PARTITIONING AND SOURCING OF DRY SEASON EVAPOTRANSPIRATION FLUXES AT THE FOOTPRINT OF THE EDDY COVARIANCE TOWER IN SARDON SEMI-ARID LOCATION IN SPAIN

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RESUMEN. Las temporadas secas en las zonas áridas y semiáridas se caracterizan por una evapotranspiración potencial alta, que bajo condiciones de acuíferos poco profundos resulta en una importante evapotranspiración del subsuelo (*ET*). La *ET* se compone de dos procesos diferentes, transpiración de la vegetación y la evaporación del suelo desnudo, ambos directamente relacionados con el agua disponible de la zona saturada y/o no saturada. La división de *ET* en estos cuatros componentes de flujo es importante en la modelación hidrológica y la gestión adecuada de los recursos hídricos subterráneos.

Hemos dividido el flujo *ET* durante la temporada seca en la cuenca granítica de Sardón (Salamanca, España) en el área cubierta por una torre de medición de la covarianza de vórtices turbulentos. La transpiración de los árboles *Quercus pyrenaica* y *Quercus ilex* dentro del área de medición de la torre fue estimada por sensores de flujo de savia usando un procesamiento nuevo de escalamiento, mientras que las fuentes de abastecimiento de agua para la transpiración fue identificado mediante el análisis de isótopos estables de la agua subterránea, de la agua almacenada en la zona no saturada y savia extraída de los troncos de los árboles. La evaporación de las áreas de suelo desnudo entre los árboles y su división en componentes de zona non saturada y de zona saturada se modeló usando mediciones de perfiles de temperatura, potencial matrico y humedad del suelo obtenidas de sondas instaladas en suelo desnudo. Los resultados por la división de la transpiración de los árboles y la evaporación del suelo desnudo se compararon, finalmente, con la estimación de la torre de *ET*.

ABSTRACT. Dry seasons in arid and semiarid areas are characterized by large potential evapotranspiration, which in shallow water table condition results in substantial evapotranspiration (*ET*). The *ET* consists of two different processes, plant transpiration and bare soil evaporation, each sourcing water either from saturated or unsaturated zone. The partitioning and sourcing of *ET* into these four flux components is important in hydrological modelling and water management.

We attempted partitioning of dry season *ET* in the granitic Sardon catchment in Spain at the footprint of an eddy covariance tower. From that tower we obtained nearly continuous estimate of *ET*. The transpiration of the trees (*Quercus pyrenaica* and *Quercus ilex* species) occurring in the footprint of the tower was measured by sap flow sensors while the sourcing of that transpiration was identified by stable isotope analysis of groundwater, moisture of unsaturated zone and stem sap. The evaporation of the bare soil areas, in-between the tree canopies, and the partitioning of that evaporation into saturated and unsaturated zone sourcing components was modelled on the base of thermal, soil water potential and soil moisture profiles installed at the bare soil locations. The partitioning results of tree transpiration and bare soil evaporation were finally compared with the tower estimate of *ET*. Total *ET* for dry season was 0.6 mm/d. Evaporation was the most relevant term in the dry season water balance, representing 84% of total *ET*, while transpiration was low, representing 6 % of total *ET*. The direct evaporation from groundwater was relevant, representing 37% of total *ET*.

1.- Introduction

In arid and semiarid areas, during dry seasons when precipitation is low or absent, the main component of the hydrological balance is the loss of water due to evapotranspiration. To perform an effective water management in dry areas, accurate measurement and calculation of actual evapotranspiration (*ET*) is therefore required.

The term evapotranspiration is a lumped component of the hydrological balance for an area; it integrates physical processes of evaporation (*E*) and plant transpiration (*T*) which result in a net output of water from the aquifer to the atmosphere. The subdivision of the lumped *ET* into *E* and *T* to assess relevance of each component is called “partitioning”. The determination of the source for evaporating water (between unsaturated and saturated zone) is called “sourcing”. Importance of sourcing and partitioning was emphasized by Lubczynski (2011) and Frances et al. (Francés, Reyes, Balugani, van der Tol, & Lubczynski, 2011).

In recent years there has been an increasing interest in *ET* partitioning due to the development of new monitoring methods that permit independent measurements of different fluxes. Both the Bowen ratio method and eddy covariance flux method (Perez, Castellvi, Ibanez, & Rosell, 1999) permit reliable measurement of *ET* over relatively narrow areas. Soil moisture content and soil matric potential can now be measured continuously in time (Kizito et al., 2008). The sap-flow technique (Granier, 1985) permits to estimate trees transpiration using the movement of the sap inside the tree.

Literature about *ET* partitioning shows many different approaches in the definition and selection of the evapotranspiration components. This depends mainly on the measurement techniques used in each particular study.

An early approach to *ET* partitioning is the study of Wallace (1997), who performed it on an annual scale; however, the closure of the water balance was not attempted, due to lack of transpiration measurements. Wilson et al. (2001) used *ET* measurements from eddy covariance method, *E* estimation using soil moisture datasets and *T* calculated from sap-flow thermal dissipation measurements. Also in this case, the water balance was not closed because the sum of the components resulted in considerably lower *ET* values than the eddy calculation. Williams et al. (2004) tested the *T* calculation from sap-flow measurements against another partitioning technique which relied on stable isotopes sampling from the air to assess *E* as a percentage of *ET*. Evaporation term was found to be in the range 5 - 24% of total *ET*. Recent studies used a modified CO_2 chamber method for soil evaporation estimates (Yaseef, Yakir, Rotenberg, Schiller, & Cohen, 2010); Cavanaugh et al. (2010) considered two layers for the soil bucket model to obtain better estimates, and Miller et al. (2010) compared total ET_g to the transpiration of groundwater only.

All these studies vary widely in the approach to:

a) eddy tower reference area (footprint) calculation;
b) sap-flow measuring technique;
c) evaporation calculation;
d) up-scaling techniques for *T* and *E*.

The footprint area calculation is usually simplified, resulting in probable errors associated to *T* and *E* up-scaling. The soil evaporation is calculated using simple bucket models, and no interaction with the groundwater is considered. The sap-flow techniques are up-scaled using simple assumptions.

The objective of this study was to propose an improved partitioning of *ET* fluxes using new methodologies during the dry season in a semi-arid savannah near Salamanca, Spain, focused on the impact of *ET* on the groundwater resources.

The focus on the dry season is explained by the relevance of *ET* during this period as main output of water from the aquifer and because the low amount of rainy events permits to retrieve high quality data for the eddy covariance method.

The partitioning proposed by Lubczynski and Gurwin (2005), which introduce also the concept of sourcing, is used in this study:

$$ET = ET_s + ET_{ss} \quad (1)$$

$$ET_{ss} = E + T \quad (2)$$

$$E = E_g + E_u \quad (3)$$

$$T = T_g + T_u \quad (4)$$

$$ET = ET_s + ((E_g + E_u) + (T_g + T_u)) \quad (5)$$

ET_s is surface evapotranspiration, ET_{ss} is subsurface evapotranspiration, E_g and T_g are the evaporation and transpiration components from groundwater, E_u and T_u are the components from the unsaturated zone.

The innovations with respect to precedent studies consist in:

1) Accurate calculation of the eddy tower footprint with statistical modelling (Van der Tol, 2011)
2) Innovative transpiration assessment applying remote sensing upscaling of sapflow measurements (Reyes-Acosta & Lubczynski, 2011)
3) Bare soil evaporation calculated accurately with a calibrated numerical model
4) Sourcing of the groundwater and vadose zone water components

2.- Materials and methods

2.1.- General methodology

This study is the result of three different methodologies harmonized under the same area. The main idea is to measure in the same period and in the same place, but with different, independent methods, both total *ET* and its components. Due to the focus on the semi-arid, dry conditions, we selected a savannah-like semiarid area in western Spain, the Sardón catchment, and performed the study in the dry season August-September.

We:

1) placed an eddy tower to measure total *ET*;
2) performed sap-flow measurements on the trees to estimate *T*;
3) sampled soil moisture at different depth together with groundwater depth to estimate *E*.

The eddy tower dataset was analyzed, eliminating the bad-quality data, and *ET* was calculated as a mean for the whole period August-September. For the two months of the measurement, we defined a probability footprint to identify the contribution of the measured evapotranspiration.

The trees in the area were sampled and studied in order to calculate and upscale *T*, to create a map of average daily transpiration for August-September. The transpiration maps were then super-imposed on the calculated footprint to obtain daily values of *T* under the eddy tower footprint.

In the same way, the soils of the catchment were sampled and studied, to calculate and upscale *E*. Evaporation has been directly calculated for the footprint area, and successively averaged to obtain a daily values.

2.2.- Study area

The Sardón catchment is located in central-western part of the Iberian Peninsula, near Salamanca, Castilla y León (Spain). It is a catchment with boundaries marked by outcrops of massive rocks. The area is characterized by a semi-arid climate, typical of the central part of the Iberian Peninsula (Lubczynski & Gurwin, 2005). Long term yearly precipitation rate is ~ 500 mm/yr; the summer average temperature is ~ 20 ˚C with a potential evapotranspiration *PET* of ~ 5 mm/d and a mean precipitation of less than 20 mm/month. The winter average temperature is ~ 5 ˚C, with a mean precipitation of 100 mm/month and *PET* of 0.5 mm/d. The population living in the area is low and the main activity, traditional animal farming, has a low impact on the area. The geology of the area consists of typical fractured granitic rocks, with a shallow soil composed by weathered granite (sand, gravels and some clay). The shallow water table

depth changes depending on the season, remaining within the first few meters during the year. There are two co-dominant tree species in the area: evergreen oak *Quercus ilex* and broad-leafed deciduous oak *Quercus pyrenaica*. Both species are able to extract water from the saturated zone using tap roots (David et al., 2007 Reyes-Acosta, 2011). Trees are scattered, creating a savannah-like landscape, characterized by green grasses and shrubs during the winter and bare soil during dry season (August-September). The area has typical meseta morphology, with hilly landscape and mild slopes. Three main soil types can be identified in the area: granitic rock outcrops in the highest parts of the hills (where no evaporation is supposed to take place), shallow sandy soils in the slopes and deeper soil with higher clay contents and water availability in the valleys near intermittent streams.

2.3.- Eddy tower measurements

An eddy covariance system has been placed in the northern part of the catchment, on an elevated point within a typical savannah landscape, in order to measure *ET* in the whole dry season. The instrument, mounted on the 10 m tall tower, consisted of:

- CNR1 four components radiometer (Kipp and Zonen, Delft, The Netherlands),
- CSAT3 sonic anemometer (Campbell Scientific Inc., Utah, USA),
- LI7500 gas analyser (Licor Biosciences, Nebraska, USA),
- WXT520 'multi weather sensor' for measurements of wind speed, direction, air temperature and humidity (Vaisala Oyj, Helsinki, Finland).

The tower was also equipped with two soil heat flux plates and nineteen soil temperature sensors for the energy balance closure. The data have been processed with the software AltEddy (www.climatexchange.nl/projects/alteddy/) of the Alterra institute (Wageningen Unversity, The Netherlands). The approach of Hsieh et al. (2000) was used to determine the preliminary tower footprint; 80% of the turbulent heat fluxes originated from an area with a radius of 180 m around the tower (Rwasoka, 2010), as seen on Fig.1 (Van der Tol, 2011).

2.4.- Sap-flow measurements

We measured sap-flow in the area using thermal dissipation probes (TDP) and heat field dissipation sensors (HFD) during the months of August and September. The two methods were combined together and corrected to remove the bias due to natural-thermal-gradients (NTG) influence, to account for radial variation of sap-flow and finally to account for night-fluxes in *Quercus pyrenaica*. We used isotopic experiments to assess the source of transpired water (T_g or T_u). The upscaling of sap-flow measurement technique required three stages: classification of trees, establishment of the upscaling functions for each species, and then to use them together with the results from the isotopic experiments to project T_g and T_u on the footprint area (Reyes-Acosta & Lubczynski, 2011).

2.5 Soil moisture measurements

Various soil profiles in the area were sampled and analysed with different techniques (permeameter, soil texture analyses, pF curves determination) to obtain information about soil hydraulic properties. The soil consisted mainly in outcrops and shallow soils with similar characteristic over the whole area. The soil properties showed vertical heterogeneity, including higher percentage of fine sediments in the upper profile and presence of gravel in the deeper part of the soil, changing into fractured granite.

Three soil profiles were equipped with hydraprobe sensors to retrieve continuous measurements of soil moisture and soil temperature at four depths: 25, 50, 75, 100 cm from the ground surface. The ground water level has been measured in the area both with pressure transducers and manual measurements in piezometers. The soil moisture, groundwater level and meteorological data measurements were taken continuously for more than one year (since June 2009) to provide a better insight about water fluxes behaviour in the area.

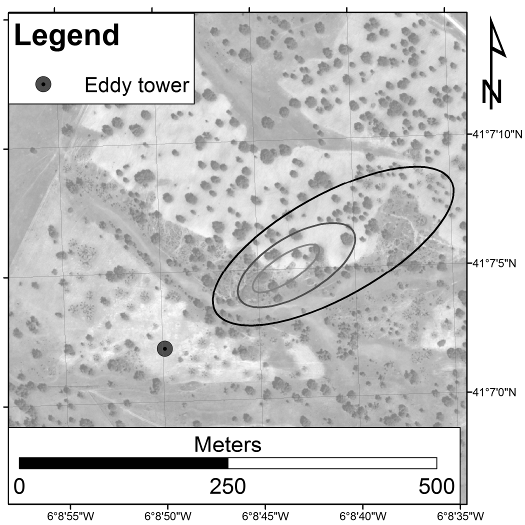

Fig. 1: Eddy tower position labelled on a satellite image of the area. The elliptical lines represent different level of probability inside the footprint area (90%, 50% and 10% probabilities, from inner ellipse to the external one). In the picture it is possible to see the savannah-like pattern of the trees in the area.

The soil water fluxes in the monitored profiles were modelled with HYDRUS 1D code (Simunek, van Genuchten, & Sejna, 2008). We used the atmospheric conditions recorded by an ADAS (Automated Data Acquisition System) weather station as upper boundary condition, and the measured groundwater level as lower boundary condition. Material properties and profile geometry were based on the field observations and laboratory analysis. The soil moisture measurements retrieved from the profiles were used as initial conditions and to fine-calibrate the model, using the inverse solution method developed by Simunek (Simunek &

vanGenuchten, 1996). HYDRUS 1D code permitted to take into account the coupling effect of heat, liquid water and vapour water flow (Saito, Simunek, & Mohanty, 2006), usually disregarded in normal bucket models. The coupled fluxes where modelled in the soil profile, using as constrain the continuous field temperature measurements.

3.- Results and discussion

3.1.- Eddy flux tower

During the months of August and September 2010 *PET* calculated with the method from Penman-Monteith (Monteith, 1980) was ~ 6,5 mm/d, with a total rainfall for this period of 55,2 mm (Fig. 2). The observed precipitation pattern was typical for the summer conditions in this area: short, rare events, with highly variable intensity, ranging from less than 1 mm to up to 14 mm, resulting in an average rainfall rate of 1,06 mm/d. The *ET* calculated from the turbulent heat flux was 0.6 mm/d, after eliminating the days corresponding to rainfall event due to low quality of the data in rainy conditions (Van der Tol, 2011). The high potential evapotranspiration rates resulted in very high ET_s during a short time after the rainfall, which reduced the amount of infiltrating water and the total *ET* calculation.

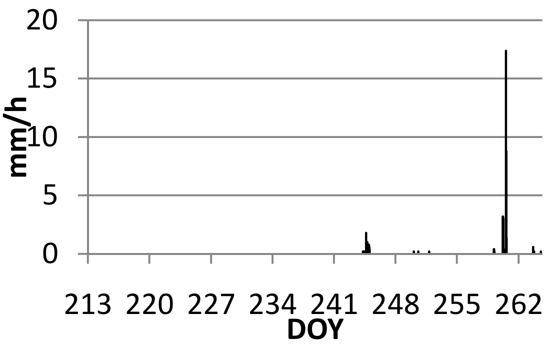

Fig. 2: rainfall measured from the station.

3.2.- Transpiration

The up-scaling of the sap-flow measurements over the footprint area calculated for the tower led to an average *T* rate of 0.036 mm/d, which is a low value, as expected for a savannah during a water stress period. The isotopic experiments showed that groundwater components of transpiration (T_g) were 70 % for *Quercus ilex* and 50 % for *Quercus pyrenaica*. Thus T_g resulted in a range of 0.018 to 0.025 mm/d, and T_u between 0.011 and 0.018 mm/d. These results showed that groundwater, even when 3.5 metres deep, is a source of water for the trees of the area during the dry period (Reyes-Acosta & Lubczynski, 2011).

3.3 Evaporation

The soil moisture dataset measured during the study period (August-September) in the area (Fig. 3) shows a very dry profile, without relevant changes even after the last strong rain event (Fig. 2). Looking at the soil moisture behaviour and at the eddy tower results, it is observed that the rain do not infiltrate deep into the soil, wetting only the first centimetres of soil and then evaporating due to very high *PET* conditions.

The soil profile calibration has been performed using the dataset of soil moisture for the spring 2010 in order to test the model in more dynamic and wetter conditions (Fig. 4, R^2 for regression of predicted versus observed = 0.93, Šimůnek, 2009). Succesively, the calibrated model has been applied to the soil moisture data of August-September to test it and calculate the dry season soil-water fluxes. The HYDRUS 1D simulation of the soil moisture changes in August and September is in agreement with the soil moisture dataset (Fig. 3). The bare soil evaporation calculated by the model, coupling heat, liquid water and vapour water flow, resulted in E = 0.5 mm/d. The coupled version was chosen because it was possible to constrain HYDRUS 1D model using the temperature dataset from the soil profiles, and obtain more reliable *E*.

To source the fluxes between E_u and E_g, a Python module was developed for post-processing of the HYDRUS 1D output files. That post-processing module automatically takes as input the output files of HYDRUS 1D and divide the modelled profile into two parts: the saturated zone and the unsaturated zone. It computes then the water flux balance for every time step for the two zones and from that it calculates the evaporation components. The two ways water fluxes for saturated and unsaturated zone are calculated are as follows:

$$E_g = S_Y \frac{dWTD}{dt}; \quad (6)$$

with *WTD* water table depth, *t* time, $E_g$in mm/d, S_y the specific yield,

$$E_u = \frac{d}{dt}\frac{d\theta}{dz}; \quad (7)$$

with θ soil moisture, *z* depth from the surface, E_u in mm/d.

The Python module labels all the step-calculations with the quality of the calculation (depending on water balance closure), computes the sourcing for the selected period and returns an ASCII file with the result.

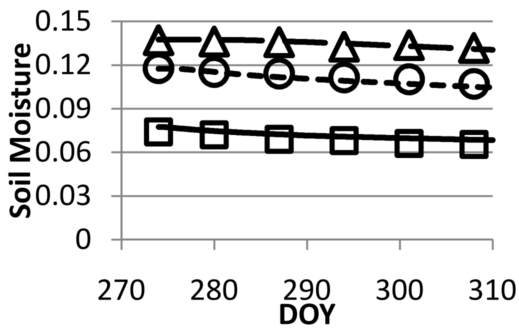

Fig. 3: Comparison between the measured soil moisture (markers) and the simulated ones (lines) for the 25 cm depth (squares and solid line), 50 cm depth (circles and shaded line) and 75 cm depth (triangles and light-shaded line).

The averaged results of the *E* sourcing analysis performed over the period August-September are E_g equal

to 44.75% (0.22 mm/d) of E and E_u equal to 55.25% (0.28 mm/d) of *E*.

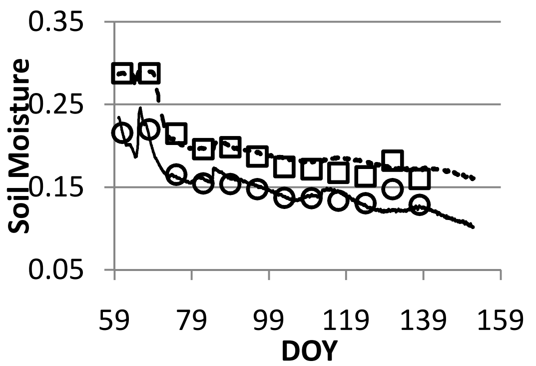

Fig. 4: Calibration results for the model in spring time. Only datasets from 25 cm (continues line for the measurements, circles for model estimations) and 50 cm depth (shaded line for the measurements, squares for model estimations) are shown for clarity.

3.4.- Water balance closure

The results were: *ET* calcultated with eddy flux covariance method 0.6 mm/d, *E* from HYDRUS 1D model calculation 0.5 mm/d (E_g = 0.22 mm/d, E_u = 0.28 mm/d), *T* calculated using sap-flow measurements 0.04 mm/d (both T_u and T_g = 0.02 mm/d) in the August-September period). As can be seen the water balance is not perfectly closed; however, the difference between the eddy tower estimation and the sum of different components is only 0.06 mm/d (10%). This study showed the following outcomes: first, in savannah-like environments, the soil evaporation, which is usually thought to be somehow very low due to the dryness of the surface (Yaseef et al., 2010), is the most important component of *ET*. The percentage of *ET* depending on *E* has been found equal to 84%, which is fairly higher than all other results shown in literature for similar environments (35% in Wallace (1997), 24% Williams et al. (2004), 36% in Yaseef et al. (2010). Second, as expected, the unsaturated zone evaporation component E_u was high due to the evaporation of the infiltrated water from rain events, which had no time to reach the tree's root zone. However, the rain events are not heavily influencing the budget, due to the exclusion of the eddy tower measurements with low quality, typically due to storm events. The rain evaporation due to surface evaporation E_s is not taken into account, and this explains why interception is not part of the overall *ET* budget.

Third, nearly half of *E* is due to the direct thermal flux of liquid and vapour water from the groundwater (E_g), even when this is supposedly too deep to evaporate at an appreciable rate (for an isothermal liquid-only calculation). During the period analysed, E_g from a water table 3,5 m deep in sandy soil resulted in 37% of the total *ET*.

The trees were in continuous water stress state so their transpiration remained low during most of the dry season. The dryness of the unsaturated zone forced them to use the groundwater resources with tap roots, resulting in higher amounts of water uptake from the saturated than from the unsaturated zone.

The results show that the evaporation does not come only from evaporation of rain in the unsaturated zone, but also from the groundwater, and that the groundwater components explain nearly half of the total *ET*.

4.- Conclusions

This study presents the results of a new approach to *ET* partitioning, based on: accurate *ET* footprint calculation using eddy flux tower method, remote sensing upscaling of sap flow measurement and their sourcing with helps of stable isotope measurement, and comprehensive soil water flux modelling. During the months of August and September 2010, the evapotranspiration in the study area measured by the eddy tower was 0.6 mm/d. In the same period, the transpiration from trees measured with sap flow method was 0,036 mm/d, while the evaporation calculated using a 1D coupled heat flow, liquid and vapour water flow calibrated against soil moisture measurements was 0.5 mm/d. The water balance is not perfectly closed with a residual of 10%. The evaporation components represent 84% of the total *ET*, a result much higher than what previously measured in such conditions in other works.

A new approach to partitioning of *ET* is also used, leading to estimates of the groundwater-relevant components, E_g (0.22 mm/d) and T_g (0.02 mm/d). The unsaturated zone evaporation E_u depends greatly on rainfall events, while E_g remains stable during the whole dry season. In the presence of one relevant rain event during the study period, E_u represented only 47% of total *ET*, while E_g the 37%. The transpiration components showed similar values of T_g and T_u in the area; both transpiration values are quite low, only 6% of total *ET*, demonstrating that the two *Quercus* species were under stress conditions even in presence of tap roots able to uptake water from the saturated zone.

Future works will include:

1) validation of the partitioning system with the use of soil columns experiments and lysimeters experiments on the field
2) test of the hydrological model MARMITE (Francés et al., 2011), which is able to compute a detailed water balance, with partitioning and sourcing of the *ET* components, at catchment scale.

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