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Application of the water table fluctuation method for estimating evapotranspiration at two phreatophyte-dominated sites under hyper-arid environments

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SUMMARY

Shallow groundwater is primarily discharged via evapotranspiration (ET_g) in arid and semi-arid riparian systems; however, the quantification of ET_g remains a challenge in regional water resource assessments of such systems. In this study, the diagnostic indicators of groundwater evapotranspiration processes and the principles of applying the water table fluctuation (WTF) method to estimate ET_g based on seasonal groundwater level changes were presented. These techniques were then used to investigate groundwater evapotranspiration processes at two sites dominated by phreatophytes (*Tamarix ramosissima* and *Populus euphratica*) within hyper-arid desert environments in northwestern China for the period 2010–2012. The results indicate that steady declines in the water table, which are commonly attributed to groundwater evapotranspiration, occurred at both sites during the growing season. Based on the proposed WTF method, the estimated ET_g was 0.63–0.73 mm/d at the *Tamarix ramosissima* site and 1.89–2.33 mm/d at the *Populus euphratica* site during the summer months (June–August). Numerical simulations using a one-dimensional root water uptake model indicate that the seasonal variations in ET_g at both sites were primarily dependent on the potential evaporation rates. Comparisons with previous studies on plant transpiration at similar sites in this area show that these results are reasonable. It is apparent that the WTF method can provide a simple and relatively inexpensive method of estimating ET_g on a large scale in arid/semi-arid regions. However, there are significant uncertainties associated with time-dependent lateral flow rates, which creates a challenge when applying this method. In addition, the selection of calculation periods that show steady declines in the groundwater level can be somewhat subjective. To enhance the performance of the WTF method based on seasonal water table declines, further research on the estimation of lateral flow rates should be performed using an effective network of groundwater monitoring.

1. Introduction

Evapotranspiration from the land surface is the process through which water is transferred from a liquid (or ice) phase to the vapor phase, which includes plant transpiration through leaf stomata and evaporation from soil, wet leaves and water bodies (Lautz, 2008; Wang and Dickinson, 2012). In arid regions with a relatively shallow groundwater table, groundwater evapotranspiration (ET_g) is a predominant mechanism of groundwater discharge (Nichols, 1994). This process leads to a decline in the groundwater table, an increase in groundwater salinity, and, consequently, deterioration of the ecosystem (Jolly et al., 2008). Therefore, the quantification of ET_g rates, particularly in arid regions where the recharge is small, is a prerequisite for sustainable groundwater resource use and management (Goodrich et al., 2000) as well as natural ecosystem protection and restoration (Drexler et al., 2004). This quantification is particularly important in regions with groundwater-dependent

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ecosystems, where all or part of the water demand is supplied by groundwater (Cooper et al., 2006; Naumburg et al., 2005; Orellana et al., 2012; Yuan et al., 2014). However, the accurate estimation of ET_g remains a challenge in that it is typically subject to uncertainties associated with climatic variables, vegetation parameters, geological variables, and hydrologic parameters (Gou and Miller, 2014; Newman et al., 2006).

Diurnal and seasonal trends in groundwater levels across large areas provide the basic information required to understand natural and human-induced processes such as groundwater recharge and discharge in the hydrologic system (Alley et al., 2002; Woessner, 2000). It is well known that seasonal fluctuations in the groundwater table can often be identified as a result of the seasonality of evapotranspiration in arid and semi-arid areas (Healy and Cook, 2002). In addition, diurnal fluctuations in the groundwater table have been widely observed in riparian areas in response to phreatophyte uptake of groundwater via evapotranspiration (Gribovszki et al., 2013; Ridolfi et al., 2007; White, 1932). The development of electronic pressure transducers and digital data recorders has recently made high-frequency groundwater level monitoring possible and provided abundant opportunities for using this type of information (Freeman et al., 2004; Gribovszki et al., 2010). The water table fluctuation (WTF) method, which is based on the premise that changes in the water table in unconfined aquifers are caused by evapotranspiration (Healy and Cook, 2002; Lautz, 2008), has been widely used to estimate ET_g rates in riparian zones in arid and semi-arid areas (e.g., Carlson Mazur et al., 2014; Gribovszki et al., 2008; Soylu et al., 2012; Weeks and Sorey, 1973; Yin et al., 2013; Zhu et al., 2011).

In this study, the patterns of daily and seasonal groundwater fluctuations in a desert environment in northwestern China with scant precipitation (less than 50 mm per year) and strong potential evapotranspiration (more than 1400 mm per year) were analyzed. We used the WTF approach to estimate ET_g at two typical phreatophyte-dominated sites (*Tamarix ramosissima* and *Populus euphratica*) in this area. The primary objectives of this study were to (i) characterize the seasonal and diurnal groundwater dynamics and analyze their controlling factors; (ii) quantify the ET_g rate using the WTF method and evaluate its seasonal patterns using a 1-D root water uptake model; and (iii) examine the relationships between the ET_g rates and corresponding values of E-601 pan evaporation (E_{601}) during multiple growing seasons.

2. Theoretical background

It is assumed that fluctuations in the depth to the water table (Z_g) in areas with groundwater ET can be viewed as a superposition of seasonal trends (Z_s), daily harmonic-like fluctuations (Z_d), and residuals (Z_r) (Wang and Pozdniakov, 2014):

$$Z_g = Z_s + Z_d + Z_r. \tag{1}$$

The WTF method, which is predominantly based on the analysis of seasonal trends in groundwater table hydrographs $H(t)$, is typically used to quantify groundwater recharge/discharge rates (Healy and Cook, 2002; Nimmo et al., 2014; Sophocleous, 1991; Varni et al., 2013). The decision to apply the WTF method to estimate ET_g in arid and semi-arid areas is primarily based on the following assumptions (Healy, 2010; Weeks and Sorey, 1973): (1) seasonal scaled declines in groundwater levels, $\Delta H = -\Delta Z_s$, which are primarily affected by ET_g, are relatively stable during the growing season; (2) the lateral flow-induced groundwater recharge/discharge rate in a near-well region does not change over the entire growing season; and (3) the value of the specific yield is representative of the selected area. Under the above conditions and using the Dupuit assumption for groundwater flow, the transient planar flow model can be written as follows:

$$\begin{aligned} &-\nabla q_{lat} + ET_g = S_y \frac{\partial H}{\partial t}, \\ &q_{lat} = -T\nabla_{x,y} H, \end{aligned} \tag{2}$$

where S_y is the specific yield [–], T is the transmissivity of groundwater flow [$L^2\,T^{-1}$], q_{lat} is the lateral groundwater flow rate per unit width [$L^2\,T^{-1}$], and H is the groundwater level [L].

Suppose the total change in groundwater level, ΔH, during the growing period can be divided into two components (Fig. 1) in which $\Delta h(x, y, t)$ is the change in groundwater level induced by lateral flow divergence due to far-field (regional) flow conditions and $\Delta z(z, t)$ is the change in groundwater level caused by local seasonal evapotranspiration ET_g, then by substituting h and z into Eq. (2), we obtain the following:

$$-\nabla q_{lat} + ET_g = S_y \frac{\partial (h + z)}{\partial t}. \tag{3}$$

According to our assumption, a change in h does not depend on the local recharge/discharge conditions; therefore, we can treat these changes as being caused by unknown lateral boundary conditions. Therefore, the flow equation for h can be written as follows:

$$-\nabla q_{lat} = S_y \frac{\partial h}{\partial t}. \tag{4}$$

Thus,

$$ET_g = S_y \frac{\partial z}{\partial t}. \tag{5}$$

From Eqs. (3)–(5), ET_g can be calculated for a finite seasonal interval Δt using the following formula:

$$ET_g = S_y \frac{\Delta H - \Delta h}{\Delta t}. \tag{6}$$

The application of Eq. (6) to the estimation of ET_g is restricted by the correct determination of the lateral flow-induced water table change rate $\Delta h/\Delta t$, which is assumed to be independent of evapotranspiration processes. The validity of the estimated value of $\Delta h/\Delta t$ can be confirmed by the identity of $\Delta h/\Delta t$ before and after the growing season (Fig. 1).

A key uncertainty in the WTF method, as mentioned by Healy and Cook (2002) and Lautz (2008), results from the difficulties in estimating the specific yield, which depends on the soil texture, initial water table depth, and rate of change in the water table (Duke, 1972; Nachabe, 2002). To evaluate these dynamics of the

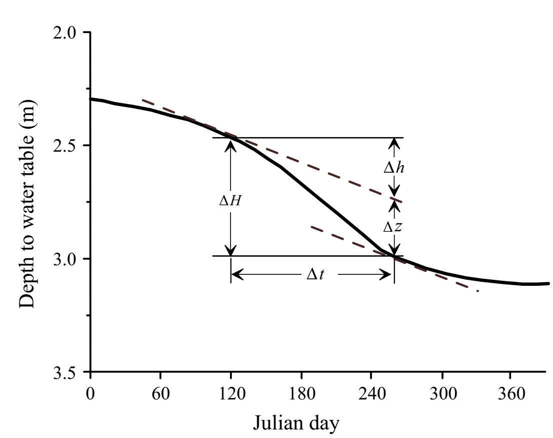

Fig. 1. Schema for calculating seasonal evapotranspiration from a well hydrograph. ΔH is the total change in the groundwater level over Δt, Δh is the change in the groundwater level that is induced by lateral flow divergence due to far-field (regional) flow conditions over Δt, and Δz is the change in the groundwater level that is caused by local seasonal evapotranspiration over Δt.