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# Evapotranspiration and simulation of soil water movement in small area vegetation

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A b s t r a c t. In Greece, crops are frequently cultivated in small isolated areas in close proximity to roads and bare soils and therefore evapotranspiration is affected by local advection. Under these circumstances, oasis effect conditions are present and evapotranspiration is higher than what is expected. In this paper, the evapotranspiration and soil water dynamics of a cotton crop cultivated in small areas under the oasis effect is studied. To this end, two isolated free-drainage lysimeters cultivated with cotton in the year 2007 were used. Soil moisture of the soil profile of both the lysimeters was monitored with two capacitance water content probes. The soil water balance method was used to estimate crop evapotranspiration and corresponding crop coefficients in one of the two lysimeters. These coefficients were 75% larger than the FAO-56 crop coefficients at the mid-season stage. The FAO-56 and the derived crop coefficients were used for the simulation of the water dynamics in the second lysimeter by the SWBACROS model. The derived crop coefficients for these conditions produced much better results than the FAO-56 crop coefficients. The results were improved when crop coefficient value equal to 2.5 was used for the mid-season stage.

K e y w o r d s: modelling soil water flow, evapotranspiration, oasis-effect, crop coefficients

## INTRODUCTION

Crop evapotranspiration ($ET_c$) can be calculated under standard or non-standard conditions and various management practices. Standard conditions refer to crops grown in large fields under non-limiting agronomic and soil conditions. Non-standard conditions and various management practices refer to management and environmental conditions that deviate from standard conditions such as salt toxicity, pests, diseases, surface mulches, small areas vegetation *etc*. (Allen *et al*., 1998).

Frequently, fields in Greece are very small (<1 000 $m^2$) representing typical non-standard conditions. Under these circumstances, the crops are growing under conditions of the oasis effect resulting in very high evapotranspiration values. Increased evapotranspiration is also observed at the upwind series of crops resulting in lower yields since these series obtain the same amount of water as the interior series. Therefore, the overall yield is reduced because of the non-satisfactory yield of the upwind series.

The climatic definition of the 'oasis effect' or 'cold island effect' refers to the phenomenon of a cooling effect caused by vegetation (Givoni, 1991; Potchter *et al*., 2008). According to Oke (1987) this cooling effect is due to the fact that the energy required for evaporation ($Q_E$) is more than that supplied by radiation (Q*). It has been observed that the ratio $Q_E$/Q* can be as large as 2.5 over an irrigated field of cotton (Lemon *et al*., 1957). Kai *et al*. (1997) also explained the cooling effect by the difference of the energy balance between oasis and the surrounding area. The oasis effect phenomenon is observed in different climates and urban or rural conditions (Oke, 1987; Potchter *et al*., 2008; Spronken-Smith *et al*., 2000). Therefore, the use of the term 'oasis effect' has a wider definition than the classical term (Potchter *et al*., 2008).

According to Oke (1987) any cool moist surface dominated by larger scale warmer, drier surroundings has the characteristics of an oasis effect situation: a lake in an area with a dry summer climate; an urban park; an isolated tree in a street or on open bare ground etc. A common characteristic of all these cases is that evaporation rates are higher than those from extensive areas of the same composition.

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Exchange of energy and matter, especially heat and water, is dominant in the interaction between oasis and desert (Zhang and Huang, 2004). The soil water content and the atmospheric humidity over the oasis are influenced and modified, resulting in larger values of evapotranspiration than the net radiation (Oke, 1981). Oke (1979) observed that the actual evapotranspiration of an irrigated suburban lawn (approximately 160 $m^2$) markedly exceeds the potential value set by Priestley and Taylor (1972).

Spornken-Smith *et al*. (2000) observed that evaporation from an urban park was 130% higher than that from a rural grass site. Eigenmann *et al*. (2011) also observed high values of evapotranspiration in a number of maize fields in Germany caused by the oasis effect.

In this paper, the evapotranspiration and the soil water dynamics of a cotton crop cultivated in two free-drainage lysimeters under conditions of the oasis effect were studied. Lysimeters provide a direct measurement of evapotranspiration (*ET*) and they are frequently used to study climatic effects on *ET* and to evaluate *ET* estimating procedures.

Irrigation scheduling requires estimation of the frequency of watering and the time variation of the available to the plants soil water. The quality of the water that returns to water receivers, the accumulation of salts to the root zone, the evaporation and the root water uptake, and the contamination of the surface and ground water depend on the redistribution of the water in the unsaturated zone. Therefore, an integrated methodology for the study of the soil water movement in the unsaturated zone is required for more efficient water management in this zone. Toward this task many mathematical models for the simulation of the water dynamics in the unsaturated zone of cultivated soils have been developed and can be found in the international literature.

The objectives of this paper were:

– estimation of the evapotranspiration of a cotton crop cultivated in two free-drainage lysimeters under conditions of the oasis effect;
– estimation of the crop coefficients under conditions of the oasis effect and their comparison there of with the FAO-56 coefficients under standard conditions (Allen *et al*., 1998);
– simulation of the water movement in a lysimeter field cultivated with cotton with the mathematical model SWBACROS (Babajimopoulos *et al*., 1995) throughout the cultivating period. In this simulation, the crop coefficients estimated in this paper and the FAO-56 coefficients were used. Additionally, a very high value of 2.5 for the mid-season stage was used.

## MATERIALS AND METHODS

Experimental data were obtained in two pre-existing free-drainage lysimeters located in a small field of the Institute of Land Reclamation (Lat. 40.63°, 6 m a.s.l.) in Thessaloniki, Greece, during the cultivation period of 2007 under conditions of the oasis effect. The oasis effect is ensured by the fact that this small field (surface area of 90 $m^2$) is isolated from any other crops. Currently, a dirt road and an area of bare soil extend around the field. Additionally the building of the Land Reclamation Institute and a small group of trees were at a distance of 50 m from the lysimeters. The two lysimeters have a surface area of 4 $m^2$ and 20 cm thick concrete walls. The lysimeters were filled with disturbed soil to a depth of 90 cm. Below that depth, there was a layer of about 30 cm consisting of coarse material (sand and gravels) for collection of percolating water.

This field was planted with cotton and all the cultivating practices common in the plain of Thessaloniki were implemented throughout the cultivation period. Sowing of cotton took place on the 11th of May 2007 (day of the year – DOY 131). Three rows of plants were planted in each lysimeter, one in the middle and two rows at a distance of 70 cm on each side of the central row. The estimated plant density was 1950 plants per 100 $m^2$. The soil was fertilized on the 18th of May with a composite fertilizer 21-8-11 N-P-K+0.5 Zn. The plants were harvested on the 25th September 2007 (DOY 268). It was observed that the four plant growth stages had the following durations: initial stage – 21 days, crop development stage – 45 days, mid-season stage – 49 days, and late season stage – 23 days.

Climatic data were obtained from an automatic weather station (AWS) that was located on a small grass field close to the lysimeters in hourly intervals. Sensors measuring air temperature (T), relative humidity (RH), solar radiation ($R_s$), wind speed ($u_2$), and rainfall (R) were included in the station. All sensors were placed 2 m above the soil surface.

Daily meteorological data were used to calculate the reference evapotranspiration ($ET_o$) according to the FAO-56 Penman-Monteith equation (Allen *et al*., 1998). Even though total precipitation was high enough to cover a large part of the plant water needs, the rain was unevenly distributed throughout the cultivation period and only a very small part of the plant needs was fulfilled. In particular, precipitation of 205.6 mm was observed during the months of May and June. About 152 mm out of the 205.6 mm dropped in few hours on three consecutive days with very severe intensity. Due to this high intensity, most of the water ran off the lysimeters because of the small height of the surrounding walls. The rest of precipitation was observed in August (66.2 mm) and September (24.0 mm).

The effective rainfall at daily time steps was calculated using the Curve Number (CN) method. The Curve Number is a dimensionless parameter indicating the runoff response characteristics of an area and related to land use, land treatment, hydrological condition, hydrological soil group, and antecedent soil moisture (AMC) (Bos *et al*., 2009). In this paper, the estimation of the CN value was made according to the land use (irrigated area consisting of row crops), hydrological conditions (poor), hydrological soil group B (the soils are moderately well to well drained) and taking into account the 5 day antecedent rainfall and irrigation. The total effective rainfall during the irrigation period was 200.82 mm. The daily values of effective rainfall were confirmed by the measurements of the water content of the whole soil profile before and after each rainfall.

The water needs of the crop were covered by drip irrigation. The dripper flow rate was $2\,l\,h^{-1}$ and two drip lines were installed on either side of each plant row so that the water was uniformly distributed on the soil surface. The distance between the drip line and crop row was 20 cm and the emitters were spaced at 30 cm intervals along the drip line. Irrigation scheduling was based on the depletion of the available water in the root zone. The date, duration, and amount of applied irrigation water in lysimeters 1 and 2 are given in Table 1. Eight irrigations at six to seventeen days intervals were applied during the growing season. The total irrigation depth during this period was 496.7 mm.

A PVC tube was installed at the centre of each lysimeter to be used for the soil moisture measurement with the Sentek Diviner 2000 and EnviroScan sensors (Sentek, 2007). In particular the Diviner 2000 probe was used in lysimeter 1 and the EnviroScan probe was used in lysimeter 2. These probes use Frequency-Domain Reflectometry (FDR) technology and have an operating frequency of 100 MHz. Both probes take measurements every 10 cm depth with a radius of influence of 5 cm. The extra feature of EnviroScan, compared to the Diviner 2000, is that it can measure and log the soil water content at regular time intervals defined by the user. In the present experiment, an hourly interval was chosen. The sensors were calibrated by measuring soil moisture gravimetrically (Paraskevas *et al*., 2012).

**T a b l e 1.** Date, duration and amount of applied irrigation water in lysimeters 1 and 2

| Date (Day/Month/Year) | Duration (h) | Applied irrigation water (mm) |
|---|---|---|
| 25/6/2007 | 2.75 | 63.5 |
| 12/7/2007 | 2.00 | 46.2 |
| 19/7/2007 | 2.75 | 63.5 |
| 25/7/2007 | 3.00 | 69.3 |
| 2/8/2007 | 3.00 | 69.3 |
| 16/8/2007 | 3.00 | 69.3 |
| 23/8/2007 | 3.00 | 69.3 |
| 5/9/2007 | 2.00 | 46.2 |
| Total irrigation water | | 496.7 |

The mechanical composition and the values of the parameters describing the hydraulic properties of each soil layer of lysimeter 1 are given in Table 2. The soil water retention curve was estimated by the pressure plate method. The values of $\theta_r$, $\alpha$ and $n$ of the Van Genuchten (1980) model were determined by nonlinear regression of the soil water retention data (Table 2). The $h$ – critical values of the $S$ function (Belmans *et al*., 1983) are also shown in Table 2. The soil water retention curves for the 0-30, 30-60 and 60-90 depths are shown in Fig. 1.

The root depth was measured by isolating the root zone of a few plants and cleaning them. The Leaf Area Index (LAI) was measured with a Delta-T Devices SunScan Canopy Analysis System. LAI and rooting depth during the cultivation period are presented in Fig. 2. The maximum rooting depth was observed at 43 cm and the maximum value of LAI was 4.

The mathematical model SWBACROS is based on the one-dimensional Richards equation, which describes the water flow in a heterogeneous unsaturated soil with the presence of a crop (Babajimopoulos, 2000; Babajimopoulos *et al*., 1995):

$$C(\theta)\frac{\partial h}{\partial t} = \frac{\partial}{\partial z}\left[K(\theta)\left(\frac{\partial h}{\partial z} - 1\right)\right] - S(h), \qquad (1)$$

where: $C(\theta)(=\partial\theta/\partial h)$ is the specific moisture capacity function (1/L), $h$ is the pressure head (L), $K(\theta)$ is the unsaturated hydraulic conductivity (L/T), $\theta$ is the volumetric soil water content ($L^3/L^3$), $z$ is the vertical dimension directed positive downwards (L), $t$ is the time (T) and $S(h)$ is the root water uptake (1/T).

In the SWBACROS model, Eq. (1) is solved by the Douglas-Jones predictor-corrector method (Babajimo-

**T a b l e 2.** Mechanical composition and hydraulic parameters of the lysimeter 1

| Depth (cm) | Sand | Silt | Clay | $\rho_b$ (g cm$^{-3}$) | USDA texture | Van Genuchten retention parameters $\theta_s$ | $\theta_r$* | $\alpha$* | n* | $h_1$ | $h_2$ | $h_3$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | (%) | | | | (cm$^3$ cm$^{-3}$) | | (m$^{-1}$) | | | (m) | |
| 0-30 | 31.2 | 40.8 | 28 | 1.043 | CL | 0.570 | 0 | 28.1110 | 1.2033 | -0.028 | -21.417 | -150 |
| 30-60 | 35.6 | 38.4 | 26 | 1.220 | L | 0.508 | 0 | 7.5918 | 1.2225 | -0.052 | -20.809 | -150 |
| 60-90 | 43.2 | 32.4 | 24.4 | 1.228 | L | 0.517 | 0 | 12.3349 | 1.2084 | -0.037 | -21.276 | -150 |

*fitted parameters, $\rho_b$ – bulk density, $\theta_s$ – saturated soil water content, $\theta_r$ – residual soil water content, $\alpha$ and n Van Genuchten constants; h1, h2, h3 are h-critical values of the sink term S function (Belmans *et al*., 1983).

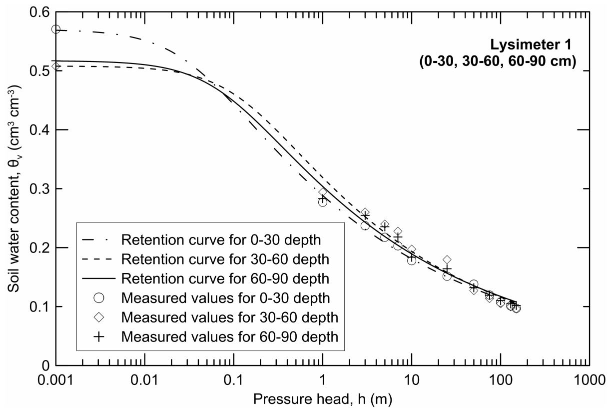


**Fig. 1.** Soil water retention curves of 0-30, 30-60, 60-90 depths.

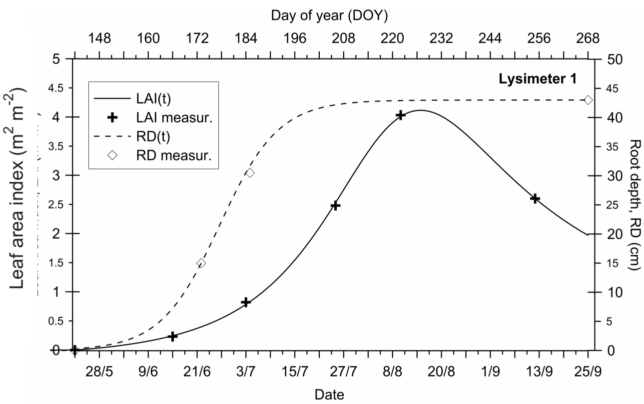


**Fig. 2.** Leaf area index (LAI) and rooting depth functions with time.

poulos, 2000). The unsaturated hydraulic conductivity and the specific moisture capacity functions are computed as in Van Genuchten (1978, 1980). The sink term $S(h)$ is computed as in Belmans *et al.* (1983) by:

$$S(h) = \alpha(h)\, S_{\max}, \tag{2}$$

where: $\alpha(h)$ is a dimensionless function of the pressure head and $S_{\max}$ is the maximum water extraction by roots defined as in Feddes *et al.* (1978).

Actual transpiration ($T_a$) is computed by integration of Eq. (2) over the root zone depth. The reference evapotranspiration rate, $ET_o$ is computed by the FAO-56 Penman-Monteith method (Allen *et al.*, 1998). Potential evapotranspiration of the crop $ET_P$, is computed by:

$$ET_P = K_c\, ET_o, \tag{3}$$

where: $K_c$ is the crop coefficient.

Potential evapotranspiration ($ET_P$) is split into two components: potential evaporation ($E_p$) and potential transpiration ($T_p$). The potential evaporation rate ($E_p$) is computed by:

$$E_P = ET_P \exp(-\alpha\, LAI), \tag{4}$$

where: $\alpha$ is an extinction coefficient of radiation (Belmans *et al.*, 1983; Feddes *et al.*, 1978) and LAI is the leaf area index. The value of $\alpha$ obtained was 0.623 as in Al-Khafaf *et al.* (1978).

Potential evaporation for the period between seeding and plant emergence (bare soil) was estimated by the Penman-Monteith equation (Allen *et al.*, 1994) with zero surface resistance.

A maximum possible flux through the canopy is used at the top of the system (Belmans *et al.*, 1983). Towards this computation, if irrigation/precipitation is less than 10 mm day$^{-1}$, actual evaporation from soil surface ($E_a$) is computed by a modified Al-Khafaf *et al.* (1978) equation:

$$E_a = E_p t^{0.6} - E_p (t-1)^{0.6}, \tag{5}$$

where: $t$ is the time in days after the dry period starts.

A detailed description of the model is given by Babajimopoulos *et al.* (1995). The model has been validated several times in the past against data from literature (Babajimopoulos, 2000) and field data (Babajimopoulos *et al.*, 1995). It has been shown that it describes water flow in the vadose zone very realistically.

The soil water balance method was used to assess crop evapotranspiration ($ET_c$) in lysimeter 2. To this end, all the components of the water balance equation were measured for the whole soil profile. The crop evapotranspiration $ET_c$ was computed by:

$$ET_c = P - R_o + I - DP - \Delta\theta = R + \mathrm{I} - DP - \Delta\theta, \tag{6}$$

where: $R = (P\text{-}R_o)$ is the effective rainfall, $P$ is the rainfall, $R_o$ is the runoff from soil surface, $I$ is the irrigation, $DP$ is the deep-percolation, $\Delta\theta$ is the change in soil profile water storage. All variables are expressed in units of equivalent mm of water and they are determined for each period between two consecutive soil water measurement days.

## RESULTS AND DISCUSSION

The water balance components for the total cultivation period are shown in Table 3. It is pointed out that deep percolation was never observed (DP = 0) (except after the heavy rains of June 2007 when negligible percolation of 0.4 mm was observed). The change in soil profile water storage between the 26th of September and 11th of May was negative by 72.94 mm. The negative value in water storage implies that the crop used part of the water stored in the lysimeter, which implies that effective rainfall and irrigation were not sufficient to satisfy the water needs of the crop. The total amount of the water used by the crop in lysimeter 2 is 770.46 mm. It is also mentioned that the water used by the crop in lysimeter 1 is 736.55 mm.

**T a b l e 3.** Crop evapotranspiration with the soil water balance method in lysimeter 2

| $\Delta\theta = \sum\theta_{(0-90)(26/9)} - \sum\theta_{(0-90)(16/5)}$ (mm) | Input (mm) | | | $ET_c = R+I-\Delta\theta$ (mm) |
|---|---|---|---|---|
| | Effective rainfall $R=P-R_o$ | Irrigation I | Total input $(R+I)$ | |
| -72.94 | 200.82 | 496.7 | 697.52 | 770.46 |

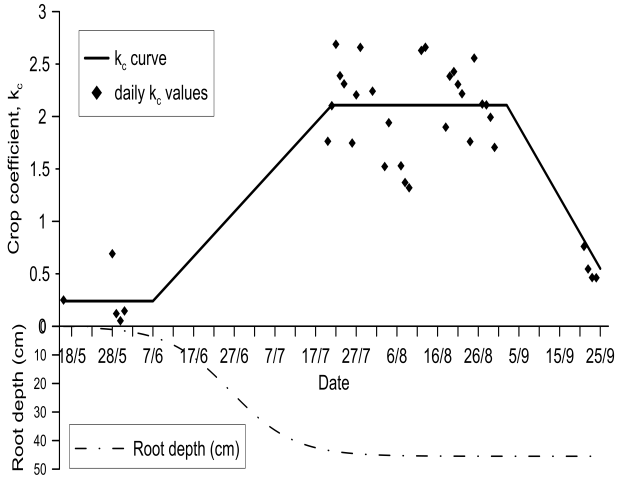


**Fig. 3.** Estimation of the crop coefficients at lysimeter 2 by the water balance method.

The water balance method was used for the estimation of the local crop coefficients in lysimeter 2 where hourly water content measurements were available. Since deep percolation was never observed (DP=0), daily local crop coefficients were estimated by the equation:

$$K_{c\,loc(t)} = \frac{R_{(t)} + I_{(t)} - \Delta\theta_{(t)}}{ET_{o(t)}}, \tag{7}$$

where: $K_{c\ loc\ (t)}$ is the locally developed crop coefficient at day $t$, $R_{(t)}$ and $I_{(t)}$ is the effective rainfall and irrigation respectively at day $t$, $\Delta\theta_{(t)}$ is the change in water storage in the whole profile (mm) at day $t$ and $ET_{o(t)}$ is the reference evapotranspiration (mm day$^{-1}$) at day $t$ computed by the FAO-56 Penman-Monteith equation.

The crop coefficient curve was constructed using the water balance method in a way similar to that described by FAO-56. The crop coefficients of the initial stage, $K_{c\ ini\ loc}$, and of the mid-season stage, $K_{c\ mid\ loc}$, were estimated as averages of the crop coefficients obtained during these periods. The minimum value of the crop coefficient of the late season, $K_{c\ end\ loc}$, was estimated as an average value of the last four crop coefficients of the late season stage. According to this procedure the values of $K_{c\ ini\ loc}$, $K_{c\ mid\ loc}$ and $K_{c\ end\ loc}$ were 0.25, 2.10 and 0.55 respectively. The $K_{c\ loc}$ curve was completed by connecting with line segments each of the four growing stages. Horizontal lines are drawn through $K_{c\ ini\ loc}$ in the initial stage and through $K_{c\ mid\ loc}$ in the mid-season stage. Diagonal lines are drawn from $K_{c\ ini\ loc}$ to $K_{c\ mid\ loc}$ within the period of the crop development stage and from $K_{c\ mid\ loc}$ to $K_{c\ end\ loc}$ within the period of the late season stage. The derived values of $K_{c\ loc}$ are presented in Fig. 3. In this figure values of $K_{c\ loc}$ at the days of irrigation or precipitation and at the days when the soil moisture content was close to the permanent wilting point ($\theta_{PWP}$) were excluded.

**T a b l e 4.** FAO-56 and locally developed crop coefficients

| Crop stage | FAO-56 $K_c$ | Locally developed $K_{c\ loc}$ |
|---|---|---|
| Initial $K_{(c\ ini)}$ | 0.35 | 0.25 |
| Mid-season $K_{c\ (mid)}$ | 1.20 | 2.10 |
| Late season $K_{c\ (end)}$ | 0.60 | 0.55 |

Table 4 shows the locally developed crop coefficients at lysimeter 2 along with crop coefficients of FAO-56. While the values of the local coefficients are smaller than the values of FAO-56 at the initial and late season stages, they are much higher at the mid-season stage. Even though the value of 2.10 at the mid-season looks unrealistic, it is within the limits set by Allen *et al*. (1998) under conditions of the oasis effect. Actually, Allen *et al.* (1998) states that under conditions of oasis effect: '…the peak $K_c$ values may exceed the 1.20-1.40 limit. The user should exercise caution when extrapolating *ET* measurements taken from these sorts of vegetation stands or plots to larger stands or regions as an overestimation of regional *ET* may occur. An upper limit of

2.5 is usually placed on $K_c$ to represent an upper limit on the stomatal capacity of the vegetation to supply water vapour to the air stream under the clothesline or oasis conditions'.

The locally developed crop coefficients derived by the water balance method in lysimeter 2 were used for simulation of the water movement in lysimeter 1 during the cultivation period of the year 2007 by the SWBACROS model. The simulation period started on 16 May, 2007 and ended on 25 September 2007. The top 80 cm of the lysimeter depth were divided into 16 compartments of 5 cm. The soil profile was also divided into three layers depending on the mechanical composition of each layer.

The saturated hydraulic conductivity ($K_s$) was obtained by calibration using the Rosenbrock method (Kuester and Mize, 1973) of the SWBACROS model with data from the beginning of the simulation until the emergence of the crop (May 24, 2007). During this period, evaporation was the only consumer of soil water. Soil water measurements at four days (17/5, 18/5, 22/5 and 24/5) were used for the calibration process.

A known flux was used as an upper boundary condition while the bottom boundary condition was considered as free drainage. This is compatible with the moisture content measurements throughout the whole period which showed that there was never significant flow below the depth of 90 cm. It is pointed out that deep percolation was never observed. Inflow to the lysimeter included irrigation and effective rainfall, while the main outflow component was due to cotton evapotranspiration.

Figure 4 shows two simulation results obtained with the SWBACROS model along with moisture content measurements. In the first simulation, the locally developed crop coefficients obtained from lysimeter 2 were used, while the FAO-56 crop coefficients were used in the second simulation. Irrigation and precipitation are also shown in this figure. The moisture content at the top layer follows the inflow to the lysimeter by irrigation and precipitation in a consistent way. The response to the deeper layers is much slower, especially to the deepest layer where the moisture content is almost constant with a small declining trend throughout the whole simulation period. The moisture content in the second layer starts diminishing at the beginning of July when the root depth exceeds the depth of 30 cm.

As shown in Fig. 4, the results obtained using the locally obtained crop coefficients are much closer to the measurements than the results obtained with the FAO-56 crop coefficients. This is more evident in the middle and bottom layers. The importance of the effect of the crop coefficients is apparent from the results of the first layer where most of the rooting system is developing. During the first stage and up to the middle of the developing stage the results of both simulations are similar. From that point on, the results start declining due to the difference of the size of the locally obtained $K_c$ and the crop coefficient of FAO-56. The measurements of the moisture content in Fig. 4 show that in a number of days, during the mid-season stage the moisture content of the soil profile is close to the permanent wilting point ($\theta_{PWP}$).

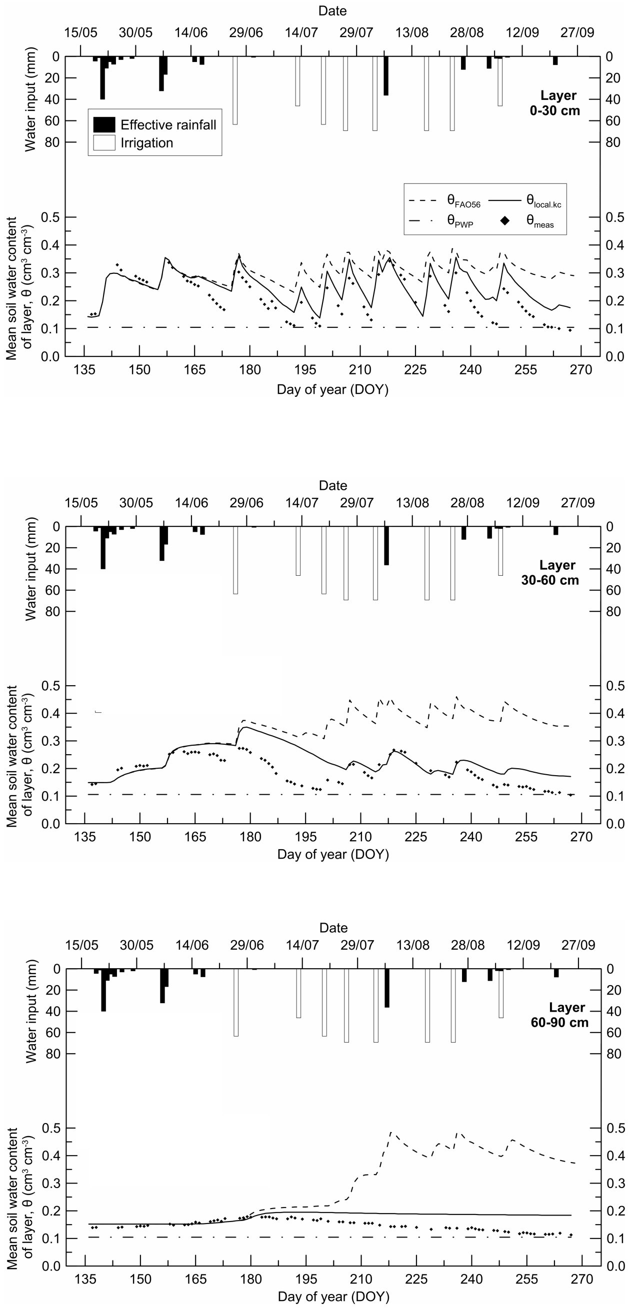


**Fig. 4.** Comparison of simulation with the SWBACROS model soil water content using locally obtained ($\theta_{local.kc}$) and FAO-56 crop coefficients ($\theta_{FAO56}$) and the measured water content ($\theta_{meas}$) for the three layers of lysimeter 1.

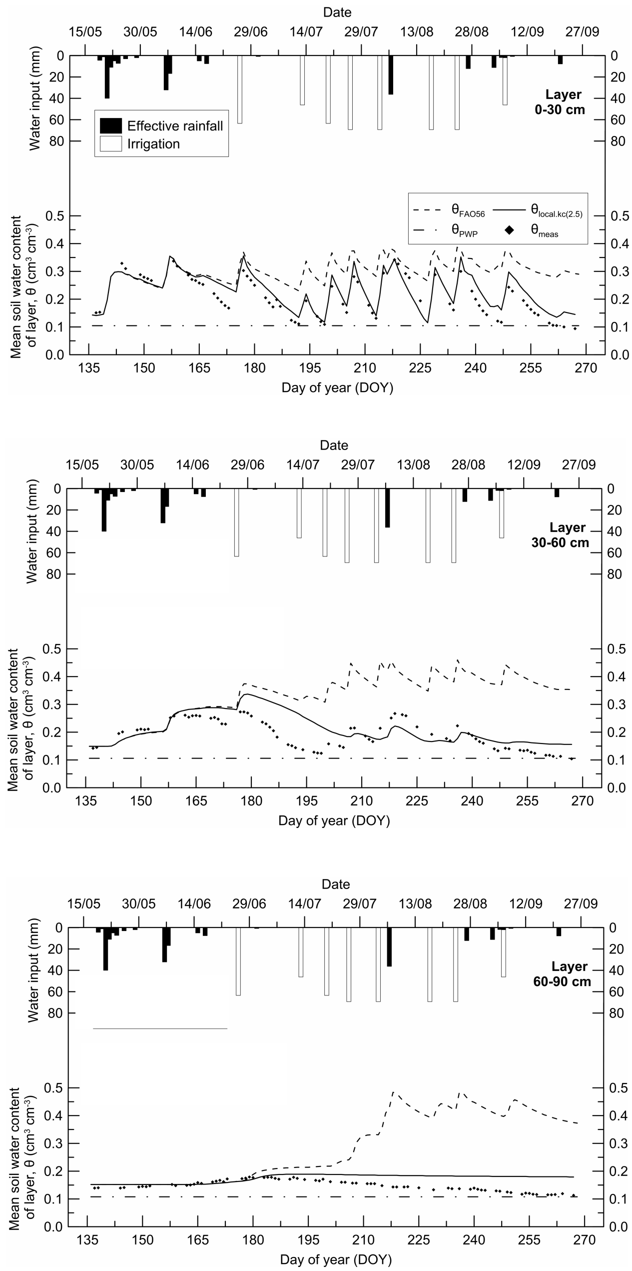


**Fig. 5.** Comparison of simulation with the SWBACROS model soil water content using locally obtained ($K_{c\ mid\ loc}$ = 2.5) ($\theta_{\mathrm{local.kc(2.5)}}$) and FAO-56 crop coefficients ($\theta_{\mathrm{FAO56}}$) and measured water content ($\theta_{\mathrm{meas}}$) for the three layers of lysimeter 1.

Figure 5 shows a computer simulation with the value of $K_{c\ mid\ loc}$ equal 2.5. As mentioned before, the upper limit of 2.5 is usually placed on $K_c$ to represent an upper limit on the stomatal capacity of the vegetation to supply water vapour to the air stream under the clothesline or oasis conditions (Allen *et al*., 1998). The computed moisture content profile is much closer to the measurements especially to those that are close to the permanent wilting point. This is explained by the fact that greater crop coefficients imply greater evapotranspiration and therefore greater depletion of the water content of the soil.

The results were evaluated statistically by the root mean square error (RMSE, %), the mean error (ME, cm$^3$ cm$^{-3}$), the coefficient of determination (CD), and the coefficient of residual mass (CRM) (Loague and Green, 1991). The optimum value of RMSE, ME, and CRM is 0.0. The optimum value of CD is 1. Positive values of CRM indicate that the model underestimates the measurements, and negative values for CRM indicate a tendency to overestimate. Table 5 shows the values of the criteria for the two simulations: locally obtained crop coefficients and locally obtained crop coefficients with $K_{c\ mid\ loc}$ = 2.5.

The RMSE values obtained with the locally obtained crop coefficients vary from 25.34% for the first layer to the value of 33.29% for the second layer, while the value of the third layer is 26.75%. These values are higher than the values obtained with the locally obtained crop coefficients with $K_{c\ mid\ loc}$ = 2.5, which are 17.75, 28.60, and 24.28% for the three layers of the lysimeter, respectively. Similar improvement can also be seen to the other three statistical criteria: mean value (ME), coefficient of determination (CD), and coefficient of residual mass (CRM). It is pointed out however that the CRM values are always negative, showing that both the models overestimate the soil water content. Since deep percolation was never observed, overestimation of the soil water content implies that more water needs to be depleted by evapotranspiration. This can be accomplished by increasing even more the value of $K_{c\ mid\ loc}$ even more, however this does not seem to be realistic even under specific lysimeter conditions.

Figures 6-8 show the total inflow of water to the lysimeter by irrigation and precipitation for the simulation period along with total values of potential and actual evaporation and transpiration and total actual evapotranspiration,

**T a b l e 5.** Statistical criteria obtained with locally obtained crop coefficients and locally obtained crop coefficients with $K_{c\ mid\ loc}$ = 2.5

| | $K_{c\ loc}$ | | | $K_{c\ loc}$ with $K_{c\ mid\ loc}$ = 2.5 | | |
|---|---|---|---|---|---|---|
| Layer (cm) | 0-30 | 30-60 | 60-90 | 0-30 | 30-60 | 60-90 |
| RMSE (%) | 25.34 | 33.29 | 26.75 | 17.75 | 28.60 | 24.28 |
| ME (cm$^3$ cm$^{-3}$) | 0.041 | 0.040 | 0.0296 | 0.024 | 0.028 | 0.026 |
| CD | 0.905 | 0.511 | 0.289 | 0.977 | 0.610 | 0.371 |
| CRM | -0.199 | -0.234 | -0.202 | -0.116 | -0.147 | -0.178 |

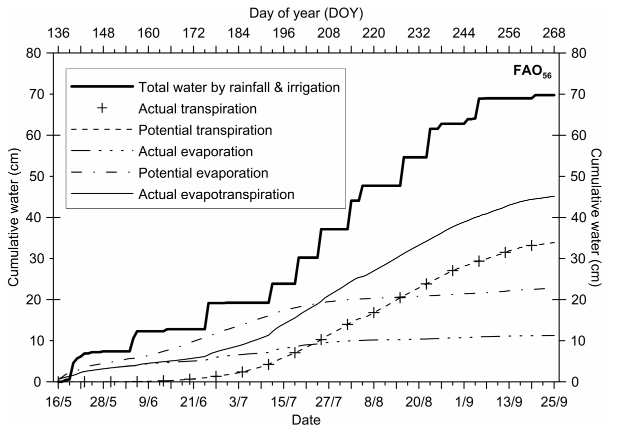


**Fig. 6.** Components of mass balance during the growing period using FAO-56 crop coefficients (potential and actual evaporation, potential and actual transpiration, actual evapotranspiration and total water applied by rainfall and irrigation).

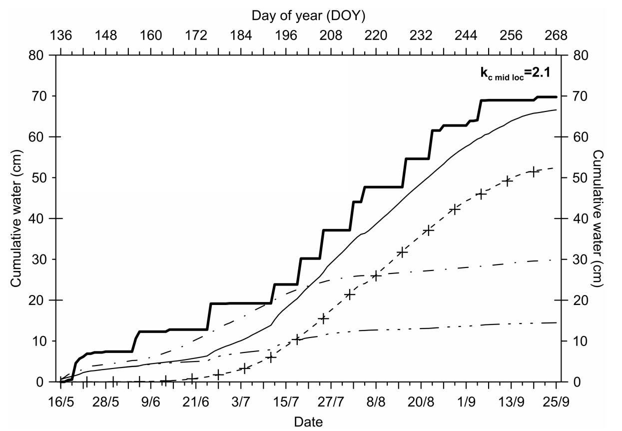


**Fig. 7.** Components of mass balance during the growing period using locally obtained crop coefficients. Explanations as in Fig. 6.

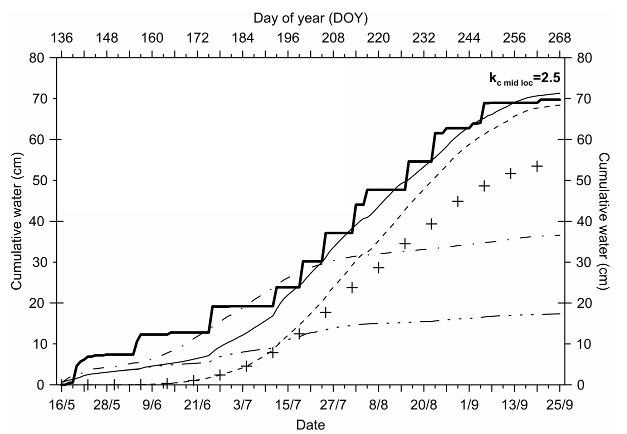


**Fig. 8.** Components of mass balance during the growing period using locally obtained crop coefficients with $K_{c\ mid\ loc}$ = 2.5. Explanations as in Fig. 6.

as they are simulated by the model using FAO-56, locally obtained $K_{c\ loc}$, and locally obtained $K_c$ with $K_{c\ mid\ loc}$ =2.5 respectively.

Total inflow is considerably larger than the computed actual *ET* when FAO-56 crop coefficients are used (Fig. 6). This is related to the fact that these coefficients represent standard field conditions and not the particular conditions of the lysimeters of this study. Actual transpiration equals potential transpiration because of the surplus water entering the lysimeters. This is not representative of the experimental conditions, where sometimes the moisture content observed was close to the threshold value.

The actual *ET* is very close to the total inflow of water when locally obtained $K_{c\ loc}$ is used (Fig. 7). The actual transpiration curve has started declining from the potential *ET* curve being more realistic to the field conditions. These conditions are even more realistically depicted when locally obtained crop coefficients with $K_{c\ mid\ loc}$ = 2.5 are used where there is an adequate difference between actual and potential *ET* (Fig. 8). This is justified by the fact that the moisture content was very close to the threshold value during some days of the cultivation period and therefore the actual *ET* is smaller than the potential *ET* during these days. The water inflow covers completely the actual *ET* with a small deficit at the end of the simulation period.

In all simulations, actual evaporation is smaller than potential evaporation. This is because evaporation is only affected by the water content of the surface soil layer, which after irrigation and rainfall rapidly decreases to the lower limit for evaporation.

## CONCLUSIONS

1. In the oasis effect conditions, crop evapotranspiration is much higher than what is expected and crop coefficients are much higher than the coefficients derived under standards conditions. Knowing these local coefficients is very important in order to quantify the water requirements of a crop under these special conditions.

2. The local crop coefficients were obtained by the water balance method and were by about 75% higher than the FAO-56 coefficients during the mid-season stage.

3. Simulated results obtained with the local crop coefficients were much better than those obtained with the FAO-56 coefficients.

4. The simulation results were improved when the value of the crop coefficient at the mid stage was equal to 2.5, which is the highest value that can be obtained under oasis effect conditions.

5. The SWBACROS model describes very well the water flow in the unsaturated zone under these non-standard conditions.

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