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Estimating groundwater contribution to transpiration using satellite-derived evapotranspiration estimates coupled with stable isotope analysis

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ABSTRACT

The relative importance of groundwater (GW) to sustain terrestrial vegetation has been well documented. However, quantifying GW use by riparian vegetation in data scarce regions may prove to be challenging. For this purpose, we coupled evapotranspiration (ET) estimates from the satellite-based surface energy balance system (SEBS) model with stable isotope analysis, to map and quantify the contribution of GW to transpiration (ET_g), along the lower reaches of a perennial river system, in the semi-arid north-eastern region of South Africa. Plant stem, soil, stream and GW samples were collected on 3 sampling occasions during the 2016 dry season. δ^2H and δ^{18}O values of the respective samples were measured and analysed. We found that while GW use was prevalent and increased with aridity, overall ET_g was fairly minimal. During the initial stages of the dry season ET_g for the study area was extremely low, approximately 0.10% of daily ET or 0.01 mm d^{-1}. However, as aridity increased, ET_g increased to approximately 10% of daily ET or 0.30 mm d^{-1}. The results of these various investigations undertaken demonstrates the potential of coupling satellite-based ET approaches with stable isotope analysis, to quantify spatial and seasonal dynamics in ET_g.

1. Introduction

In arid and semi-arid environments groundwater (GW) is often the most important source of freshwater for human consumption, for vegetation and makes a significant contribution to streamflow (Lange, 2005). Therefore, balancing the amount of GW that is used for basic human needs with environmental water requirements (EWR) is crucial for successful water resource management in these regions (Tanner and Hughes, 2015). According to Eamus et al. (2015), quantifying seasonal and spatial variations GW consumption by vegetation is one of the key areas which can facilitate the sustainable management of GW resources, especially the EWR flow allocations of this resource.

In the last decade, ET estimation, has substantially benefited from advancements in satellite earth observation techniques (SEO) (Nourhi et al., 2013). SEO techniques can be used to quantify the water use of riparian vegetation and are often utilized to overcome spatial limitations generally associated with conventional approaches, such as *inter alia*; FAO 56 Penman Monteith reference evaporation, eddy covariance, scintillometry (Allen et al., 1998; Savage et al., 2004; Fernández-Prieto et al., 2012; Jassas et al., 2015). Furthermore, SEO can be used to acquire data in remote and data scarce regions, as well as allowing for seasonal and inter-annual comparisons of hydro-meteorological variables due to the periodic updating of information (Gokool et al., 2017a).

Despite these advantages, the trade-off between the spatial and temporal resolution of available imagery and the ability of the models to accurately estimate fluxes and ET in different environmental settings, may limit the use of SEO technologies to guide water resources management decisions (Gokool et al., 2017a). While there exist approaches to address these limitations and improve upon the accuracy of ET estimates (Hong et al., 2011; Pardo et al., 2014; Gokool et al., 2017a), the ET estimate provided is often the total water used from multiple sources such as; soil water, GW or stream water. Therefore, the ET estimate acquired by these techniques requires further disaggregation to determine ET_g (Eamus et al., 2015).

Several studies have identified approaches to quantify subsurface moisture dynamics at varying spatial and temporal scales, because the movement of water in the soil-root system plays a significant role in regulating ecohydrological processes at the surface (Kumar et al., 2014; Daly et al., 2017). These techniques include; conventional approaches

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(time-domain reflectometry, gravimetric methods and neutron probes), isotope hydrology, geophysical techniques (electrical resistivity imaging), the cosmic ray probe, SEO data and root water uptake models (Robinson et al., 2012; Villarreyes et al., 2013; Kumar et al., 2014; Mares et al., 2016; Daly et al., 2017; Zhang et al., 2017).

Isotope hydrology and in particular environmental isotopes (stable and radioactive) techniques are amongst the most effective and frequently used tools to understand and quantify soil-plant-water dynamics (Yang et al., 2010; Penna et al., 2013). While both radioactive and stable isotopes have been extensively applied for ecohydrological investigations (Marwick et al., 2015; Thaw et al., 2016; Zhang et al., 2017; Evaristo and McDonnell, 2017), the use of stable isotope techniques has generally been applied more frequently for quantifying the depth and sources of water uptake for transpiration (Penna et al., 2013; Thaw et al., 2016).

For most species and locations, the uptake of water during transpiration does not generally result in the fractionation of oxygen-18 (^{18}O) and deuterium (^{2}H) within non-photosynthesising tissue (Evaristo and McDonnell, 2017). The isotopic composition of ^{18}O and ^{2}H of xylem water should represent the sources present within the root zone (Evaristo and McDonnell, 2017). Although this assumption has been supported and well documented in various soil-plant-water interaction studies (Zimmermann et al., 1966; White et al., 1985; Walker and Richardson, 1991; Dawson et al., 2002), it should be noted that certain plant species within particular environmental settings may fractionate ^{2}H during root water uptake (see: Lin and da Sternberg, 1993; Ellsworth and Williams, 2007; Zhao et al., 2016; Evaristo et al., 2017).

In this study, we aimed to quantify ET_g along the riparian zone situated in the lower reaches of a perennial river system in the semi-arid north-eastern region of South Africa, employing a relatively simplistic approach that requires two independent types of data; (i) daily estimates of ET and (ii) the stable isotopic composition of ^{18}O and ^{2}H of xylem water and all possible sources.

Once the proportional contribution of these sources to the xylem water has been established, ET_g can be derived as the product of the GW proportion and ET (Eamus et al., 2015). Based on the aforementioned approach, we implemented the satellite-based Surface Energy Balance System (SEBS) Model and two approaches, to quantify daily ET at a moderate spatial resolution (MSR) (Gokool et al., 2017a).

ET estimates acquired from these approaches were evaluated against *in-situ* measurements of ET acquired from a one-sensor (excludes Infra-Red Gas Analyser) Eddy Covariance system (EC_{ET}), in order to determine which approach most adequately represents the ET for the portion of river reach studied. During a separate investigation, we coupled isotope analysis of ^{18}O and ^{2}H with a Bayesian mixing model to determine the proportional contribution of water sources to transpiration.

The results from these investigations were then used to provide insights on spatial and seasonal dynamics in ET_g within the study area. Furthermore, the timing of this study also coincided with a large El Nino induced drought period (Kogan and Guo, 2016), providing further insights into plant water use dynamics during extreme drought conditions.

2. Methodology

2.1. Study area

The study site is situated in the Limpopo Province in the north-eastern region of South Africa, along the lower reaches of the Groot Letaba River between Letaba Ranch (B8H007; 23.658° S; 31.047° E) and Mahale (B8H007; 23.669° S; 30.991° E) weirs, as depicted in Fig. 1. According to Pollard and du Toit (2011), the Letaba River system often experiences water shortages and restrictions and has frequently been unable to meet its EWR. Therefore, understanding and accurately quantifying the dynamics of vegetation water use requirements in this region, is essential to maintain the natural functioning of this environment. A semi-arid climate, characterized by hot wet summers and mild dry winters is experienced across the region. Mean annual temperatures vary across the region ranging from 18 °C in the mountainous areas to 28 °C in the eastern regions (Katambara and Ndiritu, 2010).

A majority of the rainfall occurs in the summer months (October to March) and is predominantly characterized by thundershowers occurring from the north and north-east, as well as from tropical cyclones originating over the Indian Ocean (Katambara and Ndiritu, 2010; February et al., 2007). According to Heritage et al. (2001) approximately three quarters of the catchment is underlain by granite and gneiss. There exists a variety of morphological units within the study area which is due to the varied distribution of sediment along the river. The portion of the Groot Letaba River flowing through the study area is largely characterized by alluvial channel types (Heritage et al., 2001). The study area was categorized into three separate geomorphological zones during sampling. These were; i) the near stream northern and ii) southern banks which includes the alluvial terrace situated adjacent to the active stream channel, as well as iii) within the active river channel.

The total area of the river channel and riparian zone contributing to ET was estimated to be approximately 1.96 km^2. This was calculated by summing up the width of the river channel (approximately 60 m and constitutes 50% vegetation, 30% bare soil and 20% open water) and riparian zone (40 m on either side of the channel and complete vegetation coverage) and multiplying it by the longitudinal distance of the portion of river reach studied between the two weirs (14 000 m) (Gokool et al., 2017a; Riddell et al., 2017).

A variety of woody plant species were situated along geomorphological zones i and ii. The common species included; *Ficus sycomorus*, *Philonoptera violecia*, *Diospyros mespiliformis, Colophospermum mopane*, *Combretum microphyllum*, *Gymnosporia senegalensis*, *Cassia abbreviata and Ziziphus mucronata*. While the predominant plant species situated within geomorphological zone iii is *Phragmites mauritianus*. Additionally, numerous agricultural fields, predominantly planted with *Cucurbita moschata* and *Medicago sativa* are situated further away from the active river channel. These were however not considered during sampling.

43 individual trees from the abovementioned species; 9 *F. sycomorus*, 8 *P. violecia*, 10 *D. mespiliformis*, 3 *C. mopane,* 3 *C. microphyllum*, 5 *G. senegalensis* and 5 *Z. mucronata* distributed among the six sampling regions, were randomly selected and sampled for subsequent stable isotope analysis (Lin et al., 2016). These sampling regions were categorized, according to their respective locations with regards to Letaba Farm (20 trees) and Letaba Ranch (26 trees). Fig. 1 provides a Google Earth™ illustration of the sampling regions distributed between the farming areas and Letaba Ranch.

2.2. Estimation of daily ET

SEBS was applied in this study to estimate daily ET. Su (2002) provides a detailed conceptualization of the model. However, the underlying principle of SEBS, is to compute all components of the shortened surface energy balance (Equation (1)), as well as the evaporative fraction (*EF*), using land surface parameters which are derived from meteorological and SEO sources, respectively (Su, 2002).

$$R_n = \mathrm{Go} + \mathrm{H} + \lambda \mathrm{E} \quad (1)$$

Where *Rn* is net radiation (W m^{-2}), G_0 is soil heat flux (W m^{-2}), *H* is sensible heat flux (W m^{-2}) and λ*E* is the latent heat flux (W m^{-2}).

While the original SEBS formulation ($SEBS_O$) has been widely implemented and shown to be a credible approach for the estimation of regional fluxes and ET. Studies (Pardo et al., 2014; Gokool et al., 2017a) have shown, that the model may over-estimate the *EF* and subsequently the ET during conditions of water stress, as it is unable to adequately account for the influence of soil moisture availability and biophysical characteristics during the estimation of ET. Subsequently, a modified