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Comparing Cotton Evapotranspirations Estimated by Micrometeorological and Water Budget Methods

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Abstract: This study aimed at comparing actual water consumption of cotton obtained by the water balance method under full and limited irrigation conditions, with that estimated by a micrometeorological method (energy balance), which is being widely used nowadays. Results indicated that in the first year the total irrigation water applied was 438 mm, whereas in the second year it was 199 mm. Deep percolation losses were were 6 and 0 mm, respectively, in the first and second year of the experiment. The evapotranspirations of cotton under full irrigation condition were 496 and 629 mm for the energy balance and water budget methods, respectively. Corresponding values under limited irrigation conditions were 404 and 394 mm. Strong relationships (R^2= 0.99) were found between the evapotranspirations estimated by water balance and micrometeorological methods. Consequently, as compared to the water balance approach, the energy balance method under full irrigation conditions produced lower evapotranspiration (ET). This could be a result of the field measurements of deep percolation included in ET calculation by water balance.

Key Words: Micrometeorology, Water Budget, Evapotranspiration, Cotton

Mikrometeorolojik ve Su Bütçesi Yöntemleriyle Belirlenen Pamuk Su Tüketimlerinin Karşılaştırılması

Özet: Bu çalışma tam ve eksik sulama koşullarında pamuk bitkisinde su bütçesi yöntemiyle elde edilen gerçek su tüketim değerinin son yıllarda yaygın olarak kullanılan mikrometeorolojik yöntemlerle (enerji dengesi yöntemi) belirlenen su tüketimiyle karşılaştırılması amacıyla yapılmıştır. Elde edilen sonuçlara göre, denemenin birinci yılında toplam 438 mm, ikinci yılında ise 199 mm sulama suyu uygulanmıştır. Derine sızma kayıpları denemenin birinci ve ikinci yılında sırasıyla, 6 ve 0 mm olarak ölçülmüştür. Pamuğun mevsimlik su tüketimi tam sulama koşullarında, enerji dengesi ve su bütçesi yöntemleriyle sırasıyla, 496 ile 629 mm, eksik sulama koşullarında, 404 ile 394 mm olduğu anlaşılmıştır. Mikrometeorolojik ve su bütçesi yöntemleriyle belirlenen gerçek su tüketimleri arasında çok yakın, (R^2=0.99) doğrusal ilişkilerin olduğu saptanmıştır. Sonuç olarak, tam sulama koşullarında su bütçesi yöntemiyle enerji dengesi yaklaşımına göre daha yüksek su tüketim değerleri elde edilmiştir. Bunun tarla parsellerinde derine sızma kayıplarının ölçümünden kaynaklandığı düşünülmüştür.

Anahtar Sözcükler: Mikrometeoroloji, Su Bütçesi, Bitki Su Tüketimi, Pamuk

Introduction

Water is a prerequisite for the human being to survive and develop. It is one of the main inputs in agriculture, as well as for industry and households to meet human needs. A total of 97.5% of the water available on the earth is saline and only 2.5% is fresh water. However, a large part of the fresh water is in the glaciers. The fresh water available for use is only 0.26% of total water resources. Global warming, due to the greenhouse effect, and the rise in world population have both become increasingly important. Due to these increases in population and global warming, the fresh water requirement of the world increased 8 times since the beginning of the century. Therefore, it has become more crucial to manage scarce fresh water resources properly (Burman et al., 1983).

Since water is very important for life it must be used more efficiently in all fields in which it is utilized. Therefore, the hydrological cycle should be well designed and managed. One of the major components of the hydrological cycle is crop water consumption, consisting of the transpiration from the crop canopy and the evaporation of water from the soil surface. Crop water consumption is used in estimating crop water requirements, scheduling irrigations, deciding on supplemental irrigation, design, operation and management of irrigation systems, estimating deep percolation and the planning of multi-purpose development projects. Thus, crop water consumption is dealt with not only by agricultur alists but also by meteorologists, hydrologists, and irrigation engineers. Since it serves many proposes, it should be measured precisely (Kanber, 1977; Jensen et al., 1990; Jones, 1992; Şaylan, 1995).

Micrometeorological techniques provide an alternative means for measuring exchanges of chemicals between the biosphere and the atmosphere. Micrometeorological techniques have many advantages. First, they are in situ and do not disturb the environment around the plant canopy. Second, these techniques allow continuous measurements. Third, time-averaged micrometeorological measurements at a point provide an area-integrated, ensemble average of the exchange rates between the surface and the atmosphere (Baldocchi et al., 1988). In this study, water vapor flux from cotton canopy to atmosphere was measured in a 1 ha cotton field. Flux measurements were conducted under full and limited water conditions, and the results were compared with actual water consumption obtained by the water balance method.

Materials and Methods

This investigation was carried out during the 1998-1999 growing seasons at the research field of Agricultural Engineering Department, Faculty of Agriculture, University of Cukurova at latitute 36° 59'N, longitude 35° 18'E, altitude 20 m a.s.l.

The cotton variety, Cukurova-1518, was planted with a 70 cm row spacing on May 5, 1998 in the first and 28 April, 1999 in the second year of the experiment. Planting depth was 3-4 cm. The length of the field was 100 m. The variety crops earlier and responds to irrigation better than other varieties. It is also better than others in its resistance to *Besimia Tabbaci* Genn. (Isler, 1987). Nitrogen of 1.6 kg/ha and phosphorus of 0.6 kg/ha were applied (Guzel et al., 1983). Full and limited irrigation conditions were tested each year, as only one set of equipment to perform Bowen and Eddy observations was available. At the first irrigation, the soil moisture was brought to the field capacity. Then, class A pan data were used to determine the amount of water to be applied and the timing of irrigation. The irrigation as repeated when the class A pan evaporation reached 70 mm. The crop pan coefficient (K_{cp}) used was 0.91 (Eylen, 1988). Only one irrigation (70% of the water needed to bring the soil moisture to field capacity) was applied in the second year of the experiment. The soil was classified as clay type with average field capacity of 38.48% and a wilting point of 24.84% (weight basis). The bulk density of the soil was 1.37 g/cm^3. Soil moisture was monitored by removing soil samples weekly from the beginning till the end of the growing season. The plugged furrow irrigation method was used in both years. Irrigations were ceased when 10% of the cotton balls opened (Karaata, 1985). All the instruments were placed in the middle of the field to measure water vapor flux. Before and after irrigations, groundwater fluctuation was observed by setting up 6 observation wells of 5 cm. The actual water consumption of cotton was measured by the water balance equation (Walker and Skogerboe, 1987) as given below:

$$ET_{WB}=I+P+SF_1+L_1+G_w-R_o-L_o-L_w-D_p\pm\Delta S \qquad (1)$$

where, ET_{WB} is actual evapotranspiration, I is the irrigation water, P is precipitation, SF_1 is incoming surface water, L_1 and L_o subsurface lateral flow in and out of the field, respectively, G_w is capillary flow, R_o is runoff, L_w is leaching requirement, D_p is deep percolation, and ΔS is the change in the soil water storage. In the equation, all units are expressed in mm. The I and P values in the equation were measured using a water meter and pluviometer, respectively. R_o was considered to be zero since the furrows were plugged. SF_1, L_1, L_o and L_w values were neglected since the measurements were conducted in the middle of the field. D_p was measured by tensiometers located at 90 and 120 cm deep in the soil profile as described in Kirda (1999). G_w was considered

to be zero since no groundwater was observed. Bowen ratio energy balance (BREB) and Eddy correlation (EC) systems were used to determine the actual crop water consumption through micrometeorological methods. The schematic view of these systems was given by Ünlü (2000). The Bowen ratio is defined as the ratio of sensible to latent heat (Bowen, 1926), and is expressed as

$$\beta = \frac{H}{LE} \quad (2)$$

where β is Bowen ratio, H is the sensible heat flux (J m^{-2} s^{-1}) and LE is the latent heat flux (J m^{-2} s^{-1}). The measurements taken by the Bowen system were evaluated in the following order to determine the crop water consumption. The energy balance of a crop stand, neglecting minor terms, is expressed as

$$R_n = G + LE + H \quad (3)$$

where R_n is net radiation, LE and H are latent and sensible heat respectively, and G is the heat flux in the soil. All fluxes are expressed in units of (J m^{-2} s^{-1}).

In the energy balance equation, all the terms were considered positive and negative for heading to and from the surface, respectively. Taking the energy balance equation into account, the latent heat flux was rewritten as (Held et al., 1990)

$$LE = \frac{R_n - G}{1 + \beta} \quad (4)$$

As described before, the Bowen ratio, β, is the ratio of sensible to latent heat fluxes and is calculated by the following equation (Steduto et al., 1997)

$$\beta = \frac{H}{LE} = \frac{r_a c_p k_h \frac{\Delta T}{\Delta z}}{r_a L k_w \frac{\Delta q}{\Delta z}} = \gamma \frac{\Delta T}{\Delta e} \quad (5)$$

where ρ_a is the dry air density (mol $air^{-1} m^{-3}$), c_p is the specific heat capacity of dry air at constant pressure (J mol air^{-1} $°C^{-1}$), k_h and k_w are the turbulent exchange coefficients for heat transport and water vapor transfer (m^2 s^{-1}), Δq is the difference of the water vapor concentration of two heights of the canopy (mol H_2O mol air^{-1}), L is the latent heat of vaporization (J mol H_2O^{-1}), ΔT is the differences of temperature of two heights above the canopy (°C), Δz is the differences of the measurement heights above the canopy (m), γ is the psychometric constant (kPa $°C^{-1}$), and Δe is the differences of vapor pressure of two heights above the canopy (°C kPa^{-1}). In the study, the sensible heat flux used in the determination of actual crop water consumption was measured only by the Eddy correlation. The following formula was used to calculate the sensible heat flux (Dugas et al., 1991):

$$H = -r_a c_p \overline{w'T'} \quad (6)$$

where is the instantaneous departures from the mean vertical wind speed (m/s), and $\overline{T'}$ is the instantaneous departures from the mean temperature (°C).

The latent heat flux (actual crop water consumption) was calculated by putting the H values obtained from equation 6 in the energy balance equation.

Results and Discussion

Measuring Water Consumption of Cotton

(i) Water Balance Method

Under full irrigation conditions, five irrigations were applied. At the first irrigation, 158 mm of water was applied to bring the soil moisture to field capacity. The irrigation water amount was about 62 mm for other irrigations. For the limited irrigation conditions, only one irrigation was practiced and 152 mm water was applied. The rainfall amounts of 55 and 41 mm were recorded for 1998 and 1999, respectively. D_p values for those years were 6 and 0 mm. Irrigation water amounts applied were 438 and 119 mm for the first and the second year, respectively. Figure 1 shows the results obtained by the water balance method. The water consumption was calculated as 629 mm for 1998 (frequent irrigation) and 394 mm for 1999 (limited irrigation). The cumulative ET change was similar at the beginning of the growing season in both years. Later in the season, differences were observed depending on irrigation and climatic conditions. However, the slopes of the cumulative ET curves were steep at the vegetative stage more than other stages, meaning that the water consumption rate and soil water depletion were faster. The curves were in agreement with the change in air temperature, which is a

good indicator of incoming energy. Generally, in July and August, when the average temperature is high, the slopes of water consumption curves were steep. That indicated that in those months the water consumption rate was higher. The slope of curves was smaller at the beginning of the growing season due to the lower canopy cover. It was determined that the water consumption was largest when the canopy cover was full. In the later stages, the slopes of the curves were reduced gradually after the irrigation was ceased and readily available soil water was depleted.

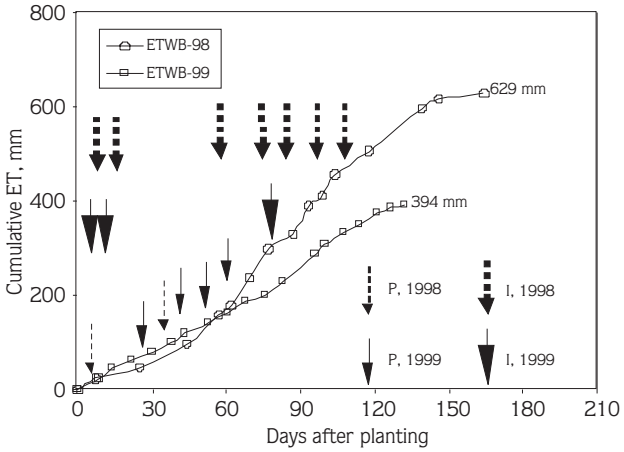

Figure 1. Seasonal actual water consumption values determined by the water balance method.

This result was observed earlier in the second year than in the first year due to the limited water application. At this stage, the matured balls were opened. Similar results were also found by Kanber (1977).

(ii) Micrometeorological Methods (Energy balance method)

In determining water consumption of cotton by the Bowen ratio energy balance (BREB), the low VPD_a and neutral atmospheric conditions resulted in a very low temperature difference (ΔT) measured at two different heights. ΔT values being mostly zero and negative (sometimes going over zero) resulted in jumps in the sensible heat flux throughout the day. To determine if the Bowen system was causing fluctuations the results were filtered by the method described by Ohmura (1982). For the filtering, a computer program developed by Şaylan (2000) was used. Results obtained indicated that only 1-20% of the data went through the filtering. It was concluded that the fluctuations in the Bowen ratio measurements resulted from the climatic conditions of the region. It was suggested that use of the Bowen system under similar conditions might result in considerable errors. Therefore, the sensible heat flux was measured by the Eddy system in the first year of the experiment, whereas in the second year it was calculated from air (T_a) and canopy (T_c) temperature difference. Then, the ET_{EB} was estimated by putting the sensible heat flux in an energy balance (EB) equation (Figure 2). As seen in Figure 2, at the earlier stages the cumulative ET curves were similar to each other in both years. At later stages, however, ET curves showed differences due to climatic and irrigation conditions. In both years, the slopes of the cumulative ET curves were steep at the vegetative stage, as seen in water balance approach. At this stage, the crop consumed more water.

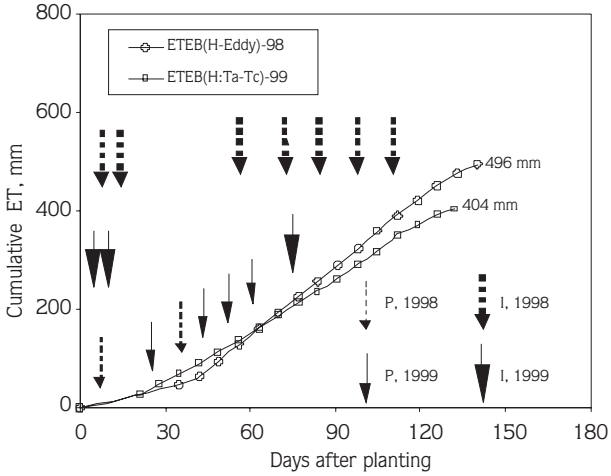

Figure 2. Seasonal water consumption values determined by the energy balance method.

Investigating Figures 1 and 2, it was concluded that the length of the growing season of the cotton under full and limited irrigation conditions was different. Under limited irrigation conditions, the crop was harvested earlier as the maturity was quicker. The differences measured between the ET values resulted from both the variations in irrigation conditions (Kanber et al., 1994) and the difference in the length of growing season (Bastug, 1987).

Comparing Energy and Water Balance Methods

The relationships between crop water consumptions obtained from both water balance (ET_{WB}) and energy balance ($ET_{EB(H=Eddy)}$ and $ET_{EB(H=0)}$, where sensible head flux was used and not used, respectively) in 1998 are

given in Figures 3a and 3b. As seen in Figure 3a, there was a 1:1 relationship between the ET_{WB} and $ET_{EB(H=0)}$ (R^2=0.99). However, the energy balance underestimated the crop water consumption by 18% at the beginning of the growing season and by 7% at the end of growing season. A similar strong relationship (R^2=0.99) was also observed between the variables given in Figure 3b. Underestimations by energy balance were 25 and 18% for the beginning and end of the growing season, respectively.

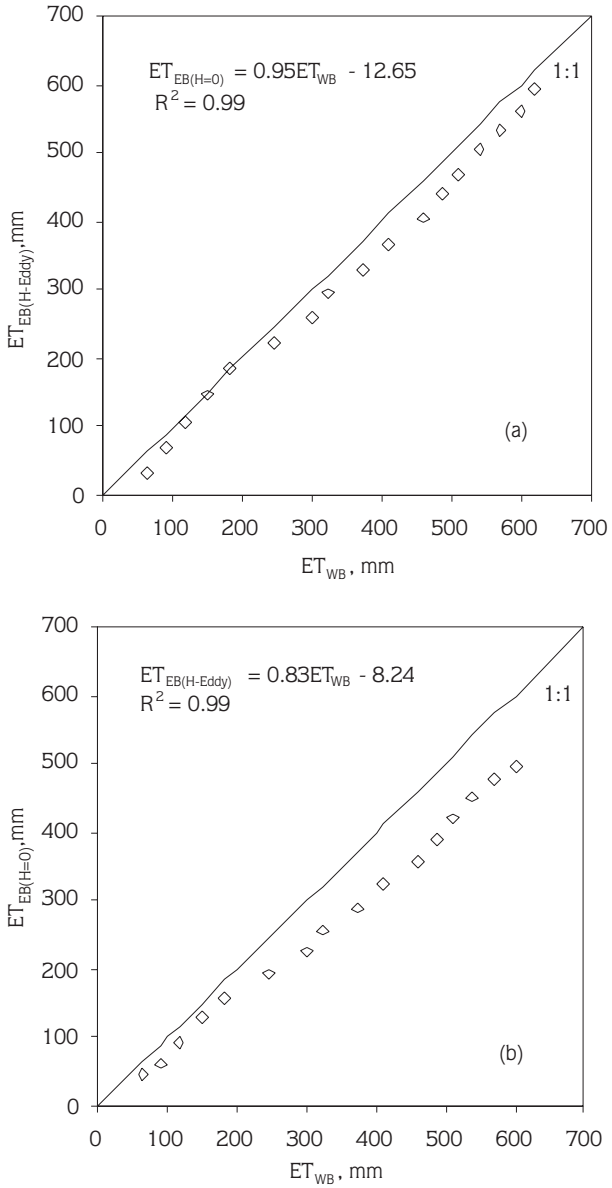

Figure 3. Relationships between ET_{WB} and ET_{EB}. ET measurements by energy balance (a) without sensible heat flux (H=0) and (b) with sensible heat flux (H-Eddy).

In the second year of the experiment, a strong linear relationship (R^2=0.99) was observed between the ETs estimated by $ET_{EB(H=Tc-Ta)}$ and ET_{WB} (Figure 4). Malek and Bingham (1993) found a similar strong relationship. The energy balance equation underestimated the crop water consumption by 18% at the early stages of the growing season. At the end of the growing stage, however, the estimates from both methods were very similar to each other. At this stage, the energy balance estimates were over the water balance estimates by 3%. Results indicated that the energy balance method produced lower ET estimates than water balance, especially under full irrigation conditions. The larger ET values calculated by the water balance method may be a result of measurements of deep percolation losses. D_p and G_w were important components in the water balance method (Beyce and Madanoglu, 1978). The approach was very simple but the measurements would be very difficult and with errors (Hillel, 1982). As a result, the ET values would be slightly higher than normal. Similarly, it was stated that the measurement of the deep percolation and the capillary rise would be crucial in estimating ET (Hartman, 1987). The main error in estimating ET from the water balance was deep percolation and the contribution of groundwater (Jensen et al., 1990).

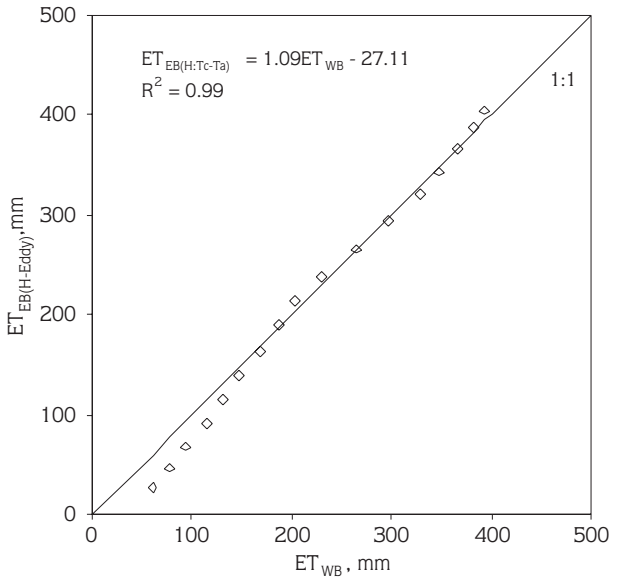

Figure 4. Relationships between ET_{WB} and $ET_{EB(H=Tc-Ta)}$. H values were calculated from the difference between air and canopy temperature.

The measurements of soil water storage could be affected by capillary movement, so the sampling time

would be an important factor (Burman and Pochop, 1994; Kanber, 1999). This could be especially important when frequent sampling was conducted. Therefore, sampling must be done 2-4 days after irrigation. The subsequent sampling should be performed 7-15 days after first sampling. From these findings, it could be concluded that in the first year of the experiment, the greater ET values obtained from water balance could be a result of deep percolation measurements and errors made in determining the soil water content, even when special care was taken. Similar ET_{WB} and ET_{EB} values obtained in the second year were due to fewer measurements. Therefore, the error became smaller (Hillel, 1982).

Conclusions and Recommendations

The water consumption determined by water balance showed variations between the years. Water consumption values obtained by the water balance method were 629 mm and 394 mm for 1998 and 1999, respectively. In the second year, water vapor flux was calculated by energy balance, ET_{EB}, and showed differences. Water consumption values obtained by the energy balance method were 496 mm and 404 mm for 1998 and 1999, respectively. The energy balance method produced lower ET estimates than water balance due possibly to the errors in the measurements of deep percolation losses. So far, the soil-water relationship was used to determine water consumption as a component in the soil-plant-atmosphere system. The use of the micrometeorological method, as a result of recent developments in technology, led to a better understanding of the plant-atmosphere relationship and to a comprehensive investigation of the soil-plant-atmosphere system. Therefore, it could be possible to obtain reliable results for crop water consumption with advances in micrometeorological methods.

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