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Comparing Eddy Covariance and Soil Water Balance Methods for Evapo- transpiration Measurement in Palmyra Oasis in Syria

مقارنة طريقتي Eddy Covariance والموازنة المائية لتحديد قيم البخر- نتح في واحة تدمر بسوريا

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Abstract: In this study th eddy covariance method results for daily evapotranspiration ET_{eddy} in the Palmyra Oasis were compared with those obtained from the water balance method ET_{bal}. The eddy covariance measurements were made with a 3D sonic anemometer and a Krypton hygrometer. Evapotranspiration estimated by the water balance method was determined using a TDR for soil moisture measurement and a tensiometer for matric potential measurement. A total of 9 pairs of ET_{eddy} and ET_{bal}. daily values were compared. Good agreements were found between the two tested methods with a RMSE of 15.

Keywords: *Evapotranspiration, Eddy covariance, Soil water balance, Palmyra Oasis,*

المستخلص: تم في هذه الدراسة مقارنة قيم البخر-نتح المحددة بطريقة Eddy covariance (ET_{eddy}) مع تلك المحددة بطريقة الموازنة المائية (ET_{bal}) وذلك للاشجار المزروعة في واحة تدمر. ولقد تم تحديد قيم ET_{eddy} بطريقة Eddy covariance بالاعتماد على قياس سرعة الرياح باستخدام مقياس سرعة رياح صوتي ثلاثي الابعاد (3D sonic anemometer)، وقياس كثافة بخار الماء باستخدام جهاز (krypton hygrometer). اما بالنسبة لطريقة الموازنة المائية فقد تم تحديد قيم ET_{bal} بالاعتماد على قياس رطوبة التربة باستخدام حساسات جهاز TDR وقياس الشد الرطوبي للتربه باستخدام أجهزة التنسيومتر. تم مقارنة تسع قيم ET_{eddy} و ET_{bal}، ودلت نتائج المقارنة على وجود توافق جيد بين طريقتي القياس وكانت قيمة الخطأ المتوسط التربيعي مساوية إلى 15.

كلمات مدخلية: *البخر-نتح، Eddy covariance، الموازنة المائية، واحة تدمر*

Introduction

Oases are prominent features within arid and semi-arid areas. They provide important economical, recreational and natural resources. Water resources in arid and semi arid areas are commonly scarce and in great demand especially in the agricultural sector where about 80% of the available water resources are used. Reliable estimates of evapotranspiration ET in an oasis are needed to increase water use efficiency and provide better management of available water resources. Oases typically have a mixture of trees with different intercrops. This results in difficulties in estimating ET in the oasis. Currently evapotranspiration from the oasis is predicted using weather based equations such as Penman, Penman Monteith, and Blaney-Criddle equations. Climatic equations perform well over uniform vegetation; but it is not known how accurate this equation will predict ET of sites that differs from sites for which the equation has been calibrated with respect to soil, climate, and vegetation. Calibration of these equations is usually achieved using crop coefficients. Unfortunately crop coefficients for a mixture of crops are not easily obtained and only an approximate method to determine it is available (Allen, *et al.*, 1998) Alternative methods to determine actual evapotranspiration are weighing lysimeters, soil water balance, and micrometeorological methods.

The weighing lysimeter is one of the most popular methods used to estimate actual evapotranspiration. However, this method is limited in that lysimeters are costly, non-portable, and difficult to establish (Kizer, *et al.*, 1990). The soil water balance is an accurate method and it has been used in many studies for ET determination (Gunston and Batchelor, 1983) but it is limited by the difficulty of determining deep percolation from the crop root zone (Ward and Robinson, 1990). Micrometeorological techniques such as eddy covariance (Swinbank, 1951) can be used to measure actual ET by correlating fluctuations of vertical wind speed with fluctuations of vapor density. This method has a major advantage that it can be applied for determining actual ET without need for calibration.

Samaan, *et al.* (2005) compared ET values from the Palmyra Oasis (in Syria) measured using eddy covariance techniques with that calculated by Penman, Penman Monteith, and Blaney-Criddle equations during the years of 2003 and 2004. They used a method suggested by Allen, *et al.* (1998) for obtaining crop coefficients for mixed crops. They found that ET estimation from climatic equations was considerably higher than that measured using eddy covariance method (Table 1). It was not clear if this deviation between results is due to use of an inappropriate crop coefficient or because the eddy covariance method underestimated ET. (Leuning and King, 1992; Schellekens, 2000) reported that micrometeorological methods may lead to underestimation of evapotranspiration.

There were several studies to compare the eddy covariance method with the Bowen ratio method (Lang, *et al.*, 1983; Tanner, 1988; Dugas, *et al.*, 1991), both methods are micrometeorological. The objective of this study was to compare the performance of the eddy covariance method for ET measurements in the Palmyra Oasis with the independent soil water balance method.

Study area

The study area is located in the Palmyra Oasis near the town of Palmyra (latitude 34° 32' N, longitude 38° 16' E) in the center of the Syrian Desert. The climate is Mediterranean arid. The average maximum temperature during the hottest month is 37.8 C° and the average minimum temperature during the coldest month is 2.4 C°. The rainy season extends from October until May with an average annual rainfall of 120 mm. Figure 1 shows rainfall distribution during the year of 2004. The estimated annual potential evapotranspiration is 1,760 mm and the pan evaporation is 2,300 mm. The whole Oasis covers 1000 hectare (ha). The main cultivations are olive trees (250,000 trees), palm trees (70,000 trees), pomegranate trees (80,000 trees), and other fruit trees (250,000). The micrometeorological and soil moisture measurements were made in a 0.4 ha field chosen to be a good representative with a fetch of around 1 kilometer in every direction.

The soil texture is sandy loam to a depth of 0.35 meters (m) and sandy clay loam between 0.35 m and 1.50 m below the soil surface. The corresponding soil bulk densities for each depth are 1.39 and 1.2 gram/cubic centimeter (g/cm^3), respectively. The oasis is irrigated with a traditional flood irrigation method. Water is delivered to the farmer once a month from a governmental public well. However, some farmers have their own wells and they apply additional irrigation to their farm land. Table 2 presents the irrigation schedule and amount of irrigation during the year of 2004 applied to the 0.4 ha field in which the instruments were installed.

Table 1. Comparison of annual ET (mm) measured with eddy covariance method with that calculated with climatic equation in the Palmyra Oasis (Samman, *et al.*, 2005).

Year	Eddy covariance	Blaney-Criddle	Penman	Penman- Monteith
2002	807	1340	1221	1210
2003	742	1360	1196	1174

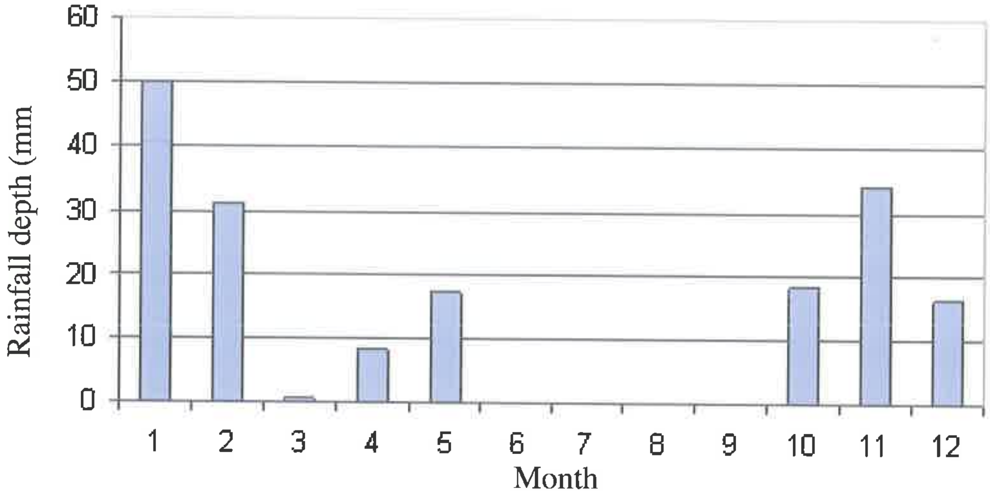

Fig. 1. Rainfall distribution during the year of 2004.

Table 2. Applied irrigation water during year of 2004 to the 0.4 ha field in which the instruments for ET measurements were installed (G: Government well, P: Private well).

Date	Total applied volume(m^3)	Type of well
30-Mar	259.2	G
17-Apr	217.9	G
18-May	214.1	G
28-May	284.2	P
08-Jun	199.4	G
28-Jun	289.1	P
10-Jul	210.5	G
26-Jul	290.0	P
10-Aug	210.5	G
29-Aug	304.6	P
10-Sep	188.6	G
30-Sep	224.3	P
11-Oct	204.2	G
28-Dec	174.9	P

Materials and Methods

a. Eddy Covariance Measurements

Eddy covariance instruments were mounted on a tower 5 m above the trees canopy. The system consists of a CSAT3 three dimensional sonic anemometer (Campbell sc.) and a KH20 Krypton hygrometer(Campbellsc.).Thethreedimensional sonicanemometerwhichpulsesultrasonicsignals between three pairs of transducers is used to determine vertical wind speed. The Krypton hygrometer measures the water vapor density. These instruments were scanned every 0.15 seconds and the vertical wind speed and vapor pressure are averaged every 15 minutes and logged into a CR23 X data logger (Campbell sc.).

The eddy covariance measurement point corresponds to a fetch of 200 m. Evapotranspiration ET_{eddy} is calculated from the following equation:

$$ET_{eddy} = \rho\lambda \operatorname{cov}(w'q') \qquad (1)$$

where,

ET_{eddy}= is the evapotranspiration calculated by the eddy covariance method (mm/day).

λ = is the latent heat of vaporization of water.

ρ = is the density of air.

w'= is the deviation in vertical wind speed fromthe average vertical wind speed.

q'= is the deviation in specific humidity of air from the average specific humidity of air.

During the year of 2004, eddy covariance measurements were made over the tree canopy in the Oasis from January 1 until November 25.

b. Water Balance Method

In the same field the eddy covariance system was installed, seven 30 cm TDR probes (CS616, Campbell Sc.) were used to measure volumetric moisture content. The probes were installed horizontally at depths of 0.1, 0.25, 0.5, 0.75, 1, 1.25, and 1.50 m below the soil surface. The TDR probes were connected to a CR10X data logger (Campbell Sc.) and soil moisture measurements were recorded every hour. Soil matric potential was measured with a mercury tensiometer (STM 2150, SDEC FRANCE). Seven tensiometers were installed at similar depths as the TDR probes. The tensiometers readings were taken manually on a daily basis.

Ignoring lateral movement of water, the water balance equation was written for the upper 1.5 m of the root zone (considered as control volume) as follows. The tensiometers were serviced once a week during dry season.

$$0 = P + I - ET_{bal.} - F \pm \Delta S \qquad (2)$$

where,

P= is precipitation.

I= is irrigation.

F= is the downward flux of soil water at the lower boundary of the control volume.

ET_{bal}= is the evapotranspiration calculated from the water balance method.

ΔS= is the change in stored soil water which is determined by multiplying the change in volumetric water content by the depth of soil layer.

Groundwater at the site is deeper than 10 m therefore upward movement of soil water into the control volume was neglected. To eliminate P, Eq. 2 will be applied in the dry season only which extends from end of May until mid October. Moreover, to eliminate I, Eq. 2 will be applied in the period between irrigations only. The downward flux from the lower boundary of the control volume is estimated by applying Darcy's Law between two points located at Z_1=1.25 m and at Z_2=1.5 m below the soil surface as follows:

$$Jw = -k(h)\frac{\Delta h}{\Delta z} \qquad (3)$$

where,

k(h)= is the hydraulic conductivity.

Jw = is the vertical soil water flux.

$\Delta h = h_{1.25} - h_{1.5}$. $h_{1.25}$ and $h_{1.5}$ are are the matric potentials measured at 1.25 m and 1.5 below the soil surface, respectively.

Δz= is the vertical distance between z_1 and z_2 i.e; $\Delta z = 1.5 - 1.25 = 0.25\ m$.

The downward soil water flux from the control volume will be omitted when Δh is negative, therefore comparison between ET_{eddy} and ET_{bal} was limited to days when $\Delta h \leq 0$.

The agreement between values of ET from the eddy covariance and those from the soil water balance were quantified using the root mean square error (RMSE) as a statistical measure of goodness of fit (Loague and Green, 1991):

$$RMSE = \left[\frac{\sum(P_i - O_i)^2}{N}\right]^{0.5} \times \left(\frac{100}{\overline{O}}\right) \qquad (4)$$

where,

P_i= are values of ET_{eddy}

O_i= are values of ET_{bal}

$\overline{O}$= is the mean value of ET_{bal}

N = is the number of observations.

RMSE= is a measure of the deviation between ET_{eddy} and ET_{bal}. Ideally it should be equal to zero.

Results and Discussions

1. Eddy Covariance Measurements

Figure 2 shows values of the eddy covariance measurements of evapotranspiration ET_{eddy} during the year of 2004. Values of ET_{eddy} ranged from 0.63 mm/day on January 14, to 5.45 mm/day on July 12 with the total evapotranspiration during the year of 2004 equal to 675 mm. This result is similar to that obtained by Samman, *et al.* (2005) (Table 1).

2. Water Balance Measurements

As mentioned earlier, comparison of ET_{eddy} with evapotranspiration values obtained from the soil water balance method ET_{bal} were limited to periods when the downwards soil water flux from the lower boundary of the control volume (top 1.5 m in this study) is zero (i.e. $\Delta h \leq 0$). Figure 3 shows the variation of Δh values as measured with tensiometers between May 20 and October 15. There were four periods when Δh was negative: 7 to 9 of July , 23 to 27 of July, 8 to 10 of August, and 24 to 28 of August. Due to instrumental problems, records for ET_{eddy} were not available for the period between the 8th and 10th of August. Table 3 shows an example of the ET_{bal} calculation on August 26. On that day, P, I, and F were equal to zero. Therefore Eq. 2 is reduced to:

$$ET_{bal.} = \Delta S \qquad (4)$$

It can be seen from Table 3 that more than 70% of ET_{bal} occurred from the top 50 cm of the soil profile, this indicates that the major root mass is concentrated at this depth.

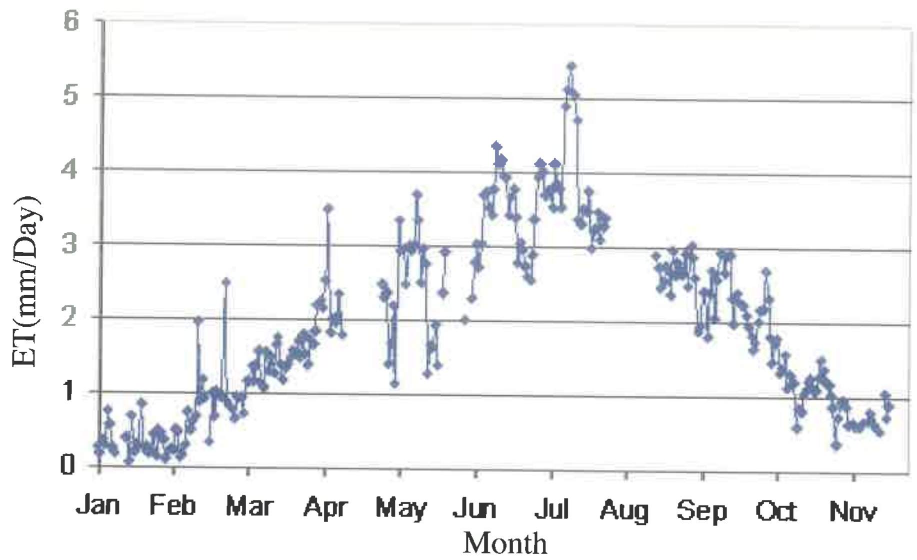

Fig 2. Values of Evapotranspiration in the Palmyra Oasis measured with the eddy covariance method during the year of 2004.

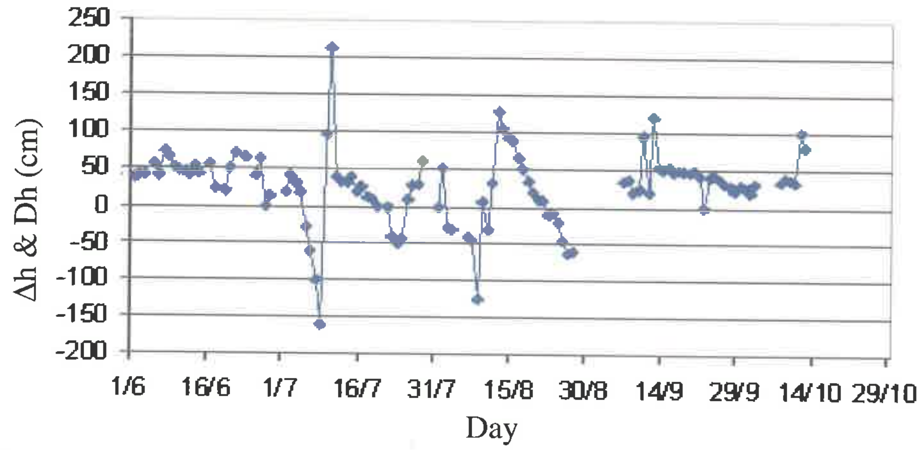

Fig 3. Daily Δh (Δh = h1.25- h1.5) values between May 30th. and Oct. 15th. 2004

Table 3. Example of daily ET calculation using soil water balance method on August 26 (a: volumetric moisture content at the beginning of the day, b: volumetric water content at the end of the day, c: thickness of soil layer, d: the change in stored soil water, e: evapotranspiration from each soil layer, cumulative evapotranspiration).

Depth TDR probs (cm)	Θ_1 [a]	Θ_2 [b]	Δθ	ΔZ [c] (m)	ΔS [d] (m)	ΔET [e] (mm)	Cum. ET (mm)	ΔET/ET× 100
10	14.061	13.625	0.436	0.225	0.098	0.981	0.981	32.0
25	14.235	13.943	0.292	0.250	0.073	0.730	1.711	55.8
50	15.800	15.604	0.197	0.250	0.049	0.492	2.203	71.9
75	22.985	22.862	0.123	0.250	0.031	0.308	2.511	81.9
100	21.213	21.115	0.098	0.250	0.025	0.246	2.757	90.0
125	19.565	19.491	0.074	0.250	0.018	0.185	2.941	96.0
150	19.589	19.540	0.049	0.250	0.012	0.123	3.064	100.0

3. Comparing ET_{eddy} with ET_{bal}

Table 4 compares values of ET_{eddy} with ET_{bal} for three periods. For the period of 7 to 9 of July, there were large differences between ET_{eddy} and ET_{bal} values with the error ranging from 40% to 48%. The difference between the two methods occurred because the field where the instruments were installed was irrigated on 28th of June from a private well (Table 2) while other fields in the Oasis were not irrigated.

Table 4. Comparison of ET_{eddy} with ET_{bal}

Date	Δh (cm)	ET_{eddy} (mm/day)	ET_{ba}(mm/day)	ET_{eddy}- ET_{bal}	Error %
July-7	-28	4.13	7.85	-3.72	-47.35
July-8	-60	3.86	7.44	-3.57	-48.04
July-9	-100	3.79	6.40	-2.61	-40.81
July-23	0	3.21	4.10	-0.89	-21.81
July-24	-40	3.25	3.43	-0.18	-5.10
July-26	-50	3.47	3.25	0.22	6.90
July-27	-44	3.11	3.12	-0.01	-0.46
Aug.-24	-10	2.37	3.40	-1.03	-30.31
Aug.-25	-8	2.97	3.31	-0.34	-10.20
Aug.-26	-22	2.63	3.00	-0.37	-12.28
Aug.-27	-46	2.81	2.88	-0.07	-2.51
Aug.-28	-64	2.70	2.64	0.06	2.19

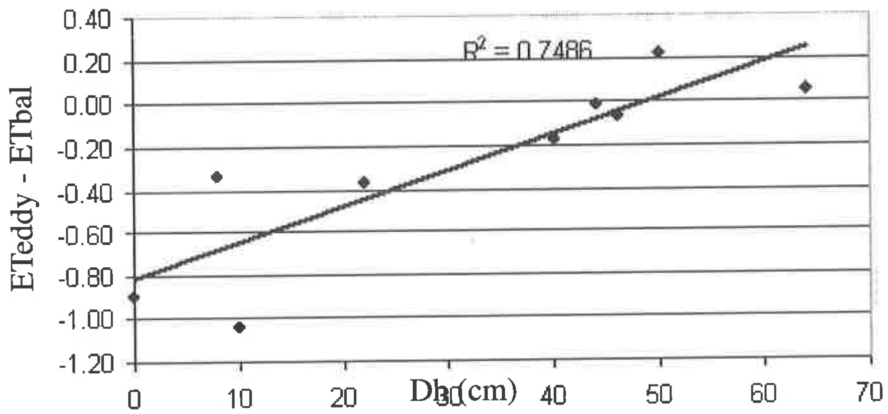

Fig 4. The relationship between Δh and (ET_{eddy} - ET_{bal}).

As mentioned previously, the eddy covariance measurement point corresponds to a fetch of 200 m (i.e. an area of 12.5 ha) while the water balance method represents the area nearby the TDR probes only. Therefore, comparison between ET_{eddy} and ET_{bal} will be valid only when the fields located within the 200 m fetch (including the field where the instruments were installed) are irrigated almost at the same time. For the other studied periods (Table 4), there was a reasonable agreement between the two methods used for ET estimation with RMSE of 15. The difference between ET_{eddy} and ET_{bal} ranged from 0.01 to 1.03 mm/day. However, it is noticeable that for Δh <-20 cm the differences between both measurements were less than 0.4 mm/day. Generally speaking, the difference between ET_{eddy} and ET_{eddy} decreased as Δh increased (Figure 4). This indicates that the difference between both measurements of ET could be due to downward movement of water at the lower boundary of the control volume in spite of that Δh values were negative. It is highly possible to get small errors in the tensiometers readings due to the air bubble in the tensiometer water.

Another source of deviation between the two measurements is the large difference in the size of the representative area for each of the studied methods (12.5 ha for the eddy covariance method compared to a few square meters for the water balance method). In fact, there is some lag time (less than 12 hours) in irrigation schedule for fields located within a 200 meter (m) fetch of eddy covariance measurement points.

Summary and Conclusion

ET values measured with the eddy covariance method in the Palmyra Oasis were checked against values of ET measured with the soil budget method. Reasonable agreements between both evaluated methods were obtained when the conditions of the comparison were met (similar irrigation schedule, no downward movement of water at the lower boundary of the control volume). Therefore the eddy covariance could be used to obtain an accurate measurement of ET in oases systems and it can be used for local calibration of the climatic equations used for ET estimation.

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