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Estimating groundwater recharge and evapotranspiration from water table fluctuations under three vegetation covers in a coastal sandy aquifer of subtropical Australia

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SUMMARY

To evaluate potential hydrological impacts of changes in vegetation over a shallow sandy aquifer in subtropical Australia, we estimated groundwater recharge and discharge by evapotranspiration (ET_g) under three vegetation covers. Estimates were obtained over two years (November 2011–October 2013) using the water table fluctuation method and the White method, respectively. Depth-dependent specific yields were determined for estimation of recharge and ET_g. Our results show that the average annual gross recharge was largest at the sparse grassland (~52% of net rainfall), followed by the exotic pine plantation (~39% of net rainfall) and then the native banksia woodland (~27% of net rainfall). Lower recharge values at forested sites resulted from higher rainfall interception and reduced storage capacity of the vadose zone due to lower elevations when the water table approaches the soil surface. During 169 rain-free days when the White method was applied, pine trees extracted nearly twice as much groundwater through ET_g as the banksia, whereas no groundwater use by grasses was detected. Groundwater use is largely controlled by meteorological drivers but further mediated by depth to water table. The resulting annual net recharge (gross recharge minus ET_g) at the pine plantation was comparable to that of the banksia woodland but only half of the corresponding value at the grassland. Vegetation cover impacts potential groundwater recharge and discharge, but in these subtropical shallow water table environments estimates of potential recharge based on rainfall data need to take into account the often limited recharge capacity in the wet season.

1. Introduction

Vegetation plays a significant role in the groundwater hydrological cycle due to its impact on groundwater recharge and transpirative discharge; conversely, groundwater hydrology impacts sensitive vegetation in shallow water table environments (e.g., wetlands or riparian areas). Vegetation affects groundwater recharge, and thus sustainable yields, indirectly by rainfall interception losses as well as extraction of infiltrating rainwater before it reaches the water table (Le Maitre et al., 1999).

The impact of changes in vegetation cover on groundwater hydrology has been investigated for a range of environments, mostly in (semi)arid or temperate areas with deep aquifer systems (e.g., Scanlon et al., 2005; Mao and Cherkauer, 2009; Brauman et al., 2012; Nosetto et al., 2012). Deep-rooted woody vegetation was generally found to reduce streamflow and groundwater recharge (Matheussen et al., 2000; Crosbie et al., 2010), compared to shallower-rooted grasses and crops, and they tend to tap groundwater with deeper rooting systems (Benyon et al., 2006; Pinto et al., 2013). For example, Scanlon et al. (2005) found that the conversion of natural shrublands with agricultural ecosystems in southwest US altered the water flow from discharge through *ET* (i.e., no recharge) to recharge (9–640 mm yr^{-1}). Benyon et al. (2006) reported that plantations of *Pinus radiata* D.Don and *Eucalyptus globulus* Labill. used groundwater at an average rate of 435 mm yr^{-1} (40% of total water use) in the Green Triangle of southeast Australia. However, while coastal systems are under pressure from human development as well as potential stresses due to climate change, there are few studies quantifying the hydrological effects of vegetation cover changes in coastal areas characterized by shallow aquifer systems with highly permeable sediments.

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Like other coastal and island sand mass aquifers around the world, significant resources of high quality groundwater are located on Bribie Island for water supply to coastal communities and local wetland vegetation. Over the past three decades, exotic pine tree plantations have been developed on the island largely for timber production, particularly in the natural distribution areas of native vegetation (e.g., banksia woodland and grassland). The changes in vegetation cover can potentially affect the local hydrological processes, e.g., groundwater recharge and evapotranspiration (*ET*).

In shallow water table environments, groundwater recharge and groundwater use by vegetation via evapotranspiration (ET_g) can be estimated from analyses of water table fluctuations (e.g., Scanlon et al., 2005; Crosbie et al., 2005; Mould et al., 2010; Zhu et al., 2011; Yin et al., 2013; Fahle and Dietrich, 2014). For such analyses, quantification of the aquifer's specific yield (S_y) is considered the main source of uncertainty as its error is translated directly to final estimates (Scanlon et al., 2002; Loheide et al., 2005). Various methods (e.g., laboratory experiment, field study and numerical modelling) are available for determining specific yield, but they usually produce inconsistent values (Neuman, 1987; Crosbie et al., 2005). Specific yield is often considered constant in hydrological studies. However, researchers have recognized that it is dependent on water table depth and drainage time (Duke, 1972; Nachabe, 2002; Shah and Ross, 2009), particularly in a shallow water table environment due to a the truncation of the equilibrium soil moisture profile at the soil surface (Childs, 1960). Use of a constant specific yield can lead to the recharge and ET_g being significantly overestimated (Sophocleous, 1985; Loheide et al., 2005). Loheide et al. (2005) suggested the readily available specific yield can be used to obtain reasonable estimates of ET_g when the water table depths >1 m, but the dependence of S_y on the water table depth needs to be considered for water table depths <1 m. In spite of this, the depth-dependant specific yield has seldom been adopted for the estimation of recharge and ET_g in published studies (e.g., Crosbie et al., 2005; Carlson Mazur et al., 2013).

Here, we investigate shallow water table fluctuations in response to rainfall and ET_g under three vegetation covers to gain a better understanding of the hydraulic relationship between vegetation and groundwater in shallow sandy aquifers. Specific objectives of this study are to: (1) examine how water table depth varies daily and seasonally under a pine plantation, a banksia woodland and a sparse grassland; (2) determine depth-dependent specific yields under both rising and falling water table conditions; (3) estimate daily and seasonal groundwater recharge and ET_g under three contrasting vegetation covers; and (4) identify the controlling factors on groundwater yields in shallow sandy aquifer systems.

2. Materials and methods

2.1. Site description

The study was undertaken on an unconfined surficial aquifer on Bribie Island (26°59′04″S, 153°08′18″E), southeast Queensland, Australia (Fig. 1). The island stretches approximately 30 km from north to south and has an average width of 5 km with a total area of 144 km^2 (Isaacs and Walker, 1983). This area experiences a subtropical climate with a hot humid summer and a mild dry winter. Mean annual rainfall over the past 30 years is 1405 (±338) mm with 70% of annual rainfall typically occurring during the wet season (November to April). The average monthly temperature ranges from 16.2 °C in July to 26.6 °C in January. Bribie Island has an average elevation of ~5 m Australian Height Datum (AHD) with the maximum value of 13 m AHD. The topography consists largely of the elevated areas which correspond to two parallel sand dune ridges and a separating swale. However, the island is generally considered to be one of low relief. The extensive unconfined upper aquifer consists of fine to medium sands lying over cemented low permeability layers, with an average water table depth of ~1.2 m below land surface. Using a constant head permeameter (Eijkelkamp-Agrisearch Equipment, Giesbeek, the Netherlands), an average saturated hydraulic conductivity of 8.5 m d^{-1} was determined for the unconsolidated sands.

The exotic pine trees have replaced large areas of native banksia vegetation along the two major sand dune ridges on the island. To minimize the effect of tides and groundwater pumping on water table fluctuations, three field sites with different vegetation cover were carefully selected in the interior of the island (Fig. 1). These were along a belt transect which was normal to the coastline and crossing a relatively elevated section (dune). The transect is aligned with expected groundwater flow to adjacent wetlands. Two study sites were established in the pine plantation and banksia woodland, ~400 m from each other. The site areas are 50 m × 50 m (~8.4 m AHD) and 25 m × 25 m (~7.8 m AHD) for pine plantation and banksia woodland, respectively (Fig. 1). The pine hybrid (*Pinus elliottii* Engelm. × *Pinus caribaea* Morelet var. *hondurensis*) was planted in 2001 with roughly 5.0 m × 2.5 m spacing. The pine trees reached an average height of 13.3 m, with a stem density of 840 trees ha^{-1} and a stand basal area of 23.6 m^2 ha^{-1}. The native banksia woodland was largely dominated by wallum banksia (banksia *aemula* R.Br.) with an average tree height of 6.8 m. The woodland had a stem density of 371 tree ha^{-1} and a basal area of 21.3 m^2 ha^{-1}. A third grassland site (30 m × 30 m) between the other two sites (but closest to the pine plantation at around 50 m distance) was covered with sparse grasses (*Leptocarpus tenax* R.Br.) and with a higher surface elevation of ~9.3 m AHD.

2.2. Field data acquisition

To characterize water table fluctuations for the vegetation covers, each field site was instrumented with a cluster of three monitoring wells (in triangle arrangement at 20–40 m spacing) equipped with pressure transducers (Level Troll 300, In-Situ Inc., USA). The average water levels obtained from three wells were used for estimates of recharge and ET_g at each site. Monitoring wells were installed to a depth of 2.0 m using a 51 mm diameter, 1.5 m long PVC screen and 1.5 m PVC riser. Augered sand was backfilled around the wells to a depth of 0.25 m below land surface and granular bentonite was then packed around land surface to avoid preferential flow. Apart from water pressure measurements, atmospheric pressure was monitored using a barometric datalogger (Baro Troll 100, In-Situ Inc., USA) to obtain water levels. The monitoring wells were vented to connect with the atmosphere and prevent air compression inside the PVC tubing. The water level data were measured from 1 November 2011 to 31 October 2013 and automatically recorded at 15-min intervals. Data were collected quarterly from the pressure transducers and the water table depth was manually measured by a dip meter during each field trip to check the logged water level values.

An automatic weather station was installed on a 15-m-high mast located above the canopy and in the center of the pine plot to measure meteorological variables, including temperature and relative humidity, wind speed and direction, solar radiation and soil heat flux. Potential evapotranspiration (PET) was estimated using the Penman–Monteith equation (Monteith, 1965) with parameters obtained from the pine plantation (Fan et al., 2014). Gross rainfall was measured using a tipping-bucket rain gauges (RG3-M, Onset Computer Corp., USA) located in a nearby well-exposed clearing next to the banksia woodland. To obtain the net