging, and $7r$ refers to 7-day averaging.

Table III. Statistical results and performances of groundwater evapotranspiration estimates based on different averaged recharge rate (r) values for the four r estimation approaches during the 2012 and 2013 growing seasons

Methods	Year	Statistical parameters ^a	Averaged r^b				
			r	$2r$	$3r$	$5r$	$7r$
r_{White}	2012	RMSE	1.16	0.89	0.83	0.74	0.72
		NSE	0.37	0.61	0.66	0.72	0.74
	2013	RMSE	0.88	0.69	0.69	0.64	0.62
		NSE	0.67	0.79	0.79	0.81	0.82
r_{Loheide}	2012	RMSE	0.97	0.76	0.71	0.64	0.62
		NSE	0.57	0.72	0.75	0.79	0.80
	2013	RMSE	0.81	0.62	0.65	0.62	0.60
		NSE	0.72	0.82	0.81	0.82	0.83
r_{Rushton}	2012	RMSE	0.95	0.70	0.66	0.62	0.61
		NSE	-0.22	-0.05	-0.02	0.00	-0.01
	2013	RMSE	0.68	0.57	0.59	0.56	0.55
		NSE	0.18	0.24	0.23	0.24	0.25
r_{Miller}	2012	RMSE	0.96	0.75	0.69	0.62	0.62
		NSE	0.44	0.60	0.64	0.67	0.68
	2013	RMSE	0.74	0.58	0.62	0.59	0.57
		NSE	0.73	0.81	0.79	0.80	0.81

^a Root mean square errors (RMSE) are in millimetre per day, Nash–Sutcliffe efficiencies (NSE) are dimensionless.

^b r refers to non-averaged, $2r$ refers to 2-day averaging, $3r$ refers to 3-day averaging, $5r$ refers to 5-day averaging, and $7r$ refers to 7-day averaging.

averaging r did not substantially improve the performance of the White method for estimating ET_g .

DISCUSSIONS

Determination of specific yield

S_y is of crucial importance to estimating ET_g because errors in specific yield estimates directly translate to errors

in ET_g estimates (Alley *et al.*, 2002; Lautz, 2008). The S_y value in our study differs by nearly twofold between 2012 and 2013 and provides a more accurate value of ET_g when compared with ET_s . If the employed S_y value was set to one of the two values in the 2 years, the estimated ET_g values in another year would be considerably larger or less than the reasonable values. These results indicate that fine, correct soil texture data must be obtained for the layers in which the groundwater level fluctuates for the S_y

determination and also indicate that the method to determine the S_y value presented by Loheide *et al.* (2005) from a saturated–unsaturated flow simulation analysis is feasible for the desert riparian forest zone with deep groundwater present in our study area.

S_y usually differs if the water table is in discharge or recharge because of the difference in drainable and fillable porosity (Nachabe, 2002). The groundwater table in our observation site exhibited two opposing long-term change trends throughout the growing season, representing the discharge process and recharge process. However, the ET_g estimations obtained using a constant S_y value did not exhibit abnormal trends between the two processes, indicating that recharge versus discharge characteristics of the groundwater system was inconsequential in this setting. This confirms that for deep groundwater conditions, a constant S_y value for a defined porous medium can often be assumed (Fahle and Dietrich, 2014).

Estimation of the recharge rate

The classical White method considers that the recharge rate between midnight and 0400 h is approximately equal to the average recharge rate for the day because the water level is approximately at its mean value of the day, that is, corresponding to the mean gradient between water level and recovery source (Loheide *et al.*, 2005). The lysimeter measurements by Fahle and Dietrich (2014) indicated that the recharge rate during this period was (slightly) lower than the daily mean, hence leading to underestimation when this period is used. However, our results indicated that the recharge rate between midnight and 0400 h did not lead to an underestimation of ET_g but to the largest daily fluctuations (largest RMSE) of ET_g among all four time spans examined (Figures 4 and 5). These results suggest that the recharge rate between midnight and 0400 h is higher or lower than the daily mean in some way but is not consistently lower than the daily mean, in contrast to the outcome predicted by Fahle and Dietrich (2014). Because direct measurements of the recharge rate cannot be conducted in field environments, we were unable to judge under what conditions the fitted recharge rate during a time span would be higher or lower than the daily mean. However, the longer time spans for fitting the r values decreased the daily fluctuations of ET_g , indicating that usage of longer time spans could decrease the daily fluctuations of r values. This result is consistent with that of Fahle and Dietrich (2014), but we observed that the longest time span, from 1800 h to 0600 h, which represented the entire groundwater level upward time period for 1 day, led to obviously low r values, particularly when groundwater consumption was high (Figure 4), indicating that the time span from 1800 h to

0600 h was not appropriate for fitting the recharge rate. This result differs greatly from that of Fahle and Dietrich (2014), who observed that the time span from 1800 h to 0600 h yielded the best estimation of the recharge rate. Contrasting results with those of Fahle and Dietrich (2014) are likely attributed to differences in groundwater depth and plant species. Our experiment was conducted in a xeric phreatophyte stand with a deep groundwater table, while Fahle and Dietrich's experiment was conducted at a grassland site with shallow groundwater depth. We recommend that the time span for r estimation should be evaluated in each study.

Our results indicated that averaging 2 or more days of r values substantially improved the performance of the White method for estimating ET_g . However, a 2-day average of r values is sufficient to improve the ET_g estimation by the White method, consistent with that of Fahle and Dietrich (2014). We concluded that determining r by employing the time span from 0000 h to 0600 h to fit the r values and then averaging 2 days of r values was optimal for the specific conditions of our study.

Influences of variable groundwater level fluctuations and anthropogenic disturbance

In the vibrant growing season from June to August in the observed tamarisk stand, the diurnal fluctuations of the groundwater level were usually regular and distinct. During this period, the estimated ET_g based on groundwater level diurnal fluctuations generally matched ET_s . However, in the early and late portions of the growing seasons, many negative or abnormal values of ET_g were obtained because of the weak diurnal fluctuation of the groundwater level. These results indicate some limits of the seasonal processes estimation of ET_g using groundwater level diurnal fluctuations in stands of phreatophytes. In the early and late portions of the growing season, weak diurnal fluctuations of the groundwater level due to low plant transpiration lead to a high uncertainty of r estimation, with high scatter and fluctuation of the r values. Smoothed r values can usually be obtained by averaging the r values over a period of days, thereby improving the ET_g estimations in these periods.

Precipitation events and daily changes in plant water consumption can affect groundwater hydrographs, resulting in complex groundwater level diurnal fluctuations. Water level signals vary at frequencies other than diurnal. Zhu *et al.* (2011) analysed the impacts of the interferences on the ET_g estimations and noted that the interfered groundwater level diurnal fluctuations caused large errors of the ET_g estimations. In our experiments, the normal groundwater level diurnal fluctuations were occasionally affected by precipitation events or daily changes in plant water consumption. These complex

groundwater level signals were usually observed in June and July (Figure 2). However, the corresponding ET_g estimated by the White method did not exhibit large errors, most likely because the effects on the groundwater level fluctuation at our experimental site were not as strong as those observed by Zhu *et al.* (2011). In general, the slight effects on the diurnal groundwater level fluctuation did not influence the ET_g estimations determined by the White method.

In our study area, the dam release from the Daxihaizi Reservoir in August every year altered the groundwater hydrographs. Two opposing long-term change trends of the groundwater level throughout the growing season occurred because of the anthropogenic disturbance. However, the additional inputs to the hydrological system did not have any effect on the ET_g estimation. The artificial water conveyance from the Daxihaizi Reservoir to the lower reach of the Tarim River mainly changed the long-term trend rather than the diurnal fluctuation of groundwater table. Consequently, the r and s estimations based on the groundwater diurnal fluctuation signals would generally not be impacted by this long-term disturbance.

CONCLUSIONS

The White method based on diurnal fluctuations of groundwater level is feasible to estimate groundwater evapotranspiration in a desert riparian tamarisk stand with deep groundwater depth when the S_y and r values are properly determined or treated. The readily available S_y must be finely determined based on the soil textures in the layers in which the groundwater level fluctuates. Estimating r values by employing the time span from 0000 h to 0600 h and averaging 2 days of r values is suggested in xeric riparian settings. Our results provide valuable references for the application of the White method for estimating ET_g in riparian forests with deep groundwater depth.

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