European Water 3/4: 25-31, 2003.

Actual evapotranspiration and soil moisture studies in irrigated cotton fields

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Abstract: The present work studies the response of cotton to soil water deficits in two experimental sites in the Thessaly plain (Central Greece) during the years 1998 and 1999. Various soil water regimes are developed due to the planned non-uniform application of irrigation water by a moving gun sprinkler operating in asymmetric angle. Frequent soil moisture measurements are conducted within the plots of every experimental cotton field and are used to evaluate the soil water status and to schedule irrigation applications. In order to simulate the various soil water regimes, the FAO-56-Penman-Monteith methodology is applied under soil water stress conditions and the actual evapotranspiration of cotton is estimated. This methodology utilises the daily meteorological measurements of every experimental site, as well as soil and crop data. Comparison results of either the measured and simulated soil moisture measurements or the cumulative evapotranspiration over specific periods, show that the FAO-56 methodo-logy describes satisfactorily the response of cotton to soil water deficits.

Key words: crop water requirements, evapotranspiration, soil moisture measurements, Penman-Monteith, evapotranspiration modelling

1. INTRODUCTION

Accurate estimates of actual evapotranspiration are a prerequisite for optimal irrigation scheduling (Doorenbos and Pruitt 1977, Doorenbos and Kassam 1979) and they usually require various meteorological data, astronomical variables (Kotsopoulos and Babajimopoulos 1997) and soil and crop data.

Many areas in Greece and especially the Thessaly Plain suffer from frequent droughts during the summer months when the inadequate water resources are in tune with the high crop water needs. Under such conditions water deficits develop in the root zone which retard the crops' growth and evapotranspiration. Since crop yield is closely related to the magnitude of actual evapotranspiration it is therefore of great importance to estimate evapotranspiration under such conditions.

In the frame of the research project "Estimation of crop water requirements of some annual crops" financed by the II European Framework Programme 1994-95, two experimental cotton fields have been installed in Thessaly plain (Alexiou et al. 2000, Kotsopoulos, 1999) and, among other parameters, the actual crop evapotranspiration under deficient irrigation is estimated.

From the analysis of the experimental results based on the climatic parameters of the nearby weather stations, the crop and the soil characteristics, the irrigation depths and the soil water measurements on specific places of the experimental fields comparison results are obtained for the actual (measured and calculated) cotton evapotranspiration and the soil moisture in the root zone.

For the estimation of actual evapotranspiration (ET_a) the modified FAO-56 (Allen et al. 1998) methodology is selected for its accuracy to predict crop potential evapotaranspiration (ET_c) compared to other estimating methods (Jensen et al. 1990, Smith et al. 1996, Alexiou et al. 2000a) and the single and dual crop coefficient (Allen et al. 1998) are introduced to evaluate its magnitude. This method overcomes the shortcomings of the previous FAO-24-Penman method and provides ET_c estimates more consistent worldwide (Jensen et al. 1990, Smith et al. 1996). Additionally a linear soil water availability function of the form proposed by Gardner and Ehlig (1963) is employed (Allen et al. 1998, Doorenbos and Kassam 1979, Kotsopoulos 1989, 1995) in order to evaluate actual evapotranspiration from crop potential evapotranspiration estimates. Therefore, the actual crop water use is evaluated under real conditions and these results could be utilized efficiently for the irrigation scheduling and the optimal management of the available water resources.

2. MATERIALS AND METHODS

The study was conducted in Central Greece during the years 1998 and 1999 in the NAGREF's experimental fields in Larissa where are placed the fields of the Institute for Forage Crops (39°38' N, 22°22,5' E) and in Palamas where the Experimental Station of Palamas (39°28' N, 22°06' E). Every experimental field was divided into a number of experimental plots where different irrigation depths were applied through a moving gun sprinkler operating in asymmetric angle (Louizakis 1996). In these sites, the irrigation depths and the soil moisture in various depths of the soil profile were measured. The soil texture in the experimental fields is: sandy loam (SL) with average volumetric content 26% at FC and 11% at PWP in Larissa whereas in Palamas the soil texture is loam (L) with average volumetric content 31% and 14% at FC and PWP respectively.

Various weather data (mean, maximum and minimum air temperatures and relative humidity, wind speed, net solar radiation and rainfall) on a daily basis were obtained from the nearby automatic weather stations which belong to the Greek Ministry of Agriculture.

For the monitoring of the soil moisture, special access tubes of up to 2m in length are inserted into the ground after the crop installation. A TRIME-FM device (based on the principle of the TDR method) is utilised to take quick and frequent measurements of the volumetric soil water content at each 17.5-cm layer in the soil profile from surface to a depth of up to 175cm.

The evaluation of crop water requirements (potential evapotranspiration) is based on the reference evapotranspiration (Doorenbos and Pruitt 1977, Jensen et al. 1990, Smith et al. 1996, Allen et al. 1998) and the crop coefficient approach (Doorenbos and Pruitt 1977, Jensen et al. 1990, Allen et al. 1996, Allen et al. 1998). Additionally, and in order to estimate the actual water consumption by crops (actual evapotranspiration) the soil water content in the root zone is taken into account (Doorenbos and Kassam 1979, Allen *et al.* 1998, Kotsopoulos 1989).

For the computation of the reference evapotranspiration the revised FAO-56- Penman-Monteith equation is used (Allen et al. 1998) for the reasons mentioned above and it is formulated as follows:

$$ET_o = \frac{0.408 \cdot \Delta \cdot (R_n - G) + \gamma \cdot \dfrac{900}{T + 273} \cdot u_2 \cdot (e_s - e_a)}{\Delta + \gamma \cdot (1 + 0.34 \cdot u_2)} \tag{1}$$

where ET_o reference evapotranspiration (mm/d), R_n net radiation at the crop surface (MJ m^{-2} d^{-1}), G soil heat flux density (MJ m^{-2} d^{-1}) which for daily intervals may be ignored, thus $G \approx 0$, T mean daily temperature at 2m height (°C), u_2 wind speed at 2m height (m s^{-1}), e_s saturation vapour pressure (kPa), e_a actual vapour pressure (kPa), e_s-e_a saturation vapour pressure deficit (kPa), Δ slope saturation vapour pressure curve at temperature T (kPa °C^{-1}) and γ psychrometric constant (kPa °C^{-1}).

The estimation of crop potential evapotranspiration, ET_c, incorporates the single or the dual crop coefficients in the following equations (Allen et al. 1998):

$$ET_c = K_c \cdot ET_o \tag{2}$$

where K_c single crop coefficient which averages crop transpiration and soil evaporation

$$ET_c = (K_{cb} + K_e) \cdot ET_o \tag{3}$$

where K_{cb}+K_e the dual crop coefficient in which K_{cb} is the basal crop coefficient and K_e soil water coefficient. K_{cb} represents the ratio ET_c/ET_o when the soil surface layer is dry but the soil water content in the root zone is adequate to sustain full plant transpiration. The introduction of the dual crop coefficient is in agreement with earlier works, e.g. Ritchie 1972, which separate evapotranspiration into evaporation and transpiration components.

The actual evapotranspiration (under soil water stress conditions), ET_a, when the single crop coefficient, K_c, is used is estimated from the equation (Allen et al. 1998) :

$$ET_a = K_s \cdot K_c \cdot ET_o \quad \text{or} \quad ET_a = K_s \cdot ET_c \tag{4}$$

where K_s water stress coefficient or soil water availability function (Allen et al. 1998, Tsakiris 1978) and its magnitude is related to the available soil water in the root zone, the crop spices and the prevailing weather conditions (Doorenbos and Kassam 1979, Allen et al. 1998, Kotsopoulos 1989).

In case that the dual crop coefficient is used ET_a is estimated as (Allen et al. 1998):

$$ET_a = (K_s \cdot K_{cb} + K_e) \cdot ET_o \tag{5}$$

In order to describe any change of ET_a over time, t, eq. (4) takes into account the available soil moisture in the root zone, x, and is modified as follows (Tsakiris 1978, Kotsopoulos 1989, 1995):

$$ET_a(x,t) = K_s(x) \cdot ET_c(t) \tag{6}$$

$K_s(x)$ may be linear of the following form:

$$K_s(x) = 1 \quad \text{when} \quad x_p < x \le ASW \quad \text{and} \tag{7}$$

$$K_s(x) = \frac{x}{x_p} \quad \text{when} \quad 0 < x \le x_p \tag{8}$$

where $x_p=(1\text{-}p)\cdot ASW$, ASW available soil water in the root zone (mm) and p parameter expressing the average fraction of total available water that can be depleted from the root zone before moisture stress occurs (Doorenbos and Kassam 1979, Allen et al. 1998). The parameter p depends on the crop species and the prevailing weather conditions which formulate the magnitude of the crop potential evapotranspiration, ET_c (mm/d) and for daily intervals is estimated by (Allen et al. 1998):

$$p_d = p + 0.04 \cdot (5 - ET_c) \tag{9}$$

where p_d the modified value of p. The values of p for the various crops are taken from tables (Doorenbos and Kassam 1979, Allen et al. 1998). For cotton it equals 0.65 (Allen et al. 1998). ET_c is the crop potential evapotranspiration at that day (mm/d).

From eq. (4)-(8), the final soil moisture in the root zone, x (mm), is calculated after time t if the initial soil moisture, x_1 (mm), and the cumulative evapotraspiration over the same period, ΣET_c (mm), are known. Then the following equations are derived (Kotsopoulos 1989, 1995):

$$x = x_1 - \Sigma ET_c \quad \text{when} \quad x_p < x < x_1 \le ASW \tag{10}$$

$$x = x_1 \cdot e^{-\frac{\Sigma ET_c}{x_p}} \quad \text{z when} \quad 0 < x < x_1 \le x_p \tag{11}$$

$$x = x_p \cdot e^{-\frac{(\Sigma ET_c - x_1 + x_p)}{x_p}} \quad \text{when } x_p < x_1 \le ASW \text{ and } x_1 - \Sigma ET_c < x_p \tag{12}$$

In case that the dual crop coefficient method is used then eq. (10), (11) and (12) are modified in order to incorporate the actual evaporation from the soil surface and the transpiration from the remaining root zone depth.

Apart from the data mentioned above, for the calculation of actual evapotranspiration are required: a) the values of the crop coefficients during the various growth stages which are taken from FAO-56 (Allen et al., 1998), b) the duration of the growth stages. It is evaluated from leaf area index (LAI) measurements through a Sun Scan Analysis System in order to incorporate into calculations the local conditions (Alexiou et al. 2000), while c) the root depths are considered constant at stage {1} and at stages {3}&{4} and to increase linearly during stage {2} (Allen et al., 1998).

3. RESULTS AND DISCUSSION

Measurements refer to the periods from April to September during the years 1998 and 1999 and the calculations are performed on a daily basis. Soil moisture was measured into various depths (up to 1.75m) very frequently even on a daily basis depending on the soil water status and the prevailing weather conditions.

From the eq. (1)-(12) and the soil water balance equation in the root zone the daily evapotranspiration (potential and actual) values are estimated as well as the soil water content in the soil profile throughout the growing period. The calculations are based on the single, K_c, and the dual, K_e+K_{cb}, crop coefficient methods. Representative results are given in Figure 1 and refer to the measured and calculated with the single and dual crop coefficient soil water depths in the soil profile (0.0-1.2m) from the experimental site in Larissa during the growing period April to September 1999. This figure reveals that the calculated values with both methods fit very well the measured ones.

Additionally, the adequacy of the aforementioned methodology is based on comparative measures between measured (observed) and calculated (predicted) soil moisture values. In the present study the selected measures are (Babajimopoulos et al. 2000, Loague and Green 1991, Antonopoulos 2001) the mean error (*E*), the root mean square error (*RMSE*), the maximum absolute relative error *(MARE),* the coefficient of residual mass (*CRM*) and the coefficient of determination (R^2):

$$E = \sum_{i=1}^{n} (O_i - P_i) / n \tag{13}$$

$$RMSE = \left(\sum_{i=1}^{n} (O_i - P_i)^2 / n \right)^{1/2} \cdot \frac{100}{\overline{O}} \tag{14}$$

$$MARE = \frac{|O_i - P_i|}{O_i} \cdot 100 \tag{15}$$

$$CRM = \left(\sum_{i=1}^{n} O_i - \sum_{i=1}^{n} P_i \right) \Big/ \sum_{i=1}^{n} O_i \tag{16}$$

where O_i and P_i are the measured (observed) and calculated (predicted) values respectively.

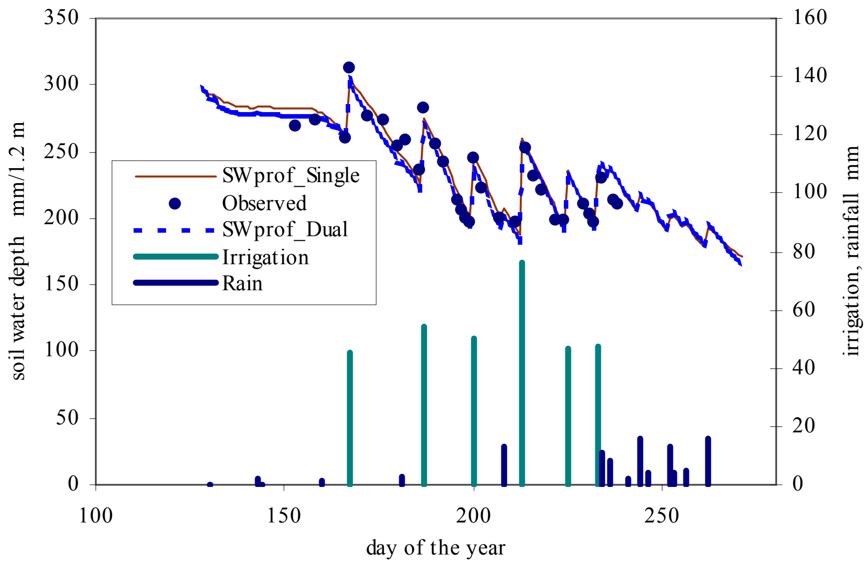

Figure 1. Measured and calculated soil moisture depths using the single and dual crop coefficient method in Larissa during 1999

The statistical indices for a number of applications for the aforementioned methodology shown on Table 1 prove that both methods are very effective and estimate soil water depths equally good. It is further confirmed in Table 2 where the cumulative evapotranspiration values during specific periods are evaluated that their percent differences between the measured and the calculated with the single and dual crop coefficient method are minimal.

Table 1. Indices used for the comparison of measured and calculated soil moisture depths in the soil profile for cotton during 1998 and 1999 in Central Greece

Year	Crop Coeffic.	E (mm)	RMSE (%)	MARE (%)	CRM	Slope *a* $SW_{meas}=a \cdot SW_{calc}$	R^2
Larissa							
1998	Single	-2.02	4.15	8.28	-0.0087	1.0106	0.9546
1998	Dual	2.05	3.76	6.98	0.0089	0.9897	0.9580
1999	Single	-3.49	3.67	8.65	-0.0151	1.0143	0.9296
1999	Dual	1.77	3.86	8.57	0.0077	0.9918	0.9120
Palamas							
1998	Single	-0.035	3.55	8.09	-0.0014	1.0025	0.9447
1998	Dual	-2.96	3.36	6.81	-0.0118	1.0119	0.9548
1999	Single	-4.18	4.24	9.62	-0.0155	1.0110	0.9188
1999	Dual	-2.19	3.51	7.50	-0.0081	1.0042	0.9424

Table 2. Comparison of measured (ΣETa_m) and calculated (ΣETa_c) cumulative values of actual evapotranspiration for cotton during specific periods in C. Greece

Period	Cumulative evapotranspiration values mm				Difference %		
	ΣET_c	$\Sigma ET_{a\ m}$	$\Sigma ET_{a\ c\ S}$	$\Sigma ET_{a\ c\ D}$			
	(1)	(2)	(3)*	(4)*	(2)&(3)	(2)&(4)	(3)&(4)
Larissa							
26-5/27-8-98	502.0	403.4	410.7	412.1	-1.81	-2.22	-0.34
stage {3}- 98	269.8	-	186.4	175.7	-	-	5.74
2-6/26-8-99	435.9	415.6	415.2	409.5	0.10	1.47	1.34
stage {3}-99	325.2	-	317.7	306.8	-	-	3.43
Palamas							
10-6/27-8-98	400.5	292.4	297.2	296.4	-1.64	-1.37	0.27
stage {3}-98	219.7	-	157.5	155.5	-	-	1.27
10-6/27-8-99	328.4	303.7	286.1	285.8	5.80	5.89	0.10
stage {3}-99	233.7	-	205.0	203.8	-	-	0.58

* S and D in columns (3) and (4) stand for the single and the dual crop coefficient method respectively

4. CONCLUSIONS

The FAO-56 Penman-Monteith methodology under non-standard conditions using the single and the dual crop coefficients is estimating efficiently the actual crop evapotranspiration and the soil moisture depths in the irrigated fields under the Greek conditions.

Estimates of actual evapotranspiration using the two methods give very similar results when irrigations are applied over the entire field and therefore the single crop coefficient one should be preferred under such conditions.

Both methods are expected to give reliable results concerning actual crop water needs and should be preferred for irrigation scheduling and crop water management when the required data for their application are available.

Further investigation is required for the cases where the soil is partly irrigated especially during the growth stages {1} and {2} when soil evaporation is significant.

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