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Characterising groundwater use by vegetation using a surface energy balance model and satellite observations of land surface temperature

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ABSTRACT

This study presents a novel 'model-data' approach to detect groundwater-dependent vegetation (GDV), through differences in modelled and observed land surface temperatures (LST) in space and time. Vegetation groundwater use is inferred where modelled LST exceeds observed LST by more than a threshold determined from consideration of systematic and random errors in model and observations. Modelled LST was derived from a surface energy balance model and LST observations were obtained from Terra-MODIS thermal imagery. The model-data approach, applied in the Condamine River Catchment, Queensland, Australia, identified GDV coincident to existing mapping. GDV were found to use groundwater up to 48% of the time and for as many as 56 consecutive days. Under driest of conditions, groundwater was estimated to contribute up to 0.2 mm h^{-1} to total ET for GDV. The ability to both detect the location and water-use dynamics of GDV is a significant advancement on previous remote-sensing GDV methods.

1. Introduction

The role of groundwater in maintaining ecosystem function is being increasingly recognised particularly during droughts (Amlin and Rood, 2002; Froend and Sommer, 2010; Kath et al., 2014; Naumburg et al., 2005). Globally increasing demand for groundwater resources in intensive multi-user landscapes is necessitating development of new methods for managing the spatio-temporal components of this resource and its associated impacts on natural groundwater-dependent ecosystems (GDEs). This includes those vegetation communities that are occasionally dependent on groundwater resources for maintenance of critical ecosystem function during protracted or seasonal droughts (Murray et al., 2003).

Traditional, field-based methods for examining water use, such as stable isotope analysis, sap flow measurements and eddy covariance technologies (e.g. Busch et al., 1992; Cramer et al., 1999; Thorburn et al., 1993; Zencich et al., 2002) have been successfully combined to determine the source, timing and/or magnitude of groundwater use at tree to plot scales (Eamus et al., 2015). However, these field programs are labour intensive and results can be difficult to extrapolate beyond the plot scale (Barron et al., 2014; Richardson et al., 2011). In contrast, satellite remote-sensing techniques can potentially identify groundwater use by vegetation at landscape, region, and continent scales (Glenn et al., 2007; Guerschman et al., 2009), through (1) empirical correlation studies between measured reflectance from plants and physiological properties (e.g. Barron et al., 2014; Fu and Burgher, 2015; Gou et al., 2015; Kath et al., 2014), (2) reflectance-based evapotranspiration (ET) studies (e.g. Guerschman et al., 2009; Maselli et al., 2014; Nagler et al., 2008); or (3) thermal-based, surface energy balance (SEB) ET measurement and modelling studies (e.g. Bastiaanssen et al., 1998; McVicar and Jupp, 2002; Thevs et al., 2015). Integrated groundwater-surface water models (e.g. Surface Water and Assessment Tool (SWAT) – Modular Three-Dimensional Finite-Difference Groundwater Flow (MODFLOW) model) can also be used to simulate groundwater ET (Kim et al., 2008).

Empirical correlation methods applied at fixed points in time (e.g. Barron et al., 2014; Fu and Burgher, 2015; Gou et al., 2015; Kath et al., 2014) make inferences about the potential for groundwater use based on the persistence of vegetation wetness and/or

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greenness. However, such methods are unable to quantify the volume of water use and may omit GDEs that are dependent on groundwater for short periods due to impacts of image temporal frequency (Lunetta et al., 2006, 2004; Kennedy et al., 2010). In contrast, existing remote sensing techniques that directly estimate ET using reflectance-based indices or physically-based energy balance approaches can be used to infer the timing and magnitude of groundwater use by vegetation at the landscape or larger scale through a simple correlation with precipitation. Where ET is larger than accumulated rainfall, the difference is assumed from groundwater (Beamer et al., 2013; Gokmen et al., 2013; Groeneveld, 2008; NWC, 2012a). However, empirical-based ET methods: (1) often use vegetation or moisture indices correlated with ET, which are not directly measurable in the field; (2) focus on detecting changes in canopy structure, thus are more suitably applied at corresponding temporal scales of months to years; and (3) are developed from often highly localised field observations, limiting their application to other vegetation types and different landscapes (Glenn et al., 2007; Guerschman et al., 2009; Scott et al., 2008).

Physically-based methods that use remotely-sensed observations of LST as model input to solve the SEB equation for estimated ET are, when coupled with soil moisture data, able to resolve variation in ET due to stomatal responses on all time scales (Glenn et al., 2007; Guerschman et al., 2009). While an improvement over methods using vegetation indices as empirical surrogates for ET (e.g. Guerschman et al., 2009; Maselli et al., 2014; Nagler et al., 2008), these thermal-based, SEB ET methods (e.g. Bastiaanssen et al., 1998; Li and Lyons, 2002; McVicar and Jupp, 2002; Thevs et al., 2015) remain reliant on remotely-sensed LST data, which when used to directly estimate latent and sensible heat fluxes, can introduce errors of up to 75% (Timmermans et al., 2007). Furthermore, some methods (e.g. SEBAL) require the presence of cool/wet and warm/dry pixels to constrain quasi-linear relationships (Kalma et al., 2008).

Determining the groundwater component of ET using SEB methods or groundwater models requires accurately accounting for all other components of the water balance (i.e. rainfall, soil water storage, groundwater recharge etc.) with groundwater ET the residual. The integrated groundwater-surface water SWAT-MODFLOW model capitalises on the ability of SWAT to compute groundwater recharge and MODFLOW to characterise groundwater flow to more accurately account for water balance components (Kim et al., 2008). However, SEB groundwater-ET studies and groundwater-surface water models are still sensitive to accuracy in precipitation data (e.g. Peeters et al., 2013; van Eekelen et al., 2015), which is subject to interpolation errors (Jeffrey et al., 2001; Jones et al., 2009). Furthermore, integrated groundwater-surface water models are highly parameterised, with considerable uncertainty associated with model inputs (Kim et al., 2008). Consequently inferred ET from groundwater can remain highly uncertain.

A recent study by Hain et al. (2015) identified neglected soil water source-sink processes through the comparison of Atmospheric-Land Exchange Inverse (ALEXI) model derived latent heat flux estimates and latent heat predicted by the Noah land surface model (Hain et al., 2015). The ALEXI Source-Sink for Evapotranspiration (ASSET) index developed by Hain et al. (2015): (1) is a qualitative indictor only; (2) is not able to differentiate easily between sources of neglected water (i.e. irrigation versus groundwater) without ancillary datasets; (3) is applicable at regional to continental scales, rather than at the local scale; and (4) has not been applied to the characterisation of water use dynamics (Hain et al., 2015). However, the study by Hain et al. (2015) highlights the potential advantages of comparing components of the surface energy balance derived from independent sources.

Considering the limitations associated with existing methods and the insight provided by Hain et al. (2015), this paper proposes a novel 'model-data' approach to detection of groundwater dependence of ET, whereby groundwater-use is detected by comparing SEB model derived LST ($T_{s.mod}$) with equivalent satellite observations of LST ($T_{s.obs}$) taking into account the requisite model and observation errors. The value of LST as a measure of ET by vegetation is well known (Anderson et al., 2011; Friedl, 2002; Glenn et al., 2007; Moran, 2003; Ozdogan et al., 2010; Ozdogan and Gutman, 2008; Zarco-Tejada et al., 2013). Taking into account all other factors (e.g. wind speed, vapour pressure, air temperature etc.), when surface soil moisture is depleted, systems with access to groundwater will have a cooler LST than systems that do not. Soil moisture is a useful surrogate of time since previous rainfall event. The SEB model used to derive $T_{s.mod}$ accounts for soil moisture in the unsaturated zone whereas $T_{s.obs}$ as observed by the satellite sensor is dependent on all available water sources. The residual 'signal' contained in model-data differences in LST, after errors are eliminated, is attributed to groundwater use. Strengths of this approach over existing ET-based methods are: (1) the use of a two-layer SEB model which better represents physical processes than single-layer or 'big-leaf' SEB models (Overgaard et al., 2006); and (2) the SEB model is forced by spatially-interpolated meteorological, soil moisture and radiation data, so is independent of satellite observations of LST. This avoids circularity in the detection of groundwater-dependent ET by vegetation.

In this study, we aimed to: (1) assess the ability of satellite thermal data to detect variation in groundwater use by vegetation taking into account the errors in the model and data; and (2) use the model-data method to detect and quantify groundwater use by vegetation in a subtropical mixed-woodland-agricultural landscape. In this paper, we describe the proposed LST model-data approach to detect variation in groundwater use by vegetation; estimate systematic and random model-data errors; and quantify inferred groundwater use in a subtropical mixed-woodland-agricultural study area.

2. Data & methods

2.1. Model-data approach to detect GDV

The model-data approach to mapping groundwater use by vegetation compares LST derived from a two-layer SEB model ($T_{s.mod}$) with LST retrieved from satellite thermal imagery ($T_{s.obs}$). Groundwater use by vegetation was evident where $T_{s.mod}$ exceeded $T_{s.obs}$ by a threshold (e), chosen from consideration of errors in both the model and observations. This inference was based on an assumption that $T_{s.mod}$ provided information, when all other factors (e.g. wind speed, vapour pressure, air temperature etc.) were taken into account, on transpiration supported by shallow soil moisture only, while $T_{s.obs}$ as observed by the satellite sensor, was determined under the same meteorological conditions as the model but from all available water sources including groundwater. The SEB model was resolved at 250 m and was averaged to 1-km resolution corresponding with $T_{s.obs}$ data. The method was applied daily at the time of Terra-MODIS overpass for the entire study area (3200 km^2), for all dates (n = 4617) between 02/02/2000 and 22/09/2012. All processing was done using the R statistical computing and graphics program.

2.1.1. SEB model

The two-layer SEB model used in this study (see Appendix A) is a modification of the model described by Friedl (2002, 1995). The model comprises six equations solved simultaneously for three temperature (soil, vegetation and at the effective height of heat exchange) and three vapour pressure variables (soil, vegetation and