Estimating and monitoring seasonal water consumption of olive orchards in a semi-arid region (Morocco) using the Eddy-covariance system

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Abstract. Planning and management of water resources have become a very important issue in arid and semi-arid regions. Accurate measurements of heat and water fluxes are required for optimizing water management and for validating models simulating crop water consumption. For the olive orchard, which is the dominant crop in Mediterranean regions, very little information exists on the exchange of heat and water fluxes between the vegetation and the atmosphere. In the context of SUDMED project, an experimental setup was conceived to monitor seasonal water consumption of olive orchards located near Marrakech, Morocco. For this purpose, an Eddy-Covariance (EC) system, a meteorological station, as well as measurements of soil moisture and temperature were continuously operated during more than one year over an irrigated olive yard, i.e. tall, sparse vegetation. The total annual rainfall and irrigation amount were around 354 and 800 mm respectively. The yearly cumulative evapotranspiration measured from eddy-covariance system was 824 mm. By using the water balance equation, the result showed also that a large quantity of water (around 330 mm) was lost due to deep percolation, infiltration and runoff. This loss is essentially due to the irrigation method (flood) which has an irregular pattern in space and time. On the other hand, the water requirements calculated following the FAO-56 procedure were 920 mm. Although the sum of irrigation and rainfall was greater than ET_c, the stress event occurred. Such behaviour can be explained by the fact that the irrigation monitoring is done by observing the physical conditions of the plant which is not sufficient to manage the irrigation.

Keywords. Eddy Covariance – Evapotranspiration – Energy Balance – Olive-Flood Irrigation – Water Balance.

Evaluation et suivi de la consommation saisonnière d'eau dans les vergers d'olivier en région semi-aride (Maroc) utilisant la méthode covariance turbulence

Résumé. *La planification et la gestion des ressources en eau est devenue une question de toute première importance dans les régions arides et semi-arides. La mesure correcte de la chaleur et des flux hydriques est indispensable pour optimiser la gestion de l'eau et valider les modèles qui simulent la consommation d'eau pour les différentes cultures. Quant à l'olivier, qui est la culture dominante en Méditerranée, les informations sur l'échange de chaleur et les flux hydriques entre la végétation et l'atmosphère restent insuffisantes. Par conséquent, dans le cadre du projet SUDMED, un dessein expérimental a été mis au point pour suivre la consommation saisonnière d'eau dans les vergers d'olivier de la zone autour de Marrakech, au Maroc. A cette fin, la méthode covariance turbulence a été appliquée et des données météorologiques et des mesures de l'humidité du sol et de la température ont été suivies pendant plus d'un an sur un couvert végétal clairsemé et développé en hauteur. Au total, les précipitations annuelles et la quantité d'eau apportée par l'irrigation ont été estimées à 354 et 800 mm, respectivement. L'évapotranspiration cumulative annuelle, mesurée par la méthode covariance turbulence, était égale à 824 mm. Les résultats obtenus en appliquant l'équation du bilan hydrique ont montré qu'une grande partie de l'eau (environ 330 mm) était perdue à cause des effets de la percolation profonde, de l'infiltration et du ruissellement. Ces pertes étaient essentiellement imputables à la méthode d'irrigation (par déversement) utilisée qui suivait un cours irrégulier dans l'espace et dans le temps. Par ailleurs, les besoins en eau estimés par la procédure FAO-56 s'élevaient à 920 mm. Bien que l'eau* *d'irrigation et les précipitations ensemble soient plus élevées qu' ET_c, un problème de stress est intervenu. Un tel phénomène peut être expliqué par le fait que le suivi de l'irrigation a été réalisé en n'observant que les conditions physiques de la plante, ce qui n'est pas du tout suffisant pour gérer l'irrigation.*

Mots-clés. *Covariance turbulence – Evapotranspiration – Bilan énergétique – Olivier-Irrigation par déversement – Bilan hydrique.*

I – Introduction

In arid and semi-arid regions, water availability is a serious limitation for crop production due to poor and irregular rainfall, high evaporative demand and inadequate management. Morocco which is classified as part of these regions suffers from limited water supply and water resources. Therefore, to manage this scarce resource under those conditions, the farmers should know at least two aspects: when do they have to irrigate and how much water do they have to apply on the ground?

Cereals and orchards are the dominating crops types in Morocco. This agriculture uses up to 80% of the total available water. Olive is the main component of the orchard, due to its resistance to drought; therefore the monitoring of olive irrigation and water balance at a regional scale is a major challenge for a sustainable development of agriculture. In this regard, the Sudmed (Chehbouni *et al.*, 2004) and Irrimed (http://www.irrimed.org) projects focus on the south Mediterranean regions within the Tensift river basin (Central Morocco) as a main region of interest. The basin size is about 30000 km^2 which includes the Atlas mountain range (headwater) and the semi-arid Haouz plain in the surrounding of the city of Marrakech. The plain spreads on a surface of 4500 km^2. In this region, the climate is characterized by low and irregular rainfall with an annual average of about 240 mm, whereas the evaporative demand is very high, around 1600 mm per year according to reference evapotranspiration estimates (Allen *et al.*, 1998). The Haouz plain contains about 85392 ha of olive and they plan to increase the surface to 95000 ha in 2010. A fundamental requirement for accurate irrigation scheduling is the determination of actual olive evapotranspiration. The most common method to calculate the evapotranspiration (ET) is a meteorological method such as Eddy-covariance, Bowen Ratio, water balance method, and sap flow combined with isotopic method. The scientific efforts in measuring or estimating the evapotranspiration of olive orchards or its components are all quite recent. Testi *et al.* (2004) used the Eddy-covariance technique which allows a direct measurement for the evapotranspiration for three years for assessing the ET of a young irrigated olive orchard in south Spain. Williams *et al.* (2004) used the sap flow method to measure the plant transpiration combined with the isotopic method to infer the evapotranspiration over olive orchards in current study area (olive yard of Agdal, Marrakech). The ET can be also simulated by using the FAO-56 model which is based on the concepts of reference evapotranspiration ET_0 and crop coefficients K_c (for more details, the reader can refer to Allen *et al.*,1998).

In this study, we used the Eddy-covariance system to measure the evapotranspiration over the olive orchards. This site is specific in several ways: the irrigation method (flood) which has an irregular pattern in space and time, heterogeneity along the site mainly caused by vegetation cover and the soil characteristics, and the surrounding orange orchards and buildings.

The objective of this paper is two-fold: 1) To analyze the energy-balance closure and seasonal variation in the olive evapotranspiration. 2) To investigate the feasibility of using the Eddy-covariance system to monitor water consumption of olive orchards. The paper is organized as follows: the area of interest and experimental data set are presented first. Then field data are analyzed. Lastly, we conclude by discussing the potential of the eddy-covariance system to monitor the water consumption over semi arid land.

II – Site description and experimental setup

The present study took place in a semi-arid basin in central Morocco (Tensift basin, see Fig. 1) within the framework of the SUDMED Program (http://www.irrimed.org/sudmed). In this region, the climate is a typical semiarid Mediterranean; precipitation falls mainly during winter and spring, from the beginning of November until the end of April with an average ranging from 192mm to 253mm. The atmosphere is very dry with an average humidity of 56% and high evaporative demand (1600mm per year), greatly exceeding the annual rainfall. The experiment was carried out between Day Of Year (DOY) 323 in 2002 and DOY 323 in 2003, at the 275 ha Agdal olive orchard, located southeastern of the Marrakech city, Morocco (31°36' N, 07°58' W). The average height of the olive trees is 6m with an average coverage that reaches approximately 55%. Two water basins are used for irrigation. Water is diverted manually to every tree through a network of ditches, each tree is surrounded by a small earthen levy that retains the irrigation water, allowing application of irrigation water to every tree. The amount of water used during each irrigation event was about 80 mm. Irrigation starts on the southern border of the field, and, depending on the available manpower, progresses towards the northern border of the site in approximately 12 days.

The field was equipped with a set of standard meteorological instruments to measure wind speed and direction (Young Wp200), air temperature and humidity using vaisala HMP45AC probes at 9 and 3.7m and radiation. The net radiation side was measured using a CNR1 (Kipp & Zonen) placed at 8.5m. The soil heat flux density was measured using heat flux plates (HFT3-L, Campbell Scientific Ltd.) at three locations differing in amount of radiation reaching the soil. The measurement depth was 1 cm. The plates were placed: one below the tree near the trunk in order not to be exposed to solar radiation; one was exposed directly to solar radiation, the last one in an intermediate position. An average of these 3 measurements was made to obtain a representative value. Soil moisture was measured at different depths (5, 10, 20, 30 and 40cm) using 5 CS616 water content reflectometers (Campbell Scientific Ltd.). All meteorological measurements were sampled at 1 Hz and averaged over 30 minutes. The prevailing wind direction is northwest.

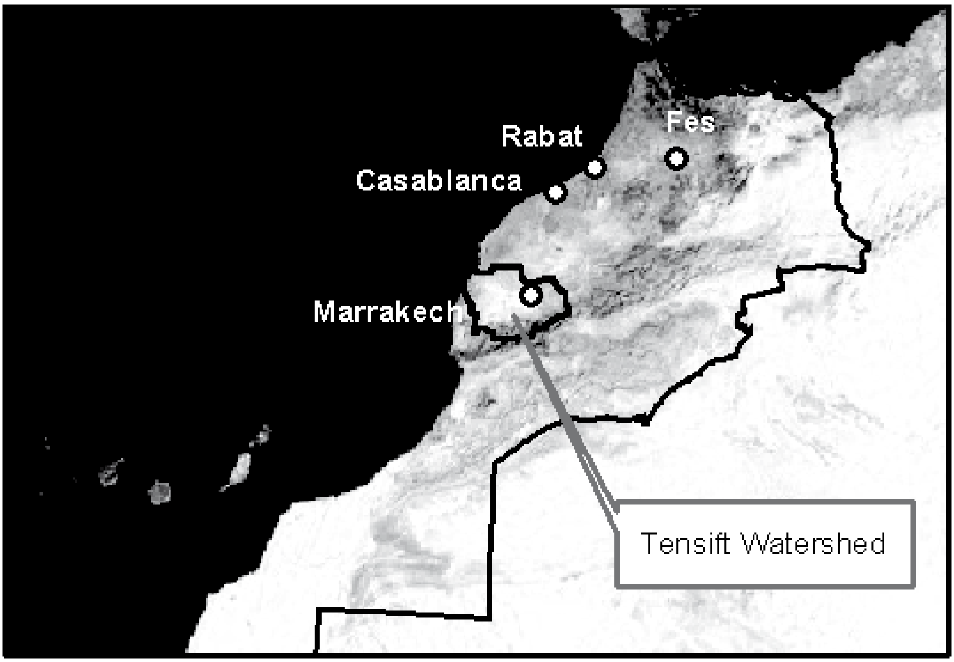

Figure 1. The study area.

An eddy-correlation system (EC) was installed to provide continuous measurements of vertical fluxes of heat, water vapour and carbon dioxide CO_2 at 3 m above the top of the canopy on the 9.2m tall instrument tower (see figure1). The EC system consisted of a 3D sonic anemometer (CSAT3, Campbell scientific Ltd.) which measured the fluctuations in the wind velocity components and temperature, and an open-path infra-red gas analyzer (Li7500, Licor, Inc.) that measured concentration of water vapour and carbon dioxide. A CR5000 datalogger (Campbell Scientific Ltd) was used for the storage of raw 10 Hz data. The half-hourly values of fluxes were later calculated using the software 'ec-pack' developed by the Meteorology and Air Quality group at Wageningen University. The software is available for download at http://www.met.wau.nl/. The annual evolution of daily reference evapotranspiration ET_0 calculated following the FAO-Penman-Monteith (Allen *et al.* 1998) during the experiment was presented in Figure 2. As can be seen in this figure, the temporal pattern of $ET0$ values is typically that of a semi-arid continental climate type. It is characterized by a high climatic demand, with a maximum value in the summer (6.77mm) and a minimum value in the winter (0.68mm).

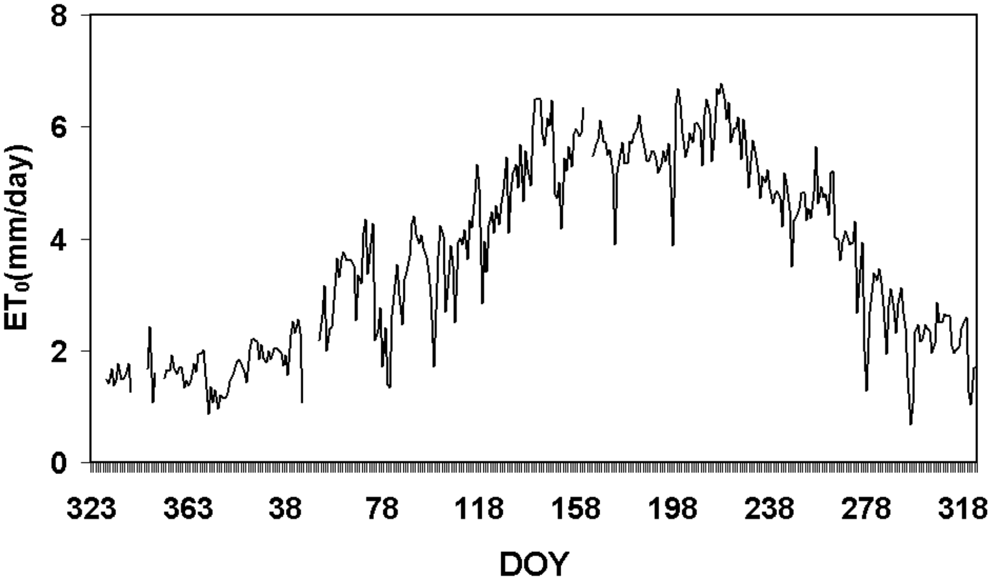

Figure 2. Annual evolution of daily reference evapotranspiration ET0 calculated following the FAO-Penman-Monteith during the experiment.

III – Results and discussion

In this section, the closure of the energy budgets of the eddy-covariance data sets was presented first. After that we present the flood irrigation effects taking into account the amount of irrigation given by the manager and the ORMVAH regional public agency ('Office Régional de Mise en Valeur Agricole du Haouz'), and we compare the irrigation events applied by the farmer and those simulated by the FAO-56 model.

1. Flux data quality assessment

The energy balance closure is the widespread method used for evaluating atmospheric flux measurements. By neglecting the heat stored in the biomass and the air below the sensors, the one-dimensional balance for the olive can be written as: $R_n - G = \lambda E + H$, where R_n is the net radiation, G the soil heat flux which was taken as an average of the three measurements (below the tree, exposed to solar radiation and at an intermediate position), and λE and H are sensible heat fluxes, respectively. As a measure of how the energy balance was closed in our observations, the sum between the turbulent fluxes, $(L_vE + H)$ was plotted against the available energy $(R_n - G)$, for daily total fluxes when fluxes were available for the 24 half-hour period in the day (see Figure 3). The linear regression (forced trough the origin) yields [W.m-2]: $R_n - G = 1.05H + L_vE$, $R2 = 0.86$, with RMSE = 17 Wm-2. The difference in terms of the sources areas of the different instruments has the biggest impact on the closure of the energy balance especially over sparsely vegetated surfaces. The source area sampled by Eddy-covariance is much larger than that of net radiation and soil heat flux and it can change rapidly depending on wind speed and direction and on surface conditions. However, comparatively to what has been reported in the literature (Twine *et al.*, 2000), the closure can be considered as fairly good. Therefore, we were confident that the Eddy-covariance measurements accurately measured H and L_vE.

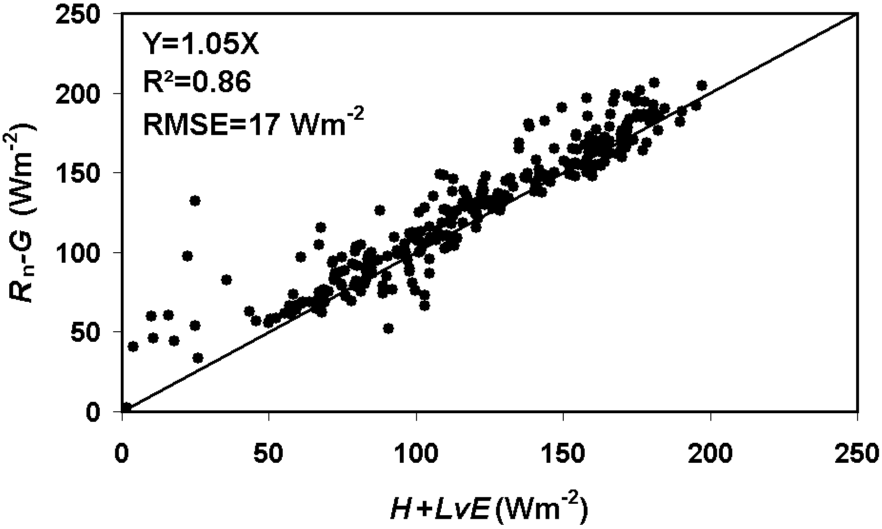

Figure 3. Daily energy balance closure, H : sensible heat flux, LvE : latent heat flux, Rn : net radiation, G : soil heat flux.

2. Irrigation efficiency assessment

Total rainfall during the experiment was 353.6 mm, while the average annual in the Tensift river basin is 240 mm. The total irrigation water applied to the orchard was around 800 mm over 10 irrigation cycles. In contrast, the yearly quantity of irrigation applied by the ORMVAH in the same conditions was about 680 mm. This quantity depends on the total available water. It decreases in case of water shortage. The yearly cumulative ET measured with the Eddy covariance system during our experiment was 824 mm. At operational basis, the FAO-56 model was applied to estimate water consumptions of olive orchards (Er-Raki *et al.*, 2004). FAO-56 model is based on the concepts of reference evapotranspiration ET_0 and crop coefficients K_c, the cumulative ET_c calculated with the FAO-56 was 863 mm and the annual reference evapotranspiration was 1269 mm (Allen *et al.*, 1998). The accumulated ET_{EC} and ET_c for olive season are shown in Figure 4. By analyzing this Figure, the accumulated ET_{EC} and ET_c curves are close over the period DOY 323 to

DOY 190. For the remaining days, ET_c was higher than ET_{EC}. This is due to the stress induced by irrigation delay. It can be noticed also in this figure, that although the sum of irrigation and rainfall was greater than ETc, one stress event occurred (from DOY 190).The frequencies of irrigation applied by the farmer and simulated by the FAO-56 were presented in Figure 5. The rainfall was presented in the same figure. For the FAO-56 model, the simulation was performed only from the 1st of March (DoY 60) through the 25th of November 2003 (DoY 329). By analyzing Figure 5, one can see that the farmer does not take into account the climatic and soil characteristics in the irrigation distribution. In general, the irrigation event should increase in the summer and decrease in the winter. On the contrary, we noticed that the farmer applied less water in the dry season. For example, the farmer made 46 days between two irrigations 169(2003) and 214(2003) while the FAO-56 model simulated three irrigations between those dates with a water amount of 64 mm, because this time period was very dry and no rainfall was recorded. The dates of the irrigation events simulated by the FAO-56 model were very different from those applied by the farmer. Sometimes, they irrigated just after heavy rainfall (four irrigations were applied in this case: days 353(2002), 109(2003), 169(2003) and 303(2003)). Some of those irrigations should be delayed (169(2003), 309(2003), 109(2003)) and the first irrigation (353(2002)) was unnecessary because it was rainy for a long period. Using the water balance equation of the FAO-56 method and ignoring the variation in the water storage in the study area (the initial conditions were similar to the conditions in the end of the experiment), the quantity lost by percolation, infiltration and runoff was approached to the sum of the total precipitation and irrigation minus the cumulative of simulated ET. The result showed that the yearly water lost by percolation, infiltration and runoff was 330 mm and 254.6 mm by taking the quantity given by the farmer and ORMVA respectively. The result revealed that the farmer applied a large amount of water and the irrigation system was not appropriate for the orchard conditions. During the winter, the soil was very wet so a substantial part of the rainfall was lost by runoff. During the dry-phase, large cracks were observed. So during the irrigation, a considerable amount of water was immediately lost by seepage through cracks. The result shows also that the monitoring irrigation amounts are not based on weather forecast, for example it was rainy directly after the third and last irrigation.

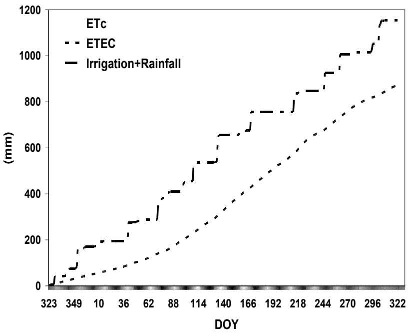

Figure. 4. Accumulated crop evapo-transpiration (ETc), Evapotranspiration derived from the EC (ETEC), irrigation applied by the farmer and sum of irrigation and rainfall.

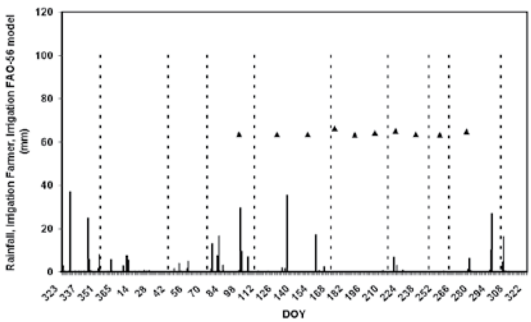

Figure 5. Irrigation interval applied by the farmer (dotted line) and those simulated by the FAO-56 model (triangles). Also the rainfall events (solid line) were shown.

IV – Conclusions

Several successful studies have investigated the use of the Eddy-covariance system in measuring the area-average sensible and latent heat fluxes. The objective of this study was to test the performance of the Eddy-covariance system to monitor the water consumption in difficult environmental conditions (tall vegetation, irrigation method which has an irregular pattern in space and time, the vegetation cover and the soil characteristics). An experiment was conducted over the irrigated oliveyard of Agdal which is located in Marrakech (Morocco). An Eddy correlation system and meteorological station were installed in oliveyard to provide continuous fluxes measurements. The analysis of the closure energy budget yielded an excellent relationship between the available energy and the turbulent fluxes with RMSE=13.12 Wm-2. So we are confident from this study that eddy-covariance systems provide reliable measurements of fluxes. The result showed also that a big amount of water (330 mm) was lost by percolation, infiltration and runoff. In contrast by taking the amount given by the ORMVA, the loss decreases to 209.6 mm. Most olive orchards are in areas where water is scarce and sometimes of low quality. So to save the water lost by evaporation from the ground, we must wet the maximum volume of root zone and the minimum soil surface.

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