

## SPATIAL ASSESSMENT OF TRANSPIRATION, GROUNDWATER AND SOIL-WATER UPTAKE BY OAK TREES IN DRY-SEASON AT A SEMI-ARID OPEN-FOREST IN SALAMANCA, SPAIN.

J.L. Reyes-Acosta<sup>1</sup>, M.W. Lubczynski<sup>1</sup>

<sup>1</sup> Water resource department, Faculty of Geo-information Science and Earth Observation (ITC), University of Twente, Hengelosestraat 99, 7514 AE Enschede, The Netherlands, l\_reyes@itc.nl

**RESUMEN.** La transpiración es uno de los componentes fundamentales de la dinámica hidrológica que influyen la disponibilidad de agua en suelos y acuíferos. En este estudio se pretende una cuantificación precisa de la transpiración ( $T$ ) en una escala espacial grande (la cuenca), desde mediciones puntuales en árboles de robles caducifolios y de hoja perenne (*Quercus pyrenaica* y *Quercus ilex*, *Q.p.* y *Q.i.* respectivamente). También se descompone  $T$  en la transpiración del agua subterránea ( $T_g$ ) y de la zona no saturada ( $T_u$ ). Para ello, se evalúan espacialmente  $T$ ,  $T_g$  y  $T_u$ , combinando mediciones obtenidas a diferentes escalas espaciales y con métodos complementarios: (a) mediciones precisas de flujo de savia; (b) mediante el uso de trazadores con isótopos naturales y enriquecidos; y (c) re-escalamiento espacial usando imágenes satelitales de alta resolución (50-60 cm por píxel). Usando estos métodos, obtuvimos una cuantificación detallada de  $T$ ,  $T_g$  y  $T_u$ , a lo largo y ancho de la cuenca de Sardón, para cada especie y cobertura vegetal. Estas mediciones se proyectaron en una cuadrícula de 1 ha, para entender mejor los patrones hidrogeológicos espaciales, y para incorporarla después en modelos matemáticos. Los resultados de transpiración total ( $T=0.05-1.2$  mm/d) son fiables ya que se encuentran: (a) en el intervalo de medidas de evapotranspiración obtenidas con una torre de mediciones de covarianza de remolinos (0.6 mm/d); y (b) en el intervalo de resultados de modelado de la misma zona (0.5 mm/d).

**ABSTRACT.** Transpiration is one of the important processes influencing the water availability in soils and aquifers of all ecosystems. In this study we focused on producing accurate quantification of transpiration ( $T$ ) from single deciduous and evergreen Oak trees (*Quercus ilex* and *Quercus pyrenaica*, *Q.i.* and *Q.p.* respectively) to higher spatial scales, and identify the sources from this flux into two constitutive elements, namely: groundwater transpiration ( $T_g$ ) and unsaturated zone transpiration ( $T_u$ ). We propose to quantify  $T$ ,  $T_g$  and  $T_u$  spatially, by combining measurements obtained at different spatial-temporal scales from three complementary methodologies: (a) accurate sap-flow measurements, (b) sourcing of water fluxes by naturally abundant and enriched isotopes-tracing (c) spatial up-scaling with high-resolution remotely sensed imagery (50-60 cm per pixel). We obtained a detailed spatial quantification of  $T$ ,  $T_g$  and  $T_u$  across the Sardón catchment study area of ~80 km<sup>2</sup> for each of the species and for the total canopy cover, projected at 1 ha grid readily available as input for hydrological models. The

obtained  $T$  estimations are between 0.05-1.2 mm/d, in the range of eddy-covariance measurements of evapotranspiration (0.6 mm/d) and modelling results obtained in the same area (0.5 mm/d).

### 1.- Introduction

The water accessibility tendencies show the imminent reduction of easily-accessible freshwater sources (Seckler and International Water Management 1998). In order to achieve better hydrological management practices, the hydrological role of the vegetation has been defined as a key element to better understand the hydrological dynamics of Water Limited Environments during the last years (WLE) (Abrahams and Parsons 1994; Lubczynski 2009). The vegetation in these environments have developed different adaptations and strategies to acquire water to transpire and photosynthesize (Porporato et al. 2001), such as: deep water uptake, stomata closure, water storage, etc. The adaptations/strategies guarantee a quasi-continuous water supply for the vegetation through the whole year, (Noy-Meir 1973), in particular during dry-season. Hence this transpiration water-uptake becomes one of the most important mechanisms influencing the water availability in soils (e.g. depletion of available water from soil) and groundwater discharge/recharge rates (e.g. direct groundwater tapping) (Lubczynski and Gurwin 2005; Lubczynski 2009). Transpiration operates and influences different bio-physical scales in the groundwater-soil-plant-atmosphere continuum. Therefore, the water-sources for transpiration and uptake processes are diverse and difficult to quantify with good accuracy (Lubczynski 2009).

Diverse approaches have been followed to measure transpiration directly (Čermák et al. 1982; David et al. 2007; Hernández-Santana et al. 2008), and/or indirectly (Calder 1978; Caspari et al. 1993; Moore et al. 2008; Verbeeck et al. 2007). However the underlying challenge is to acquire measurements and/or estimates with a high level of accuracy and to interpret and use this information on a catchment scale, a context in which water-management decisions are usually made.

The study was developed in the Sardón catchment a fractured-granite area where the vegetation is dominated by oak trees, and its hydrological dynamics are dominated by a geological fault (Lubczynski and Gurwin 2005). The water-table in the Sardón catchment can be typically found between 2 and 10 meters (Lubczynski and Gurwin 2005).

In this study we aimed to identify, quantify and characterize the contribution of the groundwater and unsaturated water (e.g. soil moisture) to the transpiration uptake regimes and water use strategies of the co-dominant tree species in the Sardón catchment. Thus we focused on: (a) producing accurate quantifications of transpiration ( $T$ ) from direct measurements in single deciduous and evergreen oak trees (*Quercus ilex* var. *ballota* and *Quercus pyrenaica* Wild, *Q.i.* and *Q.p.* respectively); (b) sourcing this flux in its two constitutive elements, namely: groundwater transpiration ( $T_g$ ) and unsaturated zone transpiration ( $T_u$ ); (c) and up-scale transpiration measurements to higher spatial scales. We used the obtained sap-flow measurements, the sourcing calculations and the up-scaling to estimate  $T$ ,  $T_g$  and  $T_u$  in hydrological units projected in 1 ha grids (mm/d) from all identified tree covers in the catchment. With the proposed procedure, we obtained a detailed spatial quantification of  $T$ ,  $T_g$  and  $T_u$  across the Sardón catchment per species readily usable as an input for hydrological models, such as the MARMITES model developed for understanding of the groundwater dynamics (Francés et al. 2011).

## 2.- Methodology

To quantify  $T$ ,  $T_g$  and  $T_u$  spatially, we proposed to combine measurements from three complementary methodologies: (a) accurate sap-flow measurements, (b) sourcing of fluxes by tracing naturally abundant and enriched isotopes tracers and (c) spatial up-scaling with high-resolution remotely sensed imagery (Lubczynski 2011).

### 2.1- Sap flow measurements

Sap-flow constitutes a widely used method to quantify water use in plants, and if it is properly applied it expresses transpiration fluxes (Lu et al. 2004). In our study we conducted a sap-flow monitoring campaign during summer time in 2009 and 2010 in trees of *Q.i.* and *Q.p.*, using thermal dissipation probes (TDP) and heat field dissipation sensors (HFD). We decided to work during the summer time because in this period the abstraction from deep sources is more likely to occur (David et al. 2007; Nadezhkina et al. 2008). To monitor climatic variables we measured the short-wave radiation (CNR radiometer, Kipp & Zonen, Delft, Netherlands), rainfall (Wallingford type of tipping bucket), wind speed, relative humidity, air temperature (Vaisala Weather transmitter WXT 520, Finland), soil moisture (Stevens probes), soil water potential (MPS-1 and WP4 Decagon) using Automatic Data Acquisition Systems (ADAS) based on Campbell logger.

For the TDP measurements we monitored 2 trees per species in June 23<sup>rd</sup> until September 21<sup>th</sup> 2009 and 10 trees per species in May 29<sup>th</sup> until September 25<sup>th</sup> 2010, using 20 mm long, standard Granier-type (Granier 1985) TDPs sensors (UP GmbH, Germany). The TDP method uses an empirical calibration relating measured temperature difference ( $\Delta T$  in °C), to the sap-flux density  $J_p$  (in

$\text{cm}^3 \times \text{cm}^2 \times \text{h}^{-1}$ ) (Granier 1985).

With the HFD method not only the sap-flux density ( $J_p$ ) but also sap-flux density radial profiles were monitored ( $J_{pi}$ ). We carried out the measurements on the same trees and during the same time periods as the TDP. Measurements were recorded every 30 s in 10 min-averages using a SL5 Smart logger (ICT International, Armidale, NSW, Australia). The HFD method determines  $J_p$  based on the spatial deformation of a heat-field around a linear heater (placed tangentially in the sapwood of the studied tree), represented by the ratio of the measured temperature differences symmetrically ( $\delta T_{sym}$ ) and asymmetrically ( $\delta T_{asym}$ ) (Nadezhkina et al. 2002; Nadezhkina et al. 1998).

In order to properly and accurately quantify sap-flow by combining TDP-HFD measurements, we applied correction schemes, as described by Reyes-Acosta and Lubczynski (2011), to remove: 1) biases from the influence of natural-thermal-gradients (NTG) (Do and Rocheteau 2002a; Do and Rocheteau 2002b; Lu et al. 2004; Lubczynski et al. in press), 2) account for variable radial and circular sap-flow profiles (Poyatos et al. 2007) and 3) to account for night-fluxes.

### 2.2.- Water uptake sourcing

In this study, we used stable isotope tracers for sourcing  $T_g$  and  $T_u$ . This method relies on the enrichment of the water source (groundwater) with a tracer (Dawson et al. 2002), removing or minimizing the problems of interpretation brought by fractionation among sources. The isotopic ratio of the enriched source is amplified relative to the signal noise becoming easier to detect (Dawson et al. 2002). Moreover, when using enriched isotopes, the labelled substance has an isotopic composition that significantly differs from any natural occurring level.

We calculated the source contributions of the transpiration based on isotopes-tracing experiments using enriched deuterium during the summers of 2008, 2009 and 2010. We used a network of piezometers for injecting constant doses of enriched  $D_2O$  into groundwater, in general, similar to the set-up of Brooks et al. (2002). The piezometric network was placed radially surrounding a pre-selected tree in 4 azimuths (N, S, W, E) at 2 m distance. Sap flow sensors were monitoring the transpiration on the selected trees. This implementation guaranteed differentiation of the water sources volume (i.e. ground-soil water), but it also required a high number of samples for tracing the isotope pulse with a good temporal resolution (3 hours sampling during 24 hours). The isotopic compositions of the sources were determined in separate sampling schemes. Groundwater samples were taken from piezometers and kept in hermetic conditions to avoid evaporation. Soil samples were taken at 25cm, 50 cm, 75 cm and 100 cm and protected against evaporation. The soil samples were further processed to extract water by azeotropic distillation (Walker and Richardson 1991). Xylem water extractions were done directly in the field from sapwood samples (Lamb and Berthelot 2002). Ground, soil and sap water isotopic ratios were analysed by the equilibration technique in the laboratory. We calculated

the source contributions based on the isotopic composition of 5 sources and an isotopic mixing model with one member to explain the sap-water isotopic composition. We followed the method of Phillips and Gregg (2003), to determine the range of feasible source contributions to a mixture when there are too many sources to allow a unique solution.

### 2.3.- Transpiration up-scaling

We applied a three steps method to up-scale  $T$ ,  $T_g$  and  $T_u$ : 1) classification of *Q.p.* and *Q.i.* tree cover using two high-spatial-resolution multispectral images; 2) establishing species-specific biometric up-scaling functions (BUF) relating the area of the canopy ( $A_c$ ) with the area of the xylem ( $A_x$ ) based on a tree biometric-survey; and 3) up-scaling of sap flow measurements ( $T$ ) and the sourcing calculations ( $T_g$  and  $T_u$ ) to the tree level and at 1 ha grids (mm/d), using the obtained BUF.

To classify the tree species for the Sardón catchment we used two satellite images with a high spatial resolution (60-40 cm per pixel), acquired in two distinctive seasons: a QuickBird image during the summer of 2009 (August) and a WorldView-II image during winter 2010 (December). These images were first processed to select and highlight just the areas covered by tree canopies, with an unsupervised classification of the spectral readings of the red, near infrared and green bands, as described by Ehlers et al. (2003). The highlighted areas were then reclassified into tree species, using an object oriented classification algorithm. This method takes into account intrinsic characteristics of the cover and not just the spectral response of the objects (Baatz et al. 2001; Dorren et al. 2003; Kimani et al. 2007). We obtained a vector map defining the location of the species and the area covered by their canopies.

To develop a robust BUF relating the elements needed for up-scaling, i.e. scalar and up-scaling parameter, a biometric survey of more than 100 trees per species was implemented at defined sectors of the Sardón catchment in 2008 and 2009. The survey focused on measuring tree parameters highlighted as suitable for up-scaling in other studies (Chavarro 2009): tree height, diameter at breast height, first active branch height, projected canopy area and sapwood area. These measurements were further processed to define the composition of the population by tree sizes and to determine the BUF with the best correlation-coefficient ( $R^2$ ).

For the final step, we integrated sap-flow measurements with the species-classification by applying the best correlated BUF. In our study we used canopy area ( $A_c$ ) as the scalar and the sapwood area as the up-scaling parameter ( $A_x$ ). This allowed us to calculate the  $A_x$  from all the trees of the catchment, using the species-classification  $A_c$  calculations. Once  $A_x$  was defined for each tree cover, we calculated the sap-flow rate ( $\sum Q_{w-i}$ ) per tree by multiplying wood rings, each 1 cm deep ( $A_{x-i}$ ) by the specific radial sap-flux density for each  $i$  depth obtaining ring sap flow ( $Q_{w-i}$ ) for a standardized summer day (no cloud conditions and incoming solar radiation higher than 800 W/m<sup>2</sup>). For large tree clusters, instead of

up scaling single trees of the cluster with canopies difficult to determine, we assumed they formed a big “surrogate” tree. Thus, we could use the  $A_c$  of the “big” tree to calculate the  $A_x$  as a lumped sum of the areas from each tree in the cluster.

By summing up the measured sap flow from each single tree in 1 ha, we derived the total transpiration normalized for that area (mm/d in 1 ha). Finally the partitioned components from  $T$ :  $T_g$  and  $T_u$ , were calculated with the highest probability source percentages obtained from the mixing models (see section 3.2).

## 3.- Results and discussion

### 3.1.- Sap-flow campaign

Detailed information about the sap-flow campaign of 2009, and the methods for applying correction necessary for measurements in dry environments can be found in Reyes-Acosta and Lubczynski (2011). For the campaign of 2010, we covered a wider range of tree sizes and we found that the variability in terms of sap-flux density was very low for *Q.p.* For *Q.i.* we found a clear difference in the radial-patterns from small- to medium size specimens (10-60 cm DBH) versus the bigger ones (>60 cm DBH). The smaller (younger) specimens tended to be more active in deeper layers of sapwood (5 to 7 cm deep) than the bigger specimens (older).

We consider that this pattern is related with the activity of deeper roots and comparable to sap-flow patterns found in other oak trees (Nadezhdina et al. 2008) and pine trees (Čermak et al. 2008). Thus the pattern suggests that younger *Q.i.* trees are more actively up-taking water from deeper sources than older trees. Unfortunately we could not confirm this hypothesis because the sourcing experiments were all done in smaller-medium trees. Nevertheless, we took into consideration the difference between sizes for *Q.i.* in the up-scaling calculations by assigning the lowest percentage obtained in the mixing-models for deep sources. Even if this assumption is not correct, the up-scaling results would not be influenced significantly. The reasons are that an erroneous  $T_g$ - $T_u$  sourcing of bigger trees at 1 ha calculations would not be significant, as based on our survey, trees with DBH larger than 60 cm correspond to less than 10% of the *Q.i.* tree population.

In general we found that during the summer *Q.i.* had a mean maximum of sap flux density measurements of 5.7-6.3 cm<sup>3</sup>×cm<sup>-2</sup>×h<sup>-1</sup> and *Q.p.* 10-13 cm<sup>3</sup>×cm<sup>-2</sup>×h<sup>-1</sup>, during cloud-free days for the first 2 cm of sapwood. This suggests that *Q.p.* potentially uses more water than *Q.i.*, and thus demand more water from the environment. Complementary soil moisture (SM) and soil-water potential (SP) data provided further evidence of the influence of the water uptake mediated by the transpiration on the hydrological dynamics of the soil during the dry season. We found that SM and SP measured directly under the canopy of both tree species was lower (<10% and  $\Psi_m$  <-4 Mpa) as compared to bare soil measured at 12 meters from the tree (<20% and  $\Psi_m$  >-3 Bar).

### 3.2.- Mixing-models and sourcing results

The results obtained from the sourcing-enrichment experiments varied temporarily. The range of feasible source contributions obtained for *Q.i.* at 11:00 hours in the morning, clearly shows that groundwater predominated (70-75%) upon the other waters sources “Fig.1a”. This tendency decreased towards the end of the day, at 20:00 hours, when the groundwater contributed less to the sap-water mix (40-50%). These results are in agreement with findings of similar experiments performed in the same species (David et al. 2007) and other phreatophyte species (Zencich et al. 2002). Furthermore, our result provided new evidence on the dynamics of deep water abstraction as we determined that is not static through time. Based on the results we concluded that the deep-water abstraction reaches a maximum during the maximum peak of transpiration, and decreases towards the day. This is supported by a strong agreement between the sap-flow patterns and the 24-hour sourcing data.

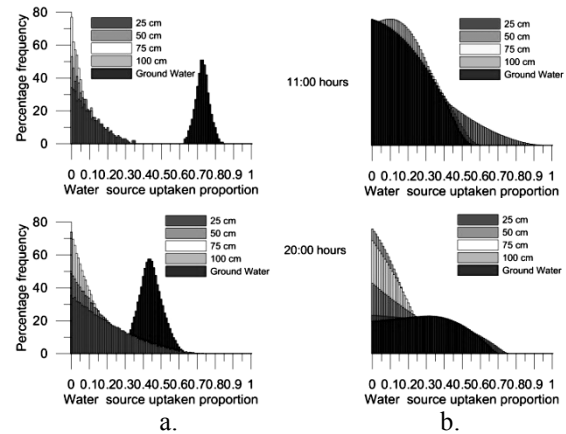
For *Q.p.* the results show a different dynamic, even though a temporal variation was also found “Fig.1b”. The range of feasible source contributions at 11:00 hours did not show any predominance for any of the sources, all of them contributing with nearly ~25% of the mix. This tendency was reversed at 20:00 hours, when the groundwater showed a higher but not completely dominant contribution (30-50%). As compared to *Q.i.*, there was a wider range of possible combinations of sources for *Q.p.*, indicating that the system was less well constrained. This situation is normally observed during winter conditions (Phillips and Gregg 2003; Zencich et al. 2002), when there is more precipitation and the sub-surface layers are less depleted, therefore isotopic compositions of water sources are similar. As we performed our experiments on the peak of the dry season, when the soil normally reaches the wilting point, it seems there is an inconsistency. However, *Q.p.* in the Sardón catchment tends to be located in areas closer to streams and the river valley (see next section for the spatial patterns), where the soil moisture in the soil has a tendency to be less dry due to the shallow depth of the water table.

Based on this evidence we can affirm that *Q.p.* in the Sardón catchment behaves as a riparian species, and uptakes groundwater sources if these are close enough to the first meter of soil where it holds a high concentration of roots (Cano 2010). Our results provide more details on the water-use strategy described by Reyes-Acosta and Lubczynski (2011); Hernández-Santana et al. (2008); and Mediavilla and Escudero (2003). These authors pointed out that *Q.p.* has a non-conservative water-use strategy, which together with the new evidence of our data, further suggests that: 1) *Q.p.* systematically depletes de water from the sampled soil layers and shallow water table, and 2) during the night it passively replenishes water transpired from its tissues preferably from deeper sources with higher water potential.

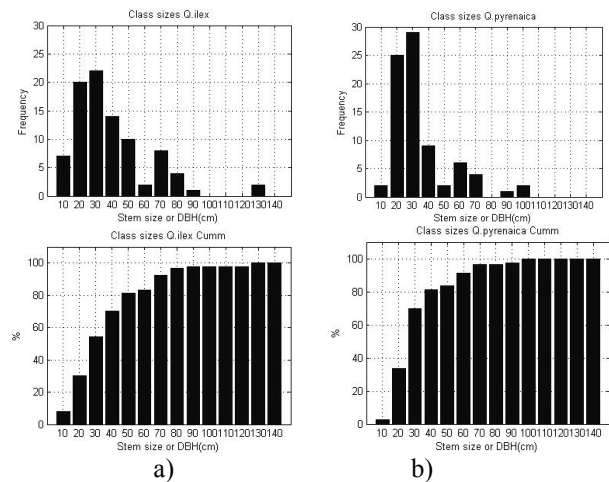
### 3.3.- Up-scaled transpiration and spatial patterns.

The classification results showed that the vegetation follows a distinctive distribution pattern. *Q.p.* dominates

and clusters following the streams areas, the river valley and the upper side of the catchment, whereas *Q.i.* mainly dominates in the lower side of the catchment, further from streams and the river valley. This spatial distribution pattern suggests a remarkable niches division between the oak species. Likely, to lower interspecific competition for the limiting resource, in this case the water availability. In the catchment both species are rarely found close to each other.



**Fig.1** Distribution of feasible contributions from each source to the sap water extracted from the plant at 11:00 hours and 20:00 hours, for (a.) *Q.i.* and (b.) *Q.p.* Time zone: GMT +2 “summer time”.



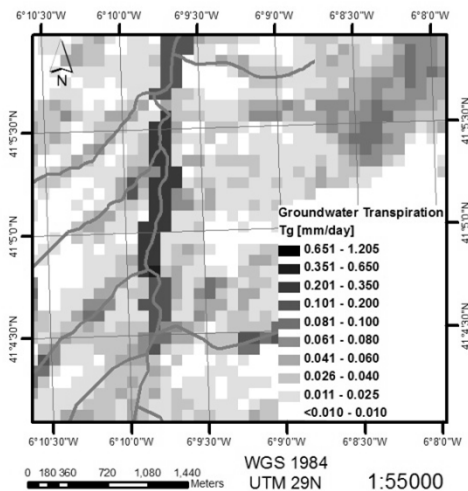
**Fig. 2.** The frequency histogram shows the distribution of DBH, representing the surveyed tree sizes and ages for a.) *Q.i.* and b.) *Q.p.* The cumulative histogram depicts the DBH variability covered by each newly sampled size category.

The bio-metric survey showed that we properly covered the tree-size statistically variability for both species populations “Fig.2”. Moreover, 90% of both species populations are composed by sizes of 10 to 70 cm of DBH. Hence, big and older trees are less representative in terms of vegetated cover and transpiration.

We determined that the best BUF to be used during the up-scaling procedure was a lineal relation between the projected area of the canopy ( $A_c$ ) and the xylem or sapwood area ( $A_x$ ), with a correlation coefficient of  $R^2$  0.92 for *Q.i.* and 0.91 for *Q.p.* The BUF for *Q.i.* ( $y=0.009x$ ) was higher than for *Q.p.* ( $y=0.008x$ ), indicating

that the  $Q.i.$  has in proportion more  $A_x$  than  $Q.p.$  with the same  $A_c$ . Therefore, for this study  $A_c$  was used as the scalar and  $A_x$  as the up-scaling parameter.

The results from up-scaling  $T$ ,  $T_g$  and  $T_u$ , had a high spatial variability “Fig. 3”. The highest transpiration fluxes were specifically located closer to the streams, valley areas and the lower part of the Sardón catchment, with values that ranged between 0.3 and 1.2 mm-day. However, such areas were relatively small as compared to the rest of the catchment. Most of the catchment showed  $T$  values between 0.01 and 0.02 mm/d. The up-scaled  $T$  estimations were in the range of actual ET measurements reported from an eddy-covariance tower 0.7 mm/d (Balugani et al. 2011), suggesting that the up-scaling and sourcing methodology produced acceptable results. Nevertheless, it is also evident that other processes than  $T$  could be contributing to the overall evaporative dynamics where the tower is located. In terms of water used for  $T_g$ , as expected from the sourcing results, it was more important in the areas dominated by  $Q.i.$  In the case of  $T_u$  it was higher than  $T_g$  and it was more important in the areas dominated by  $Q.p.$



**Fig. 3.** Up-scaled groundwater transpiration ( $T_g$ ) of the Sardón catchment (zoomed-in), showing highest  $T_g$  at the riparian zones of the Sardón river and medium to high  $T_g$  at the clusters of  $Q.i.$  (north-east 41°53'30"N) (1 cell= 1 ha).

In relation to other studies in semi-arid areas, our estimations of  $T$  (0.036 mm/d) as compared to actual evapotranspiration from an eddy tower ( $ET_a=0.6$  mm/d) are lower (6%). Williams et al. (2004), found that  $T$  before irrigation was nearly 95% during comparable dry conditions and no irrigation. However, the conditions and plant arrangements between their site (olive trees orchard) and ours (semi-natural open forest) is too different to allow a direct comparison. Yaseef et al. (2010) and Cavanaugh et al. (2010) reported  $T$  values between 42 and 54% from forest under very dry conditions. However, once again a direct comparison with our results might be difficult because: a) the structure of the vegetation cover might be very different between areas, b) Yaseef et al. (2010) and Cavanaugh et al. (2010) do not account for possible biases in sap-flow measurements (e.g. uneven radial flow); and c) do not provide details on their up-scaling techniques

(scalars, BUFs, etc.).

The estimated  $T$  in average seems to be rather low as compared to  $ET_a$  but we consider that the reasons are due to: a) the very dry conditions in which the  $T$  was investigated, and b) a high standard deviation of  $T$  (0.06 mm/d), with considerable higher values than average in areas closer to the river banks where  $Q.p.$  clusters are; and very low values in areas with low tree cover. These reasons seem plausible, but the conditions in the Sardón catchment are such, that direct evaporation from the groundwater seems to be a dominant flux contributing to  $ET_a$ . For further details please check Balugani et al. (2011)

#### 4.- Conclusions

The method outlined in this paper provides a reliable procedure to measure and up-scale  $T$ , and how to integrate it with other methods to estimate  $T_g$  and  $T_u$  in different spatial scales. We confirmed that  $Q.i.$  and  $Q.p.$  have low  $T$  during the summer but are dedicated phreatophytes, with clear differences on their water use strategies affecting the soil water availability. Moreover, we concluded that  $T_g$  is more dominant than  $T_u$  as a discharging element of the hydrological system in the Sardón catchment during the dry season, but  $T_u$  importantly influences the soil moisture properties of the soil. Thus, the up-scaled transpirations and the highlighted spatial patterns hold a great potential for future water and vegetation management uses.

*Acknowledgements.* We thank the Faculty of Geo-information Science and Earth Observation (ITC) of the University of Twente, for founding this research. Also the CIALE institute of the University of Salamanca, in special to Dr. Jose Martínez-Fernández, and Dr. Nilda Sanchez. Finally, to all the MSc and PhD students that supported field campaigns.

#### 5.- Bibliography

- Abrahams, A.D. and A.J. Parsons 1994. Geomorphology of deserts environments in *Geomorphology of Deserts Environments* edited by A.D Abrahams and A.J. Parsons, p. 1-12. Chapman & Hall, London; New York.
- Baatz, M., U. Benz, S. Dehghani, M. Heynen, A. Holtje, P. Hofmann, I. Lingenfelder, M. Mimler, M. Sohlbach and M. Weber 2001. eCognition Object Oriented Image Analysis. User Guide, Definiens Imaging, München, Germany
- Balugani, E., J.L. Reyes-Acosta, C. van der Tol, A.P. Francés and M.W. Lubczynski 2011. Partitioning and sourcing of dry season evapotranspiration fluxes at the footprint of the eddy covariance tower in Sardón semi-arid location in Spain. *ZNS conference proceedings*
- Brooks, J.R., F.C. Meinzer, R. Coulombe and J. Gregg 2002. Hydraulic redistribution of soil water during summer drought in two contrasting Pacific Northwest coniferous forests. *Tree Physiol.* 22:1107-17.
- Calder, I.R. 1978. Transpiration observations from a spruce forest and comparisons with predictions from an evaporation model. *Journal of Hydrology.* 38:33-47.
- Cano, C., Ana. 2010. Dinámica hídrica edáfica y distribución radicular en un bosque de Quercus pyrenaica Willd. del Sistema Central.P. *In Memoria de grado. Universidad de Salamanca*, Salamanca, España.
- Caspari, H.W., S.R. Green and W.R.N. Edwards 1993. Transpiration of well-watered and water-stressed Asian pear trees as determined by lysimetry, heat-pulse, and estimated by a Penman-Monteith model. *Agricultural and Forest Meteorology.* 67:13-27.
- Cavanaugh, M.L., S.A. Kurc and R.L. Scott 2010. Evapotranspiration partitioning in semiarid shrubland ecosystems: a two-site evaluation of soil moisture control on transpiration. *Ecohydrology*

- Čermak, J., N. Nadezhkina, L. Meiresonne and R. Ceulemans 2008. Scots pine root distribution derived from radial sap flow patterns in stems of large leaning trees. *Plant and Soil*. 305:61-75.
- Čermák, J., J. Ulehla, J. Kucera and M. Penka 1982. Sap flow rate and transpiration dynamics in the full-grown oak (*Quercus robur* L.) in floodplain forest exposed to seasonal floods as related to potential evapotranspiration and tree dimensions. *Biol. Plant*. 24:446-460.
- Chavarro, R., D.C. 2009. Transpiration mapping from up-scaled sapflow. In *PhD dissertation thesis. ITC, University of Twente Enschede, The Netherlands*.
- David, T.S., M.O. Henriques, C. Kurz-Besson, J. Nunes, F. Valente, M. Vaz, J.S. Pereira, R. Siegwolf, M.M. Chaves, L.C. Gazarini and J.S. David 2007. Water-use strategies in two co-occurring Mediterranean evergreen oaks: surviving the summer drought. *Tree Physiology*. 27:793-803.
- Dawson, T.E., S. Mambelli, A.H. Plamboeck, P.H. Templer and K.P. Tu 2002. Stable Isotopes in Plant Ecology. *Annual Review of Ecology and Systematics*. 33:507-559.
- Do, F. and A. Rocheteau 2002a. Influence of natural temperature gradients on measurements of xylem sap flow with thermal dissipation probes. 1. Field observations and possible remedies. *Tree Physiology*. 22:641-648.
- Do, F. and A. Rocheteau 2002b. Influence of natural temperature gradients on measurements of xylem sap flow with thermal dissipation probes. 2. Advantages and calibration of a noncontinuous heating system. *Tree Physiology*. 22:649-654.
- Dorren, L.K.A., B. Maier and A.C. Seijmonsbergen 2003. Improved Landsat-based forest mapping in steep mountainous terrain using object-based classification. *Forest Ecology and Management*. 183:31-46.
- Ehlers, M., M. Gahler and R. Janowsky 2003. Automated analysis of ultra high resolution remote sensing data for biotope type mapping: new possibilities and challenges. *ISPRS Journal of Photogrammetry and Remote Sensing*. 57:315-326.
- Francés, A.P., J.L. Reyes-Acosta, E. Balugani, C. van der Tol and M.W. Lubczynski 2011. Towards an improved assessment of the water balance at the catchment scale: a coupled model approach. ZNS conference proceedings
- Granier, A. 1985. Une nouvelle méthode pour la mesure du flux de sève brute dans le tronc des arbres. *Annales des Sciences Forestières* 42:193-200.
- Hernández-Santana, V., T.S. David and J. Martínez-Fernández 2008. Environmental and plant-based controls of water use in a Mediterranean oak stand. *Forest Ecology and Management*. 255:3707-3715.
- Kimani, J.M., Y.A. Hussin, M.W. Lubczynski, D. Chavarro and O.T. Obakeng 2007. Mapping Savannah Trees in Kalahari using High Resolution Remotely Sensed Images and Object-Oriented Classification. *International Journal of Geoinformatics*. 3
- Lambs, L. and M. Berthelot 2002. Monitoring of water from the underground to the tree: first results with a new sap extractor on a riparian woodland. *Plant and Soil*. 241:197-207.
- Lu, P., L. Urban and P. Zhao 2004. Granier's Thermal Dissipation Probe (TDP) Method for Measuring Sap Flow in Trees: Theory and Practice. *Acta Botanica Sinica*. 46:631-646.
- Lubczynski, M. and J. Gurwin 2005. Integration of various data sources for transient groundwater modeling with spatio-temporally variable fluxes--Sardon study case, Spain. *Journal of Hydrology*. 306:71-96.
- Lubczynski, M.W. 2009. The hydrogeological role of trees in water-limited environments. *Hydrogeology Journal*. 17:247-259.
- Lubczynski, M.W., R. Chavarro, D.C. and J. Roy in press. New, cyclic thermal dissipation method for the correction of natural temperature gradients in thermal dissipation probe sap flow measurements. Part 1. Theory and field application
- Mediavilla, S. and A. Escudero 2003. Stomatal responses to drought at a Mediterranean site: a comparative study of co-occurring woody species differing in leaf longevity. *Tree Physiology*. 23:987-996.
- Moore, D.J.P., J. Hu, W.J. Sacks, D.S. Schimel and R.K. Monson 2008. Estimating transpiration and the sensitivity of carbon uptake to water availability in a subalpine forest using a simple ecosystem process model informed by measured net CO<sub>2</sub> and H<sub>2</sub>O fluxes. *Agricultural and Forest Meteorology*. 148:1467-1477.
- Nadezhkina, N., J. Čermák and R. Ceulemans 2002. Radial patterns of sap flow in woody stems of dominant and understory species: scaling errors associated with positioning of sensors. *Tree Physiology*. 22:907-918.
- Nadezhkina, N., M. Ferreira, R. Silva and C. Pacheco 2008. Seasonal variation of water uptake of a *Quercus suber* tree in Central Portugal. *Plant and Soil*. 305:105-119.
- Nadezhkina, N.J., Cermak and V. Nadezhdin. 1998. The heat field deformation method for sap flow measurement. In 4th International Workshop on Measuring Sap flow in Intact Plants. Eds. J. Čermak and N. Nadezhkina. Ed. Z. Proc 4th Int Workshop, Czech Republic, IUFRO Publications, Brno, pp. 72-92.
- Noy-Meir, I. 1973. Desert Ecosystems: Environment and Producers. *Annual Review of Ecology and Systematics*. 4:25-51.
- Phillips, D.L. and J.W. Gregg 2003. Source partitioning using stable isotopes: coping with too many sources. *Oecologia*. 136:261-269.
- Porporato, A., F. Laio, L. Ridolfi and I. Rodriguez-Iturbe 2001. Plants in water-controlled ecosystems: active role in hydrologic processes and response to water stress: III. Vegetation water stress. *Advances in Water Resources*. 24:725-744.
- Poyatos, R., J. Cermak and P. Llorens 2007. Variation in the radial patterns of sap flux density in pubescent oak (*Quercus pubescens*) and its implications for tree and stand transpiration measurements. *Tree Physiol*. 27:537-548.
- Reyes, A.J.L. and M. Lubczynski 2011. Improved sap-flow measurement scheme by combining TDP with HFD methods on *Quercus ilex* and *Quercus pyrenaica* trees in a semi-arid open forest in Salamanca, Spain. In press, *Ecohydrology*
- Seckler, D.W. and I. International Water Management 1998. World water demand and supply, 1990 to 2025 : scenarios and issues. International Water Management Institute, Colombo, Sri Lanka.
- Verbeeck, H., K. Steppe, N. Nadezhkina, M. Op de Beeck, G. Deckmyn, L. Meiresonne, R. Lemeur, J. Cermak, R. Ceulemans and I.A. Janssens 2007. Stored water use and transpiration in Scots pine: a modeling analysis with ANAFORE. *Tree Physiology*. 27:1671-1685.
- Walker, C.D. and S.B. Richardson 1991. use of stable isotopes of water in characterising the source of water in vegetation. In: *Chemical geology : isotope geoscience section*, 94(1991)2, pp. 145-158
- Williams, D.G., W. Cable, K. Hultine, J.C.B. Hoedjes, E.A. Yezpe, V. Simonneaux, S. Er-Raki, G. Boulet, H.A.R. de Bruin, A. Chehbouni, O.K. Hartogensis and F. Timouk 2004. Evapotranspiration components determined by stable isotope, sap flow and eddy covariance techniques. *Agricultural and Forest Meteorology*. 125:241-258.
- Yaseef, N.R., D. Yakir, E. Rotenberg, G. Schiller and S. Cohen 2010. Ecohydrology of a semi-arid forest: partitioning among water balance components and its implications for predicted precipitation changes. *Ecohydrology*. 3:143-154.
- Zencich, S., R. Froend, J. Turner and V. Gailitis 2002. Influence of groundwater depth on the seasonal sources of water accessed by *Banksia* tree species on a shallow, sandy coastal aquifer. *Oecologia*. 131:8-19.