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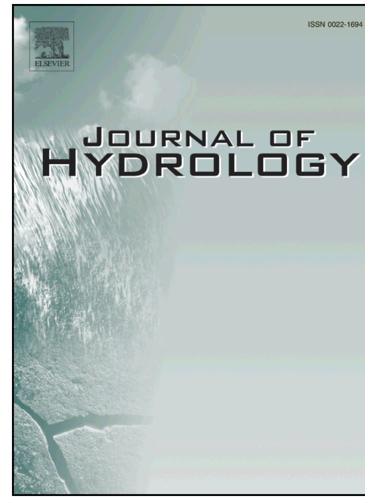

Research papers

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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 hr^{-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.

Key words

Pine plantation; diurnal water table fluctuations; White method; depth-dependent specific yield; night-time water use

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 et al. (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, S. P. 2008). Several studies have applied the methods in a variety of ecosystems ranging from wetlands (Mazur et al. 2013; McLaughlin & Cohen 2013), savannah (Miller et al. 2010) and forests (Vincke & Thiry 2008) to riparian corridors where most studies have been conducted (Butler Jr. 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, S.P. 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 & 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 (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% to 30 % of daily water use (Snyder et al. 2003; Bucci et al. 2004; Daley & Phillips 2006; Dawson et al. 2007; Novick et al. 2009; Zeppel et al. 2010) and Daley and Phillips et al. (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, CO_2, etc. 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.

Materials and Methods

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 x *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 & 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 & Baer, 1999), with a homogenous vertical particle size distribution.

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, S.P. et al. 2005).

$$ET_g = S_y\left(24r \pm s\right) \quad \text{(Eq. 1)}$$

Where, S_y is the specific yield (-), r is the rate of water table rise at night-time (*e.g.* 00:00 to 04:00) (mm hr^{-1}), and s is the net change in water table level over the 24 hr 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, S.P. et al. 2005).

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. Augered 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 minute 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.

Specific yield

During the selected monitoring period, the water table was positioned within 0.4 m to 1.2 m from the soil surface. Within this interval specific yield (S_y) cannot be assumed constant (Loheide, S.P. 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 & 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; M. Th. 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 eight simulations, the upper boundary condition was set as a zero flux boundary, while a gravitational drainage boundary condition (*i.e.* seepage) was defined at the bottom of the soil column. Each simulation was run until the model reached a steady state.

Estimated S_y values from both drainage experiments and numerical modelling are presented in Fig. 1, where D1 and D2 represent a local S_y measurement close to W1 and W2, respectively.

Fig.1

The drainage experiments were only able to estimate S_y down to 0.8 m due to the in-situ sampling process and high water table conditions. S_y values from drainage experiments were thus used from 0.4 m to 0.8 m and numerical modelling estimates from 0.8 m to 2.0 m. As seen in Fig. 1, the simulated values of S_y corresponded well with the experimentally measured values, especially at the 0.7 m to 0.8 m interval. The simulated S_y values were therefore expected to be able to represent actual S_y values at depths greater than 0.8 m. S_y for finer sediments is usually time dependent, but in coarser grained sediments, like the sandy sediment on Bribie Island, it is generally expected less dependent on time (Healy & Cook 2002).

Sap flux density measurements

Sap flux density (*SFD*) was measured using the commercially available heat ratio method (HRM) sap flow sensors (ICT International Pty Ltd, Armidale, Australia). A total of 6 trees were instrumented with HRM at breast height within a 50 m x 50 m plot with two HRM sensors per tree (*i.e.* North and South cardinal direction), each of these having 2 measurement points located at 12.5 mm and 27.5 mm into the sapwood given a total 24 measurement points. Measurements from two of the six trees closest to W1 and W2 (i.e. T1 and T2) were selected for further analysis in this study. Two sensors at two depths per tree have been shown to give a reasonable result, as compared to a benchmark of 24 measurement points in this particular conifer species (Guyot et al. 2015). The external temperature effect on sensors was limited under the canopy cover, but sensors were covered with foam insulating as a precaution. Measurements were corrected for the wounding effect following Burgess et al. (2001) based on the wound width determined from dummy probes installed simultaneously with SFD measurements. Wound width was determined from colour distinction and was measured after one month, six months and twelve months. The average wound width was 2.5 ± 0.3 mm and did not seem to increase over the study period after its initial stabilisation (*i.e.* one month). It was therefore assumed constant over the study period and between trees, although small variations between dummy probes were observed. Measurements of the gravimetric sapwood moisture content were conducted during wet conditions (*i.e.* February 2012) and during the transition to dry conditions (*i.e.* November 2012). Each time a total of 10 samples was collected. Gravimetric sapwood moisture content was found not to vary significantly between dry and wet conditions with an average value of 0.98 ± 0.18 $kg_{water}\ kg_{dry\text{-}wood}^{-1}$. A constant value of 0.98 $kg_{water}\ kg_{dry\text{-}wood}^{-1}$ was used with a dry wood density of 520 ± 8 kg m^{-3} for correction following Vandegehuchte & Steppe (2012c). Furthermore, each measurement probe was corrected for offset (*i.e.* probe misalignment) by examining the SFD at night when VPD and wind speed were close to zero. Zeppel et al. (2010) found no significant difference in offset correction when using this method compared to cutting the sapwood below and above the measurement probes.

Estimating tree stand transpiration flux

To upscale the whole tree transpiration flux to stand transpiration flux (T_{flux}), a linear relationship (R^2=0.92, p=0.03) between tree trunk diameter at breast height (DBH) and sapwood area ($A_{sapflow}$) in the pine plantation was established at the plot based on 11 cut stem samples (Fig. 2). The SFD measurements were upscaled to a 50 m x 50 m plot in this study.

Fig.2

Based on the developed linear relationship between *DBH* (cm) and sapwood area (cm^2) in Fig. 2, estimates of T_{flux} (mm hr^{-1}) can be calculated from:

$$A_{sapwood} = \sum_{i=1}^{n} \left(9.0 \cdot DBH_i + 38.6\right) \qquad \text{(Eq.2)}$$

$$T_{flux} = \frac{SFD_{avg} A_{sapwood}}{10^4 \cdot A_{plot}} \quad \text{(Eq.3)}$$

where n is the number of trees within the 50 m x 50 m plot, SFD_{avg} is the average area-weighted SFD (mm hr^{-1}) from the 6 monitored trees based on the positions of the radial measurement points, and A_{plot} is the area of the study plot (m^2).

Tree swelling and shrinkage

Point dendrometres were installed on the trunk at a height of 1.0 m above soil surface on the western tree side (Zweifel et al. 2006), so as to prevent from affecting sap flux measurements on the north and south sides. Stainless steel threaded rods anchored the instrument into the centre of the tree, while a temperature and insensitive carbon-fibre frame held the sensing rod against the tree at a perpendicular angle following Zweifel & Zeugin (2008). A major portion (*i.e.* 3 - 6 mm) of the outermost bark was removed with a rasp prior to installation, to minimise abiotic changes in diameter. A minimal layer of phloem (*i.e.* 1 - 2 mm) was retained to prevent any wound responses in the tree. Stem radius was measured at 10 minute intervals using a Campbell Science CR800 logger. The high-resolution point dendrometres (Zweifel Consulting, ZN-11-T-WP) had a temperature sensitivity of less than 0.28 micrometres per degree Celsius and a minimum resolution of 0.4 micrometres (Zweifel *et al.* 2006; Zweifel and Zeugin 2008). In addition to the robust, weather-resistant design of mounting hardware and dendrometre, a custom built two tiered plastic shelter was installed to shield from the effects of solar heating or rainwater wetting, while still enabling air circulation.

Soil matric potential

To obtain water content conditions in the unsaturated zone, soil matric potentials were monitored at depths of 0.2, 0.4, 0.6, and 0.8 cm by pF meters (GeoPrecision GmbH, Karlsruhe, Germany). Two soil matric potential profiles were installed 0.5 m away from the tree trunks of T1 and T2, respectively.

Micrometeorology

At the 50 m by 50 m plot, micrometeorological data, including air temperature and relative humidity (HMP155 sensor, Vaisala, Finland), net radiation (R_n) (CNR4 net radiometer, Kipp & Zonen, Delft, The Netherlands), wind speed and direction (03002 wind sentry set, RM Young, USA) were continuously measured at 1 min intervals and stored at 15 min intervals using a automatically recording datalogger (CR3000, Campbell Scientific, USA). Measurements were conducted 2 m above the forest canopy using a 15 m mast (Clark Mast, Belgium). Daily vapour pressure deficit (*VPD*) was calculated from air temperature and relative humidity, and reference evapotranspiration (ET_0) was estimated using the FAO Penman–Monteith equation (Allen et al., 1998).

Results

Seasonal variability

The study period covered the dry season of 2012 from August 1st to December 31st. Rainfall events did occur during the dry season with the largest event of 52 mm on November 18th (Figure 3a).

Fig.3

The atmospheric forcing on evapotranspiration from R_n and *VPD* strengthened from winter to summer (Figure 3b). A small data gap was present in the atmospheric dataset from the end of November to early December. Generally, the depth to groundwater table dropped from approximately 0.4 m to 1.2 m below the surface over the study period. However, obvious recharge from rainfall events occurring in September, October and November can be observed in the groundwater level signal, with the largest rise in November corresponding to the largest rainfall event on November 18th. The rainfall events in December were not detected in the groundwater level signal (Figure 3c). Days with more than 5 mm rise in groundwater level abruptly after rainfall events were excluded from the data analysis.

Soil matric potentials at 0.2 m and 0.4 m depths continued to increase from 0 to 1000 KPa over the study period, which indicated that the water content of upper soil layers declined from near-saturated to super dry conditions due to increasing soil evaporation and tree water uptake. However, decreases in soil matric potentials can also been seen from Figure 3c, following soil water replenishment by scattered rainfall events. Soil layers at 0.6 m and 0.8 m depths were saturated before November due to the high water table, but they stared to get drier as the water table dropped 1.0 m below the surface.

Diurnal water table signal

A clear diurnal signal was detected in both W1 and W2 (Figure 4). The time of decline in water table elevation corresponded with increase in *SFD*. Similarly, a rise in water table elevation in the afternoon was seen when *SFD* reduced. This suggested that the detected diurnal signal was a result of evapotranspiration from the groundwater. The magnitude of the diurnal signal between the two wells was slightly different, but small variations can be expected, as they both represented a local measurement of the unconfined aquifer.

Fig.4

Night-time observations

Night-time *SFD* varied between the presented days (Fig. 4) and was close to zero on the 3rd and 5th of August. However, T1 and T2 exhibited values that were close to zero at different times during those two days. On the other hand, SFD was found to be 20 to 40 mm hr^{-1} for the remaining days in which the SFD was not zero, which verified the presence of night-time water use, as it was considerably higher than the *SFD* equipment error up to 5 mm hr^{-1}. Measurements of diurnal shrinking and swelling of the tree trunk (Fig. 5) also verified the presence of T_n. Swelling occurred in the very late afternoon near sunset for both T1 and T2 when the evaporative demand decreased considerably (Fig. 5a and Fig. 5b). The swelling continued throughout the night and was replaced by shrinkage following an increase in evapotranspiration demand during the daylight hours. A time lag of approximately 2 hours from sunrise to shrinkage was found for both T1 and T2, which indicated that shrinkage started to occur at relatively higher evapotranspiration demands. The diurnal signal of *SFD* and cumulative radial growth of T1 and T2 clearly suggested that night-time water use happened in this particular conifer species. This can be a result of water storage in the tree trunk or transpiration.

Fig.5

Upscaled measurements of *SFD* from August to December showed a constant average transpiration flux (T_{flux}) of 0.02 mm hr^{-1} at the plot scale from 23:00 to 05:00 with the lowest T_{flux} occurring between 00:00 and 04:00 (Fig.6). This was in line with the original recommended time frame where White (1932) assumed T_n to be zero. For the purpose of this study an average T_{flux} from 00:00 to 04:00 for each day was used to test the implications from assuming T_n to be zero during this period of time.

Fig.6

Estimation of ET_g

The modified White method was applied from August 1st to December 31st except on days where recharge from rainfall was occurring. Daily ET_g fluxes varied between 0.3 and 4.6 mm day^{-1} and ET_g was found to gradually decrease with the increasing depth to the groundwater table (Fig. 7). The lowest ET_g estimate was found in December where groundwater level was at its lowest value (Fig. 3c), even though the highest values of R_n and *VPD* were observed in December.

Neglecting T_n can result in underestimation of daily ET_g, as r in reality will be larger than that when the night-time water use is present. Based on the average hourly T_{flux} from 00:00 to 04:00 for each day, the daily error on ET_g from neglecting T_n varied from 0.14 mm day^{-1} to 1.28 mm day^{-1} (Fig.7) with an average error of 0.50 mm day^{-1}. 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%.

Fig.7

Comparing daily ET_g with daily values of T_{flux} from the site revealed a trend of ET_g underestimating T_{flux} when T_n was not taken into account (Fig. 8a), except for shallow groundwater depths of 0.4 m to 0.6 m. When T_n was taken into account, a more evenly distributed relationship between ET_g and T_{flux} was achieved (Fig. 8b). A strong linear relationship between ET_g and T_{flux} was though not expected, as the trees water source could vary over time depending on soil moisture in the unsaturated zone.

Fig.8

Discussion

An apparent diurnal signal was observed in the shallow groundwater table below the pine plantation forest. Only Vincke and Theiry (2008) have discovered a similar signal for Pinus *sylvestris* L. in Belgium. The winter and early spring generally showed higher values of ET_g, although the highest R_n and *VPD* were recorded in the summer, indicating that the depth to the groundwater table played an important role in governing evapotranspiration. This trend could potentially be a result of estimation uncertainties of S_y, as it is known to introduce large errors in ET_g estimates if not determined properly (Loheide, S.P. et al. 2005). As depth-dependent S_y was determined vertically from in-situ drainage experiments, it was not expected to affect the ET_g estimation at different depths to groundwater table.

The progressive decline in ET_g with the increasing depth to the groundwater table also suggested that the pine root zone was restricted to approximately the first meter of the soil column under shallow groundwater conditions. Moreover, the majority of active roots were expected to be in the top 0.6 m of the soil column, as the soil matric potentials at depths of 0.6 m and 0.8 m (Fig. 3c) were still around 1 kPa in

December, indicating that the water content was above the field capacity. A similar extinction coefficient of 1.0 m below the soil surface was also suggested for pine trees and native vegetation on Bribie Island (Harbison & Cox 1998; Fan et al, 2014).

T_n was found to occur in this particular pine species, and assuming it to be zero at night-time can potentially introduce an error of 25% in the total ETg estimation over the study period. The highest daily error was found to be 1.24 mm day^{-1}. It is important to note that night-time water use may not only be a case of groundwater use, but could also be from soil water. The error was therefore considered as a potential maximum. In this case, it was expected to primarily be a case of groundwater use, as limited recharge occurred during the study period (Fig. 3c). Therefore, groundwater will be the primary source of water use by pine forests during the driest periods. The results indicate that the development of the commercial pine plantation may result in groundwater losses in these areas.

Previous studies have shown that T_n varied between species (Caird et al. 2007) and assuming it to be negligible without prior investigation can lead to significant underestimation of daily water use. T_n will most likely vary depending on climate zones, vegetation types and water availability. The experienced error at this site is likely to be different between sites and species. Therefore, a local and species specific knowledge of night-time water use is recommended prior to applying any diurnal water table methods. The sap flow technique can be useful tool to validate the assumption of zero night-time water use.

An absolute comparison between T_n and T_{flux} was not possible, but the relationship between $ET_g + T_n$ and T_{flux} showed that $ET_g + T_n$ overestimated T_{flux} during high water table conditions. This was expected as soil evaporation and transpiration from shallower scrubs was not included in the T_{flux}, whereas it was less likely to occur at deeper water table conditions. The overestimation of T_{flux} under dry conditions can be a result of the trees using water from the unsaturated zone instead of groundwater following the smaller rainfall events occurring in December. These rainfall events have not been detected in the groundwater signal, as the available water storage indicated by the high antecedent soil matric potentials (100 - 1000 KPa), hence the unsaturated zone had large capacity to absorb all infiltrated rainfall. Plants' capability of redistribution of soil water from wetter soil areas (*e.g.* capillary fringe or groundwater) to drier parts through hydraulic lift also has to be taken into account (Warren et al. 2007; Domec et al. 2010). This could support the higher T_{flux} during conditions with deeper groundwater tables, as redistribution of groundwater to the unsaturated zone will affect the calculation of the night-time slope similar to T_n. Although the depth-dependent S_y was properly determined in this study, S_y can be still dependent on time, which may also result in uncertainty in ET_g estimates.

Conclusions

The modified White Method with T_n correction was applied for the dry season of 2012 in the subtropical coastal climate at Bribie Island. Looking at the overall potential of the diurnal water table method in this environment, it is clear that it is capable of capturing the dynamics of ET_g. However, the subtropical coastal environment experiences a distinct wet season normally starting in early summer and continuing through spring, which limits the application of the White method, as groundwater recharge will conceal the diurnal water table signal for the majority of days (*i.e.* only possible to apply on 36% of the days in 2012).

Neglecting night-time tree water use was found to introduce an error of 25% on the estimate of accumulated evapotranspiration from groundwater when using a modification of the original diurnal water table fluctuation method. It is recommended that future application of any ET_g methods based on diurnal water table fluctuations assuming zero night-time water use investigates the validity of this assumption prior to use.

Moreover, the spatial representation is often based on a few discrete measurements (*i.e.* limited number of wells). As root distribution can vary significantly spatially, this method is more likely to be used in areas where a multiple-well network is available as part of a groundwater monitoring system to inform water balance models.

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