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Estimating groundwater evapotranspiration by a subtropical pine plantation using diurnal water table fluctuations: Implications from night-time water use

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ABSTRACT

Exotic pine plantations have replaced large areas of the native forests for timber production in the subtropical coastal Australia. To evaluate potential impacts of changes in vegetation on local groundwater discharge, we estimated groundwater evapotranspiration (ET_g) by the pine plantation using diurnal water table fluctuations for the dry season of 2012 from August 1st to December 31st. The modified White method was used to estimate the ET_g, considering the night-time water use by pine trees (T_n). Depth-dependent specific yields were also determined both experimentally and numerically for estimation of ET_g. Night-time water use by pine trees was comprehensively investigated using a combination of groundwater level, sap flow, tree growth, specific yield, soil matric potential and climatic variables measurements. Results reveal a constant average transpiration flux of 0.02 mm h^{-1} at the plot scale from 23:00 to 05:00 during the study period, which verified the presence of night-time water use. The total ET_g for the period investigated was 259.0 mm with an accumulated T_n of 64.5 mm, resulting in an error of 25% on accumulated evapotranspiration from the groundwater if night-time water use was neglected. The results indicate that the development of commercial pine plantations may result in groundwater losses in these areas. It is also recommended that any future application of diurnal water table fluctuation based methods investigate the validity of the zero night-time water use assumption prior to use.

1. Introduction

Increased attention has been given to the use of diurnal water table fluctuations to quantify vegetation evapotranspiration from groundwater (ET_g) within the last decade. The method's simplicity and cost-effectiveness have made it a popular tool to quantify ET_g in phreatophytic ecosystems compared to other more complex methods, such as eddy covariance that has its limitations in heterogeneous landscape (*e.g.* riparian corridors) (Drexler et al., 2004).

White (1932) proposed a method for estimating daily ET_g from diurnal water table fluctuations assuming constant daily groundwater inflow to the point of measurement. In recent years the method has been further developed to account for variations in diurnal groundwater inflow and enabling sub-daily estimates of ET_g (Gribovszki et al., 2008; Loheide, 2008). Several studies have applied the methods in a variety of ecosystems ranging from wetlands (Carlson Mazur et al., 2014; McLaughlin and Cohen, 2014), savannah (Miller et al., 2010) and forests (Vincke and Thiry, 2008) to riparian corridors where most studies have been conducted (Butler et al., 2007; Schilling, 2007; Lautz, 2008; Martinet et al., 2009). One of the main assumptions behind the method is that groundwater inflow from the background to the point of measurement representative for the inflow at both day and night can be calculated from predawn behaviour in the groundwater water table, commonly defined from midnight to 4 am when vegetation water use is assumed negligible (Loheide et al., 2005).

Night-time water use (T_n) has generally been assumed negligible due to stomata closure, as a response to deficiency in photosynthetically active radiation at night (Daley and Phillips, 2006). Recent advances in technology have enabled more accurate and detailed measurements of vegetation water use and led to an increased awareness, that T_n occurs in a range of ecosystems

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(Caird et al., 2007; Zeppel et al., 2013). T_n can be a result of both water up-take used to re-saturate storages in vegetation, as well as transpiration. Several studies have reported T_n rates to account for 1–30% of daily water use (Snyder et al., 2003; Bucci et al., 2004; Daley and Phillips, 2006; Dawson et al., 2007; Novick et al., 2009; Zeppel et al., 2010) and Daley and Phillips (2006) found that T_n occurred in many different vegetation types.

A range of studies suggest that the dominant controller of T_n is vapour pressure deficit (*VPD*) (Herzog et al., 1998; Benyon, 1999; Oren et al., 2001; Fisher et al., 2007; Kavanagh et al., 2007; Zeppel et al., 2010), but this can vary between species, as other factors such as soil water and nutrient availability, genetics, stomatal density, and CO_2 also play a role (Caird et al., 2007). A study by Daley and Phillips (2006) found T_n in red maple to be negligible and contributed this to the species' drought and shade tolerance, highlighting the complexity of inter-species T_n.

Not accounting for T_n can potentially result in an underestimation of ET_g by under predicting the inflow to the point of measurement. An example of this can be seen in Miller et al. (2010), where measurements of sap flow in a concurrent study (Fisher et al., 2007) showed T_n to be 10–20% of daily ET_g and thereby violated the assumption of zero T_n conditions. A similar violation was also discovered for salt cedar by Gatewood et al. (1950). To the authors' knowledge, not one study has directly investigated the implications from the assumption of zero T_n, although it could have a significant effect on ET_g estimations (*e.g.* monthly to seasonal time-scales).

Large areas of the native banksia forests have been replaced by exotic pine plantations for timber production in the subtropical coastal Australia, which may exert important impacts on local groundwater discharge, especially ET_g. The diurnal groundwater signal was thus investigated for a pine plantation forest situated on a shallow groundwater system to: (i) test the application of diurnal water table fluctuations to quantify ET_g in such a subtropical coastal environment, and (ii) quantify the implications of T_n on ET_g estimations. To achieve these objectives, a combination of high resolution measurements of groundwater level, sap flux density, tree diurnal swelling and shrinkage, specific yield, soil matric potential and climatic variables was used.

2. Materials and methods

2.1. Site description

The study site is located in the central part of Bribie Island, a 148 km^2 sand barrier island in South-East Queensland, Australia (26°59′04″S, 153°08′16″E, 10 m above sea level). The climate is subtropical with a distinct wet summer and a dry winter. The annual rainfall is on average of 1605 ± 279 mm over a period of 40 years with 77% of annual rainfall occurring in the wet season (BOM, 2013). The mean monthly temperature varies from 25.0 °C in January (summer) with an average relative humidity of 64% to 15.4 °C in July (winter) with an average relative humidity of 59% (BOM, 2013). The surrounding native forests were largely dominated by wallum banksia (*Banksia aemula* R.Br.), with an average tree height of 7.0 m and stand density of 370 trees per hectare. The exotic forest consisted of an 11 year old conifer hybrid plantation (*Pinus elliottii* Engelm var. elliottii × *Pinus caribaea* Morelet var. hondurensis) with a height of approximately 13.0 m and a stand density of 840 trees per hectare.

A 6 m thick unconfined aquifer is found at the site, separated from a deeper aquifer by a 12.5 m thick indurated sand layer with very low permeability (Harbison and Cox, 1998). The unconfined aquifer is situated in a beach ridge system consisting of fine to medium Aeolian sand deposits based on USDA soil classification system (Gerakis and Baer, 1999), with a homogenous vertical particle size distribution.

2.2. Diurnal water table fluctuation method

The original White method (White, 1932) has performed with reasonable accuracy in environments with coarser sediments like sands and gravels (Loheide et al., 2005).

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

where S_y is the specific yield (−), r is the rate of water table rise at night-time (*e.g.* 00:00–04:00) (mm h^{-1}), and s is the net change in water table level over the 24 h period (mm).

A slight modification to the original White method was applied considering the night-time water use, where the net inflow rate to the point of measurement (*i.e.* well) at night was calculated from the day of interest and the following day (Loheide et al., 2005).

2.3. Water level monitoring and data processing

Four monitoring wells were installed in the shallow sandy aquifer in a 50 m by 50 m square within the pine plantation forest using a hand auger to a depth of 2.0–2.5 m. Each well was constructed from a 50 mm (ID) PVC pipe screened over the entire subsurface length to ensure no storage effect from the well structure. Augured sand was used to backfill the annular space to 0.1 m below the surface and bentonite was put around the well casing to seal from surface water impacts. Groundwater level monitoring was conducted using Level Troll 500 (In situ inc.) with a ventilation cable to avoid the measurement uncertainty from barometric corrections. The Level Troll 500 was set to log at a 15 min intervals. Water level dips were conducted on a monthly basis to quality control the groundwater level data. The logged water level data was processed using a median smoothing filter implemented by the MATLAB software to remove noise. Measurements from two wells along the diagonal line (*i.e.* W1 and W2) were selected for data analysis, as a complete data-set was available from these wells. Differences between the two wells were expected to be minimal, as the pine plantation forest was evenly distributed and little variation in topography was present at the site.

2.4. Specific yield

During the selected monitoring period, the water table was positioned within 0.4–1.2 m from the soil surface. Within this interval specific yield (S_y) cannot be assumed constant (Loheide et al., 2005). S_y values were thus determined at 0.1 m intervals from 0.1 m to 2.0 m below the soil surface using a combination of drainage experiments (Cheng et al., 2013) and numerical modelling (Shah and Ross, 2009).

Two undisturbed soil columns were excavated from the site using 0.8 m stainless steel pipes with an inner diameter of 150 mm. Each column was fully saturated and drained simultaneously layer by layer using 8 evenly spaced taps along one side the columns (4 replicate runs). Specific yield was then calculated for each layer using the drained water volume recorded by an electronic balance (Ohaus Scout-Pro balance: 0.01 g resolution). S_y was estimated for the midpoint between two drainage levels.

HYDRUS 1D software (Simunek et al., 2005) was also used to simulate drainage using in-situ measurements of layered soil water retention characteristics (*i.e.* 0.2 m intervals) fitted with the van Genuchten-Mualem constitutive relationship (Mualem, 1976; Van Genuchten, 1980). The initial water table depth was set at 0.1 m above the bottom of the column and the initial pressure distribution for all simulations was set as hydrostatic. In all