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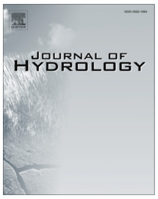

Research papers

Groundwater and unsaturated zone evaporation and transpiration in a semi-arid open woodland

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ABSTRACT

Studies on evapotranspiration partitioning under eddy covariance (EC) towers rarely address the separate effects of transpiration and evaporation on groundwater resources. Such partitioning is important to accurately assess groundwater resources, especially in arid and semi-arid areas.

The main objective of this study was to partition (evaluate separately) the evaporation and transpiration components of evapotranspiration, originated either from saturated or unsaturated zone, and estimate their contributions in a semi-arid area characterized by relatively shallow groundwater Table (0–10 m deep).

Evapotranspiration, tree transpiration and subsurface evaporation were estimated with EC tower, using sap flow methods and HYDRUS1D model, respectively. To set up the HYDRUS1D model, soil material properties, soil moisture, soil temperature, soil matric potential and water table depth were measured in the area. The tree transpiration was sourced into groundwater and unsaturated zone components ($\sim$0.017 mm d^{-1} for both) and accounted for only $\sim$6% of the evapotranspiration measured by the EC tower ($\sim$0.565 mm d^{-1}), due to the low canopy coverage in the study area (7%). The subsurface evaporation fluxes were also sourced into groundwater and unsaturated zone components using the SOURCE package, and their relative relevance in total evapotranspiration was assessed.

Subsurface evaporation was the main flux year-round ($\sim$0.526 mm d^{-1}). During late autumn, winter and early spring time, the unsaturated zone evaporation was dominant, while in dry summer the relevance of groundwater evaporation increased, reaching one third of evapotranspiration, although errors in the water balance closure point still at its possible underestimation. The results show that, in arid and semi-arid areas with sparse vegetation, the often neglected groundwater evaporation is a relevant contribution to evapotranspiration, and that water vapor flow should be taken into account in the calculation of extinction depth.

1. Introduction

In arid and semi-arid areas the scarce water resources are usually stored as groundwater. While the precipitation in the Mediterranean region is decreasing (Gualdi et al., 2013; Mariotti et al., 2015), the demand for the limited groundwater resources is increasing (Scanlon et al., 2006). In such conditions it is imperative to quantify the main water input constraining groundwater resources, i.e. the net groundwater recharge (Chenini and Ben Mammou, 2010). The evapotranspiration of groundwater resources is often underestimated, both because evaporation processes are not yet included in the theory (Zeng et al., 2011a) and because transpiration from roots tapping the water table is not taken into account (Favreau et al., 2009; Miller et al., 2010). The underestimation of groundwater evapotranspiration often results in the overestimation of the net recharge. Therefore it is critical to define accurately groundwater evapotranspiration which may represent a small but relevant reference percentage of total evapotranspiration.

There are various methods to estimate groundwater recharge, but it is difficult to know which one is the most reliable (Scanlon et al., 2002); for routine recharge estimation the best choice is a soil moisture recharge technique, provided all the important physical and physiological processes are represented adequately (Rushton et al., 2006). For example, water infiltrating in the soil after sparse rain events often evaporates completely before

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reaching the water table (Tweed et al., 2011); another example is that of the transpiration of water from trees, which can tap the water table with their roots (Favreau et al., 2009; Miller et al., 2010). A good knowledge of evapotranspiration processes is, therefore, fundamental to sustainable agriculture and groundwater management, particularly in water scarce environments.

During dry seasons, mainly in arid and semi-arid locations, high evapotranspiration (ET) quickly depletes the unsaturated zone water, exposing the saturated zone to groundwater evapotranspiration (ET_g) or, following the partitioning concept, to the processes of groundwater evaporation (E_g) and groundwater transpiration (T_g). The process of separating saturated from unsaturated zone fluxes is hereafter referred as *sourcing*.

ET is composed of two different processes, the physical process of evaporation and the biological process of transpiration, the two having different spatial and temporal characteristics (Lubczynski, 2009). ET includes three components: surface evaporation (E_s), which includes evaporation from surface water (rivers, lakes and other surface water bodies) and from water intercepted by plants; evaporation of water from below the ground surface (E_{ss}, subsurface evaporation) (Kampf et al., 2005); and transpiration of water by plants (T_{ss} Scott et al., 2003; Miller et al., 2010), together defined as subsurface evapotranspiration (ET_{ss}). The process of separating different components of ET is referred here as *partitioning*. This study presents an experimental, field based example of such partitioning and sourcing.

In this paper, we followed the terminology of Lubczynski and Gurwin (2005):

$$ET = E_s + ET_{ss} \tag{1}$$

$$ET_{ss} = E_{ss} + T_{ss} = ET_u + ET_g \tag{2}$$

$$ET = E_s + (E_u + T_u) + (E_g + T_g) \tag{3}$$

ET_g is groundwater evapotranspiration ($ET_g = E_g + T_g$) where E_g and T_g are the respective evaporation and transpiration components depleting groundwater; ET_u is the unsaturated water evapotranspiration ($ET_u = E_u + T_u$), where E_u and T_u are the respective evaporation and transpiration components depleting the unsaturated zone (all in $\mathrm{L\,T^{-1}}$ units). Subsurface evaporation is $E_{ss} = E_u + E_g$ and plant transpiration is $T_{ss} = T_u + T_g$.

In recent years, interest in ET_{ss} partitioning into T_{ss} and E_{ss} has increased due to the development of new monitoring methods, which permit independent measurement of various water fluxes at different time scales and under different climatic conditions (Zhang et al., 2016). Both the Bowen ratio (only in wet conditions) and the eddy covariance (EC) methods (Perez et al., 1999) permit reliable measurement of latent heat flux (and therefore ET) but over relatively small areas and only in specific conditions (e.g. stable conditions for Bowen ratio). Thanks to so called *footprint* models, the area sampled by both Bowen ratio and EC methods can be determined with large spatial and temporal precision. Besides, it is possible nowadays to estimate E_{ss} from models applying semi-continuous soil moisture and matric potential profile measurements (Kizito et al., 2008), while E_s can be estimated from pan evaporation and measurement of tree interception using tipping buckets and gutters placed under a tree canopy (Ghimire et al., 2012; Ghimire et al., 2017) and by interception models. Finally, in situ sap flow measurements (Granier, 1985) can be used to estimate tree transpiration (T_{ss}) when using appropriate sampling, measuring and upscaling techniques (Granier, 1987; Reyes-Acosta and Lubczynski, 2013; Reyes-Acosta and Lubczynski, 2014). In this study we propose to combine all these techniques to determine the contributions of E_s, E_{ss} and T_{ss} to the total ET for different land covers.

The partitioning of ET is particularly effective in landscapes where few plant species are present and individual tree canopies can be identified. In these landscapes T_{ss} is restricted to trees and can be defined using sap flow measurements, while E_{ss} is the only water output in the bare soil areas outside tree root influence. Tree root influence area is understood as the area where chemical and physical conditions (including water pressure head) are influenced by the presence of roots. Wallace (1997) presents an example of an ET partitioning study in such a landscape; ET was measured by means of EC over an area with a clear heterogeneity of land cover, i.e with patches of woodland and bare soil.

The sap flow technique does not work for grass. Whenever grass is present and active another technique is required to assess grass transpiration, either by modeling (Feddes et al., 1978) or by direct measuring, for example using a gas chamber (Yepez et al., 2005). Sometimes, however, in ET partitioning studies, grass transpiration is lumped together with subsurface evaporation and both regarded as the difference between the EC tower measurements of ET and the sap flow measurements of tree transpiration (Paço et al., 2009).

No groundwater influence on ET rates has been a common assumption in partitioning studies, although groundwater evapotranspiration can be a substantial component of water balance, particularly in dry conditions, which, when not taken into account, can result in underestimation of total ET. In Wilson et al. (2001) the depth at which soil water was supposed to play a negligible role in total ET was set to 0.75 m below the ground surface (b.g.s.), probably due to the wet climate characteristic of the area studied. Baldocchi et al. (2004) showed the typical condition of a semi-arid, open woodland landscape: a poorly developed soil lying on top of a fractured granite bedrock regarded as non-evaporating (no information on water table depth was given in the article); in that case all subsurface evaporation was assumed to come from the unsaturated zone while the groundwater contained in the bedrock was assumed to be non-evaporating. Yaseef et al. (2010) defined bare soil E_{ss} as 36% of ET within a year in a semi-arid climate, assuming zero E_g because of the ~300 m b.g.s. groundwater table.

Williams et al. (2004) was conducted in a periodically irrigated semi-arid area olive orchard (400 trees $\mathrm{ha^{-1}}$; water table depth, soil composition and type of bedrock are not provided). When the top soil layer was irrigated it was moist enough to meet the potential evapotranspiration demand ($E_u = ET_p$) without affecting soil moisture in the deeper soil profile; in contrast, when the soil was dry long after irrigation, E_{ss} was assumed to be negligible ($ET_{ss} = T_{ss}$). The study used the isotopic method (Zhang et al., 2010) to partition the ET sources: water evaporated from the soil is depleted in the heavy isotopes compared to the water transpired from leaf surfaces; therefore the analysis of water vapor collected at the EC station gives indication of the individual contributions of E_{ss} and T_{ss}. The tree sap flow measurements (T_{ss}) underestimated the EC measured ET_{ss} by 24% in the period before irrigation. The authors assumed that this was due to their sap flow method underestimating the total sap flow of the trees, based on the fact that the isotopic partitioning showed no soil evaporation for the period before irrigation. To overcome the mismatch, the T_{ss} calculation from sap flow measurements was re-calibrated based on the EC measured ET.

The relevance of groundwater evapotranspiration, and hence the importance of sourcing, is supported by recent studies. For example, groundwater uptake from tree tap-roots was studied by Miller et al. (2010) using the water table fluctuation method (Loheide et al., 2005) in an oak savanna located in the western Sierra Nevada foothills. Tree canopy cover was ~40% of the studied