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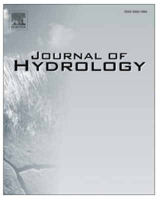

Research papers

Estimating groundwater evapotranspiration from irrigated cropland incorporating root zone soil texture and moisture dynamics

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ABSTRACT

Estimating evapotranspiration from groundwater (ET_g) is of importance to understanding water cycle and agricultural water management. Traditional ET_g estimation was developed for regional steady condition and is difficult to be used for cropland where ET_g changes with crop growth and irrigation schemes. In the present study, a new method estimating daily ET_g during the crop growing season was developed. In this model, the effects of crop growth stage, climate condition, groundwater depth and soil moisture are considered. The method was tested with controlled lysimeter experiments of winter wheat including five controlled water table depths and four soil profiles of different textures. The simulated ET_g is in good agreement with the measured data for four soil profiles and different depths to groundwater table. Coefficient of determination (R^2) and coefficient of efficiency (NSE) are mostly larger than 0.85 and 0.70, respectively. This result suggests that the new method incorporating both soil texture and moisture dynamics can be used to estimate average daily groundwater evapotranspiration in cropland and contribute to quantifying the field water cycle.

1. Introduction

Shallow groundwater exists in many areas of the world (Babajimopoulos et al., 2007). Evapotranspiration from shallow groundwater (ET_g) can cause a significant loss of groundwater storage. ET_g occurs when water moves from the capillary zone to replenish soil water storage which has been depleted by surface evaporation and root water uptake. A shallow water table can contribute part of water requirement for crop growth in agriculture land (Ayars and Schoneman, 1986; Prathapar and Qureshi, 1998; Yang et al., 2000; Kahlown et al., 2005; Wu et al., 2015). However, in some situation it may lead to soil salinization (Northey et al., 2006; Ibrahimi et al., 2014). Accurate estimation of ET_g is important for quantifying groundwater contribution to crops and investigating soil salinization processes, especially in arid and semi-arid regions (Salama et al., 1999; Northey et al., 2006; Zipper et al., 2015).

Irrigation supplies crop water demand in the crop growing season (Ayars et al., 2006). Babajimopoulos et al. (2007) estimated that irrigation consumes more than 80% good quality water in irrigated agriculture areas globally, which makes it the greatest user of water among it and other competitors, namely urban, industrial and environmental use. With limited available water, reducing irrigation water use and making full use of shallow groundwater resources are desired and necessary (Xu et al., 2015), especially during the crop growing season in dry areas. Thus good estimation of ET_g for crop field is required for better irrigation management. Any efforts toward improving ET_g estimation methods are worthwhile for agricultural water management and land and water environmental protection.

It is complex and difficult to estimate ET_g. Daily ET_g can vary in a range of 0–10 mm, depending on many factors such as weather condition, depth to water table, soil hydraulic properties, and land cover (Sepaskhah et al., 2003). Previous estimation of ET_g assumes a steady-state soil water content above the water table. With this assumption, Gardner (1958) and Willis (1960) provided equations to calculate ET_g as a function of water-table depths for homogeneous and layered soils, respectively. Under the hypothesis of steady-state evaporation, different types of empirical and semi-empirical approaches have been proposed to estimate ET_g as a term in the soil water balance for the regional groundwater evaporation. Schoeller (1961) proposed an empirical approach which has been

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widely used because of its simple form (Zammouri, 2001; Yang et al., 2011). The equation is:

$$ET_g = \begin{cases} E_{pot}\left(1 - \frac{H}{H_{max}}\right)^n & if\ H < H_{max} \\ 0 & if\ H \geqslant H_{max} \end{cases} \tag{1}$$

where E_{pot} is the potential evaporation or pan evaporation (mm day^{-1}); H is the actual water table depth (m); H_{max} is the critical water table depth (m) beyond which the groundwater evapotranspiration ceases; n is an empirical coefficient usually ranging from 1 to 3. These methods, without considering the surface and vadose zone condition, are not suitable for calculating ET_g in cropland.

$\mathrm{ET_g}$, defined as the upward flux through the capillary rise from the groundwater table caused by soil evaporation and crop transpiration (Jorenush and Sepaskhah, 2003), depends on the root depth and the non-uniform root water uptake pattern. The upward flux through unsaturated conductive layer (capillary rise zone) is consumed by evapotranspiration eventually. Doorenbos and Pruitt (1977) proposed a method to calculate ET_g through the change of soil water storage in the root zone.

$$ET_g = \begin{cases} \mathrm{ET}_{g-max} & if\ W < W_{WP} \\ \mathrm{ET}_{g-max}\left(\frac{W_P - W}{W_P - W_{WP}}\right) & if\ W_{WP} \leqslant W < W_P \\ 0 & if\ W \geqslant W_P \end{cases} \tag{2}$$

where W is the actual soil water storage in the root zone (mm); W_{wp} is the soil water storage at the wilting point (mm), W_p is the root zone soil water storage without leading to plant water stress (Askri et al., 2010). This equation accounts for the relationship between groundwater contribution to $\mathrm{ET_g}$ and soil water content in the crop root zone. As the maximum rate of the upward flux, $ET_{g\text{-}max}$ is influenced by soil characteristics, water table depths and crop evapotranspiration (Liu et al., 2006). Eq. (2) has been used to estimate ET_g in the soil water balance models. Liu et al. (2006) presented an alternative approach to estimate ET_g through the lower boundary of the root zone (about 1.0 m depth) which is adopted in ISAREG model (Teixeira and Pereira, 1992). Askri et al. (2010) developed a hydrological model, OASIS-MOD, to investigate the influence of irrigation management on water table fluctuation and soil salinity. The physical processes presented in the model include irrigation, infiltration, percolation to the shallow groundwater, drain discharge, soil evaporation, crop transpiration, capillary rise flux, and groundwater flow.

In addition to these empirical and semi-empirical approaches, ET_g can be estimated by deterministic soil water flux models based on the Richards equation with the presence of water table, such as WAVE (Vanclooster et al., 1994), SWAP (Ahmad et al., 2002), UPFLOW (Raes and Deproost, 2003). However, the soil hydraulic properties are required in the upward flux models, which limit their applicability because of a lack of such soil parameters or difficulty to accurately acquire them.

Considering the impact of crop growth process on $\mathrm{ET_g}$, Liu and Luo (2012) combined two different approaches proposed by Doorenbos and Pruitt (1977) and Schmid et al. (2006) to simulate ET_g from water table depths less than 1.5 m in the presence or absence of irrigation (precipitation) supply. This approach adopts a negative linear relationship between soil water storage of the root zone and ET_g. However, when groundwater depth is deeper than 1.5 m, the variation of ET_g and the effect of irrigation can make the relationship deviate from the linear one.

Calculation of daily $\mathrm{ET_g}$ under field condition is complex. Without irrigation and rainfall recharge, $\mathrm{ET_g}$ is affected by several factors such as soil characteristics, crop water demand, available soil water storage and groundwater depth (Mermoud and Seytoux, 1989). When irrigation or rainfall occurs under the crop growth condition, the soil profile may be patterned with a mixed upward and downward water potential gradients (Liu and Luo, 2012). The wet-event induced downward fluxes can result in local downward water potential gradient progressing gradually toward the bottom of the root zone. $\mathrm{ET_g}$ in several days after irrigation is influenced by the amount of irrigation water. It quickly decreases due to replenishment of the root-zone water storage and then increases gradually with the depletion of the soil water due to evapotranspiration. Therefore, to estimate the daily $\mathrm{ET_g}$ in crop growing season, the effect by irrigation and precipitation events should not be neglected.

However, the published empirical approaches do not have capacity to simulate the variation of daily $\mathrm{ET_g}$ in cropland under the influence of irrigation and precipitation. The objectives of this study are: (1) to propose a new method to estimate groundwater evapotranspiration under conditions of various irrigation levels and depths to groundwater table, and (2) to test the method based on data collected from a winter wheat site during the 2008–2009 growing season.

2. A new daily $\mathrm{ET_g}$ estimating method for cropland

For cropland with shallow groundwater, $\mathrm{ET_g}$ is determined by groundwater depth, soil hydraulic properties, micrometeorological condition, soil moisture of the root zone, and crop condition (Babajimopoulos et al., 2007). Soil texture, a property reflecting particle size distribution, determines water transfer and retention capacity. The micrometeorological condition can be integrated in the potential evapotranspiration. Crop coefficient is used to represent the crop effect. When infiltration increases root zone water content, the depletion of groundwater by evapotranspiration becomes weaker. Thus, the effect of irrigation and precipitation on $\mathrm{ET_g}$ can likely be described based on a function of the root zone water content. Based on the approach proposed by Doorenbos and Pruitt (1977) and Averianov equation (Schoeller, 1961), a new equation integrating multiple influencing factors to estimate ET_g in crop growing season is developed. The new equation is as follows:

$$\mathrm{ET_g} = \mathrm{K_C} \times \mathrm{ET_0} \times \left(1 - \frac{\mathrm{H}}{\mathrm{H}_{max}}\right)^n \times \frac{\theta_{fc} - \theta}{\theta_{fc} - \theta_r} \tag{3}$$

where K_c is crop coefficient (–), ET_0 is reference crop evapotranspiration (mm day^{-1}); H is the actual water table depth (m); H_{max} is the potential maximum depth (m) beyond which no ET_g occurs; n is the soil characteristics parameter (–); θ is the actual averaged soil water content in the root zone (it is about 60 cm below the soil surface in this paper) (cm^3 cm^{-3}); θ_{fc} is the field capacity of the soil in the root zone (cm^3 cm^{-3}); θ_r is the soil water content close to permanent wilting point (cm^3 cm^{-3}), and in this paper a constant value 0.05 is used (Loheide et al., 2005). The method was tested and validated against the data from the lysimeter experiments.

3. Methodology

3.1. Lysimeter experiments

The lysimeter experiments were conducted at Hongmen experimental station (113°53′E and 35°19′N), located in Xinxiang City, Henan Province, China. The area has a semi-humid climate with a mean annual temperature and precipitation of 14.1 °C and 589 mm, respectively. The experimental station was equipped with meteorological observation instruments, lysimeters with an underground observation room. Micrometeorological data including air temperature, air pressure, humidity, precipitation, wind speed, net radiation were recorded using an automatic weather station. Each lysimeter (Fig. 1) consists of a soil container in an