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ACTUAL EVAPOTRANSPIRATION OF THE ORANGE ORCHARD IN NORTHERN SINAI, EGYPT

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Abstract. Studies on soil-water management in the Nile Delta and Northern Sinai (Egypt) were carried out in 2011–2013 by the Institut de Recherche pour le Développement. The El-Salam orange orchard was selected as a 'standard' station to study the management of appropriate irrigation, including the development of a model to assist in the management of irrigation of other crop covers in the Nile Delta. The model simulated actual evapotranspiration with a one-day step resolution, using the approach of Penman-Monteith (with daily input data, i.e. standard data from the national network of weather stations), by taking account of the specificity of the crop cover (cover resistance). We compared the amounts of irrigation applied to the orange orchard (I_{mean} = 994.3 mm · year^{-1}; 2.7 mm · day^{-1}; crop coefficient Ea/ET_0 = 0.78) with the requirements of water estimated by the model ($Ea_{simulated}$). This comparison enabled us to propose a daily amount required for irrigation. It is reasonable to sustain water losses of 94,570 m^3 water · year^{-1} for the total area of the plantation (80 ha; drainage from the root zone), that is, 1,182 m^3 water · year^{-1} · ha^{-1}. These water losses involve hydraulic adjustment of the sites of crop production and the costs of routing water.

Key words: irrigation, Bowen ratio, actual evapotranspiration, orange orchard, Nile Delta, Egypt

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INTRODUCTION

This study on soil-water management in the Nile Delta was conducted from 2011 to 2013 within the framework of Sustainable Management of Adverse Impacts on Farming and Soil Ecosystem Associated with Long Term Use of Low Quality Irrigation Water, in collaboration with the National Research Centre, Soils and Water Use Department, of Cairo [Braudeau and Zaghloul 2010].

The orange orchard known as the El-Salam Farm (northern Sinai), irrigated with mixed water, i.e. drainage and Nile waters (the west-east El-Salam Canal), was chosen as a 'standard' study site for research on the mode of management of precision irrigation, including the development of a model which could also be used for the management of irrigation of other crops throughout the Nile Delta (wheat, sugar beets, beans, clover, peas, rice, cotton, watermelon, sunflower, maize).

Irrigation doses for the orange grove had heretofore been selected using a crop coefficient (actual evapotranspiration/potential evapotranspiration, Ea/ET_0) [Allen et al. 1998] which was estimated in a 'classic' manner from: (a) the soil-water balance equation of root zones of a soil plantation located in semi-arid zones [Rana and Katerji 2000], and (b) the potential evapotranspiration value referring to a lawn well supplied with water. The application of this coefficient to citrus plantations has been discussed [Rana et al. 1994, Steduto et al. 1996]. We compared the values of this crop coefficient with those obtained from a bibliography concerning other plantations in semi-arid zones.

Currently there are two experimental methods to accurately determine actual evapotranspiration: the Bowen ratio method and the Eddy correlation method [Heilman et al. 1996, Villalobos et al. 2000]. We estimated the actual evapotranspiration of the orange grove with a twenty-minute time step resolution using the Bowen ratio method [Bowen 1926], which enables quantification of actual evapotranspiration and the resistance of plant covers on the basis of measurements of temperature and humidity gradients of air, net radiation, and heat flux in soil.

We compared the irrigation doses applied to the orange grove with the evapotranspiration from the model: this comparison enabled us to propose daily management of irrigation which would lead to greater water savings.

MATERIALS AND METHODS

Study site

Local climate and vegetation

Geographical location and climate. The study site is located in the Nile Delta (*Batn el Baqara*), in the north-western part of Sinai, close to the Mediterranean coast of Egypt (Fig. 1). This region is subject to a Saharan climate (i.e. very hot and dry) in the south part, becoming milder towards the north, thanks to the influence of the Mediterranean Sea. The main climatic parameters are: mean annual precipitation $Pi_{(2005\text{-}12)} = 95.4 \text{ mm} \cdot \text{year}^{-1}$, potential evapotranspiration [Penman 1948, Allen et al. 1998] of $1{,}271 \text{ mm} \cdot \text{year}^{-1}$

($ET_{0(2005\text{-}12)}$ = 3.48 mm · day^{-1}), mean daily global radiation of 21.6 MJ · day^{-1}, daily duration of insolation of 9.1 hours, mean annual air temperature of 20.3°C (T_{max} = 27.0°C, T_{min} = 14.3°C), mean relative humidity of air of 66.6%, mean wind speed of 8.2 km · hour^{-1} (data for the reference station El-Arish, latitude 31.08°N, longitude 33.83°E, elevation 31 m, 190 km from the El-Salam Farm orange grove, i.e. the study plot; www.fao.org). For future studies, five study plots were selected, based on irrigation water quality: Abu-Rawash and Zenin (waste; north-west of Cairo); Kafr el-Sheikh (drainage water; north of the Nile Delta); Tanash (waters of the Nile; north of Cairo); El-Salam (mixed: drainage waters and Nile waters; Northern Sinai).

Vegetation. The citrus production sites of the Nile Delta are found mainly in the governorates of Qalyubia, Beheira, Sharqia, Ismailia, and Monufia, where cleared areas have been transformed to introduce perennial crops. Citrus (*Citrus sinensis*, originating in China) was introduced to Egypt between the eleventh and thirteenth centuries, transmitted to the Arabs by the Persians. At present, plantations of citrus extend over 111,200 ha (2012) (of which 30% are orange groves). The production of oranges is 2,430,000 tonnes · year^{-1} (2012; about 33% were exported, which places Egypt eleventh in the world). There are many varieties of oranges, among them the variety studied here, the Valencia or Valencia Late orange (*Citrus sinensis*), is a variety of sweet orange hybridised by the agronomist William Wolfskill (1798–1866) in southern California

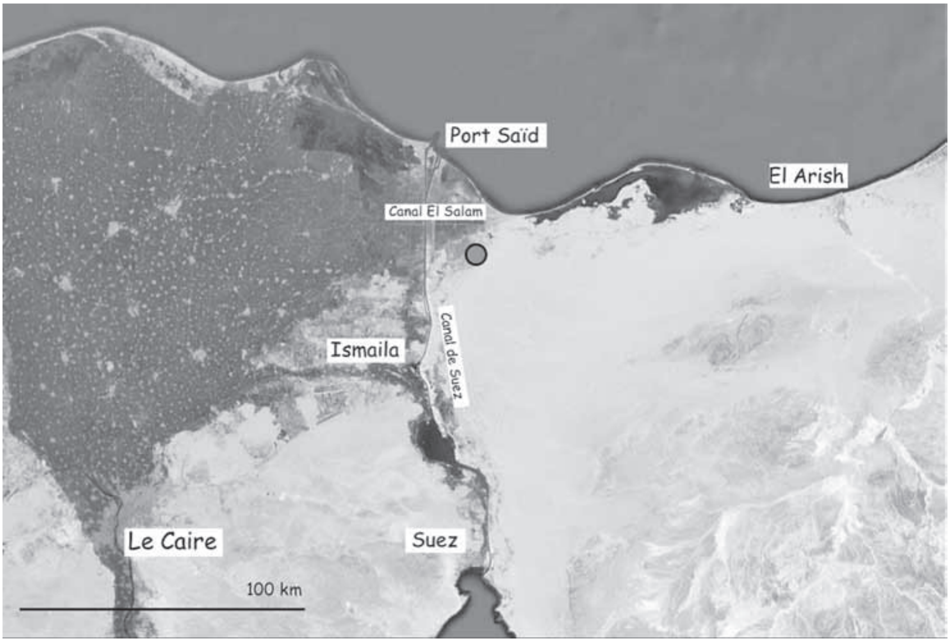


Fig. 1. Location map of the study region: the Nile Delta (Batn el Baqara) and north-western part of the Sinai, located on the Mediterranean coast of Egypt (area: 24,000 km^2). Five study plots: Abu-Rawash and Zenin (sewage in north-west Cairo); Kafr el-Sheikh (drainage water; north Nile Delta); Tanash (Nile water, north of Cairo); El-Salam (mixed water – drainage water and Nile water, north of the Sinai

in the USA in the nineteenth century. The Valencia Late orange (summer orange) is harvested from February to July for fruit juice and as table fruit (www.fao.org). The El-Salam Farm orange orchard, with an area of 80 ha, was planted in June 2005 with seedlings of ø 6 cm and height = 0.6 m, in rows of 6.0 × 4.0 m, with the Valencia Late variety grafted onto the strain *Folca matricana*. The El-Salam Farm orange orchard is irrigated by a drip system with mixed water consisting of drainage waters and Nile waters from the west-east El-Salam Canal.

Sampling and measurement technique

Results presented in this paper are based on measurements carried out over 16 days, from 9 to 24 April 2013. Calculations of actual evapotranspiration, E_a were made starting from diurnal values of air and soil temperature gradients (dT), vapour pressure gradient at air temperature T (de), and net radiation (measured over the duration of the astronomical day) from 6:00 a.m. to 6:00 p.m., thus a duration of approximately 12 hours, the duration varying with the date for the location of the El-Salam Farm. The duration of the day on the first day of measurement (the 99th day of the year, 9 April) was 12.0096 hours, whereas on the last day of measurement (the 114th day of the year, 24 April) it was 12.0163 hours. For a time step resolution of 20 minutes, we measured the air temperature, relative air humidity (HMP35A relative humidity probe C, Vaisala, Helsinki, Finland), and wind speed (A100R anemometer, Vector Instruments, Rhyl, UK) on two levels, at 5 and 2 m above the orange orchard. Global radiation (LI-200SZ pyranometer sensor, Li-cor, NE, USA) and net radiation (REBS/Q-7 net radiometer, Campbell Scientific, Logan, USA) were measured at 6 m above the soil surface of the orange orchard. The mean soil temperature was measured at depths of 0.15, 0.25, 0.35, and 0.45 m (using Model 107 probes, Campbell Scientific, Logan, USA). The HMP35AC relative humidity probes and anemometers were installed on removable and fixed masts of the UT920/UT930 type (Campbell Scientific, Logan, USA) (Fig. 2). Sensors were placed on a mast 6 m high. In order to minimise the influence of the supports on the measurements, the sensors were held by metal arms between 1 and 2 m long (according to the sensitivity of the sensor) and insulated from the supports. Measurements were taken with a 20-minute time step resolution and cumulated or averaged over the day to yield values of net radiation, air temperatures, relative humidity, and vapour pressure. The temperature measurements were accurate to an error of less than ±0.01°C, thus, for both sensors, of dT = ± 0.02°C; the water vapour pressure measurements were accurate to an error of less than ±0.01 kPa, thus, for both sensors, of de = ±0.02 kPa [Revfeim and Jordan 1976]. Uninterrupted measurements were recorded on a Micrologger CR1000 (Campbell Scientific, Logan, USA) and then transferred to the computer using an RS232-SC32A optical interface and PC208E Edlog Version 6.6 software (Campbell Scientific, Logan, USA).

Model description: soil-water content and actual evapotranspiration

Soil-water content: the model output [Nizinski and Saugier 1989] in daily soil-water content ($RP_{(d)}$) is based on the water balance equation, whereby the water balance of the root zone is the difference between the input, i.e. throughfall ($Ps_{(d)}$) and irrigation

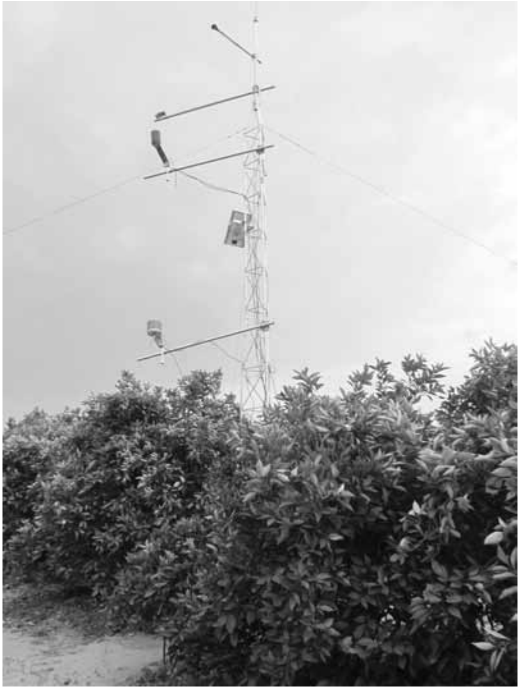


Fig. 2. Site of the study plot (orange grove of 80 ha): equipments for measuring the necessary parameters to determinate the actual evapotranspiration, using the Bowen ratio method

($I_{(d)}$), and the output, i.e. drainage from the root zone ($Dr_{(d)}$) and water uptake by roots ($ABS_{(d)}$). The litter has a protective function (self-mulching); thus in the model, evaporation occurred in the litter only. The soil profile is supplied only by irrigation and throughfall, the daily value of which was calculated from the interception model of Nizinski and Saugier [1988]. It is assumed that the soil at this site never attained saturated hydraulic conductivity (the plot's soil was measured at $k_s > 500 \text{ mm} \cdot \text{day}^{-1}$) and that therefore there was no runoff (gross annual precipitation: $Pi_{(2005\text{-}12)} = 95.4 \text{ mm} \cdot \text{year}^{-1}$). The soil profile is composed of n layers (i); each layer is characterised by its own soil-water retention thresholds, i.e. maximum at field capacity ($R_{\mathrm{FC}}(i)$) and minimum at wilting point ($R_{PWP}(i)$). The soil layers are seen as n tanks in series. Each layer drains to the layer below when the volume of water drained from the preceding layer ($Dr(i-1)_{(d)}$) is added to the volume already present ($RP(i)_{(d-1)}$) and reduced when the water volume taken up by roots ($ABS(i)_{(d)}$) is greater than the field capacity of this layer ($R_{FC}(i)$). When the soil-water content of the last layer (n) exceeds its field capacity, water drainage from the root zone takes place, thus $Dr = (Dr(n)_{(d)})$.

$$Dr(i-1)_{(d)} - E_{soil(d)} + (RP(i)_{(d-1)} / (d-1)) - ABS(i)_{(d)} \approx 0 \text{ mm} \cdot \text{day}^{-1} \qquad (2)$$

The simulation started on the first day of the year (day $j = 1$) and the initial condition was assumed as follows: the soil-water content of each layer equalled field capacity ($RP(i)_{(1)} = R_{FC}(i)$). The inputs for the model, expressed daily, were: potential evapotranspiration ($E_{P(d)}$), throughfall ($Ps_{(d)}$), irrigation ($I_{(d)}$), and leaf area index ($LAI_{(d)}$). Four main parameters were used: the ratio of stomatal resistance to leaf water potential (r_{st}/Ψ_{leaf}), distribution of root length ($LR(i)$), field capacity ($R_{FC}(i)$), and wilting point of each soil layer ($R_{PWP}(i)$).

Actual evapotranspiration, aerodynamic resistance, stomatal resistance, and leaf water potential: the water vapour flow through the stomata is equal to the water vapour pressure gradient divided by resistance to vapour transport through the stomata, cuticle, and leaf boundary layer. For this simulation, the Monteith method [Monteith 1965] was adopted, whereby the evaporative surface was considered as a single layer in which the mean stomatal resistance of the canopy is equal to the sum of the values of stomatal resistance of all the leaves. Thus the transpiration (E_a) rate from the grove canopy can be quantitatively expressed as follows [Allen et al. 1998]:

$$Ea = ET_0/(1 + (\gamma/(\Delta + \gamma))(r_{st}/LAI\ r_a)) \quad \mathrm{mm \cdot day^{-1}} \tag{3}$$

where: Ea is actual evapotranspiration ($\mathrm{mm \cdot day^{-1}}$); ET_0 is potential evapotranspiration ($\mathrm{mm \cdot day^{-1}}$); γ is a psychrometric constant (mb $°\mathrm{K}^{-1}$); Δ is the slope of the saturation vapour pressure vs the temperature curve (bar $°\mathrm{K}^{-1}$); r_{st} is stomatal resistance ($\mathrm{s \cdot cm^{-1}}$); LAI is the leaf area index ($\mathrm{m^2 \cdot m^{-2}}$); and r_a is aerodynamic resistance ($\mathrm{s \cdot cm^{-1}}$).

The turbulent diffusion resistance for heat and water vapour flow from the leaf boundary layer into the atmosphere (r_a) is related to wind speed and forest height. Under neutral stability conditions, r_a is given by Monteith (1965) as:

$$r_a = (1/(k^2 \cdot u_{2M}))[\ln((z - d)/z_0)]^2 \quad \mathrm{s \cdot cm^{-1}} \tag{4}$$

where: r_a is aerodynamic resistance ($\mathrm{s \cdot cm^{-1}}$); k is the von Kármán constant (0.39); u_{2M} is wind speed ($\mathrm{m \cdot s^{-1}}$); z is height above the ground (m); z_0 is roughness height (m); d is zero plane displacement height (m).

The surface roughness parameters z_0 and d were estimated according to an empirical formula which relates both parameters to mean tree height (m) [Thom 1972]:

$$d = 0.75\ h \text{ and } z_0 = 0.1\ h \quad \mathrm{m} \qquad (5) \text{ and } (6)$$

where h is mean tree height (m).

RESULTS AND DISCUSSION

Morphological characteristics of the study plot

To compare our measurements with those of other papers, we parameterised the study stat+ion. The parameters involved in our model are: stand density, mean stem circumference at the 0.3m level, total basal area, leaf area index (LAI), cover resistance, stomatal resistance, leaf water potential (critical leaf water potential, $\Psi_{leaf\text{-}crit}$; maximal leaf water potential, $\Psi_{leaf\text{-}max}$), and average tree height of the orange orchard. These parameters are presented in Table 1 and comparable to the parameters obtained by

Green and Moreshet [1979], Hoffman et al. [1982], Castel et al. [1987], Chartzoulakis et al. [1999]. This orange orchard has raised its level of production (from 0.09 tonnes $\cdot$ ha^{-1} in 2007 to 25.0 tonnes $\cdot$ ha^{-1} in 2013) but has not yet reached its optimal level, which is expected to equal approximately 45.9 tonnes $\cdot$ ha^{-1} (forecasts) by 2017 (in Morocco, according to Bouazzama and Bahri [2009], average production equals 30.0 tonnes $\cdot$ ha^{-1}).

Stand height. The average tree height of the orange orchard is h = 2.48 m (±0.402 m; N = 756) (Table 1).

Table 1. Morphological characteristics of the El-Salam orange orchard study plot (80 ha)

Date of planting (orange tree seedling, Ø = 0.06 m; *h* = 0.6 m), June 2005
Species: Citrus sinensis
Hybrid parentage: pomelo × mandarin orange
Cultivar: Valencia Late
Spacing: 6.0 × 4.0 m
Mean height of trees: 2.47 m
Area of the study plot: 1.89 ha
Number of trees: 756 trees
Stand density: 400 trees ha^{-1}
Area occupied by an individual tree: 25 m^2
Mean stem circumference at a height of 0.3 m: 0.5275 m
Mean stem diameter at a height of 0.3 m: 0.1660 m
Total basal area: 9.23 m^2 $\cdot$ ha^{-1}
Leaf area index (LAI): 3.24 m^2 $\cdot$ m^{-2}

Leaf area index. The real area occupied by a tree (m^2 $\cdot$ tree^{-1}) is 17.0 m^2 $\cdot$ tree^{-1}, with an *LAI* of 6.24. Taking into account the surface of the area between rows (2 metres wide), the area occupied by a tree is 25.0 m^2 $\cdot$ tree^{-1}, with an *LAI* of 4.24 (±1.399; *N* = 300) (Fig. 3).

Measurement of cover resistance and stomatal ***re**sistance and the relationship between stomatal resistance and leaf water* potential. The measurements were carried out continuously from 9 to 24 April 2013: the average daily cover resistance was r_c = 580.88 s $\cdot$ m^{-1} (±215.56 s $\cdot$ m^{-1}; N = 615) with a mean aerodynamic resistance r_a = 137 s $\cdot$ m^{-1} (average tree height of the orange orchard: 2.48 m). This cover resistance is comparable to an average of 500 s $\cdot$ m^{-1} in a citrus population studied by Rana et al. [2005], obtained using the Eddy correlation method. When the cover resistance obtained by the Bowen ratio method and the leaf area index (LAI = 4.24) are known, the average stomatal resistance of a leaf can be calculated (for a time step of 20 minutes, which is the scanning time of the Bowen ratio method). The measurements were made under optimal water availability conditions (irrigated plantation; soil-water content close to field capacity); thus, the measured values of stomatal resistance were as follows: minimum stomatal resistance $r_{stomatal\text{-}min}$ = 176.01 s $\cdot$ m^{-1} (±91.397 s $\cdot$ m^{-1}; N = 615) for the period from 9 to 24 April 2013, which is very close to the values obtained for comparable stands [Cohen and Fuchs 1987, Cohen et al. 1987, Cohen and Cohen 1983, Cohen et al. 1983]. We took the values of critical leaf water potential from the bibliography [Green and Moreshet 1979, Cohen and Cohen 1983, Cohen et al. 1983, Castel et al. 1987, Cohen and Fuchs 1987, Cohen et al. 1987, Chartzoulakis et al. 1999]: critical leaf water potential $\Psi_{leaf\text{-}lim} = -15.0$ bars and a maximum leaf water potential $\Psi_{leaf\text{-}max} = -25.0$ bars; these values were obtained for the same variety, the Valencia Late orange.

Soil-water potential measurement. We applied the empirical formula of Gardner [1960]: (a) to volumetric soil-water content at the field capacity, $R_{FC}(i) = 0.2388\ \mathrm{cm}^3 \cdot \mathrm{cm}^{-3}$ ($R_{FC}(i) = 18.32$ mm at 0.10 m), soil-waste potential at field capacity $\Psi_{FC}(i) = -0.100$ bars; (b) to volumetric soil-water content at the permanent wilting point, $R_{PWP}(i) = 0.0716\ \mathrm{cm}^3 \cdot \mathrm{cm}^{-3}$ ($R_{PWP}(i) = 5.00$ mm at 0.10 m) corresponding to the soil-water potential at the permanent wilting point, $\Psi_{PWP}(i) = -16.000$ bars; (c) the coefficients depending on the hydraulic characteristics of the soil of layer i were derived from measurements of soil samples from the study site, thus $A_{(i)} = 2.396 \cdot 10^{-4}$ and $B_{(i)} = -4.2134$; (d) the available soil-water content calculated for 0.10 m was $R_{AW}(i) = 13.2$ mm; this was extrapolated to the entire height of the profile.

The mean soil-water potential for the 16 days of measurements was, for depths of 0.15, 0.25, 0.35, and 0.45 m, –0.1926, –0.0616, –0.0768, and –0.0816 bars, respectively (Fig. 4), with soil water content from 89.9 to 92.0% of R_{FC} (without water stress; Ea/ET_0 of 0.80) for the entire profile.

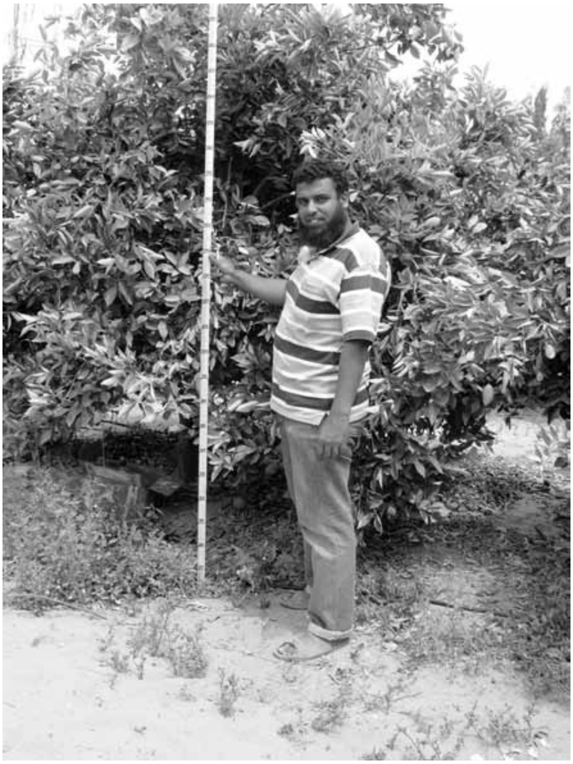


Fig. 3. Levelling of trees of the orange grove using a graduated rule, 9 and 16 April 2013

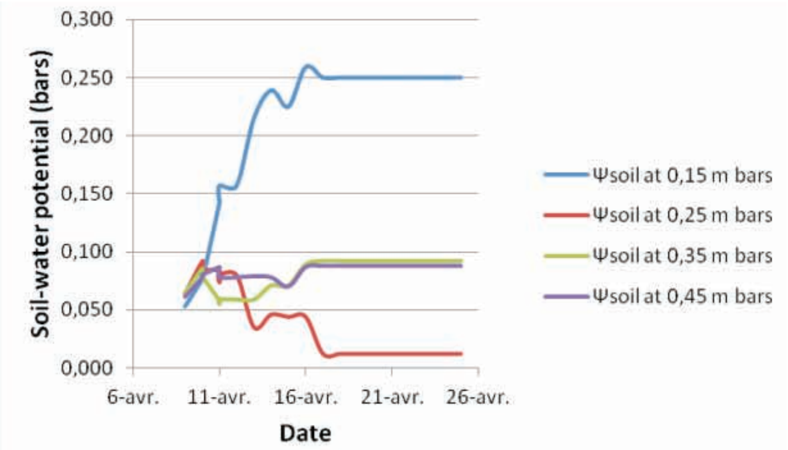


Fig. 4. Daily values of soil-water potential for 16 days of measurement from 9 to 24 April 2013 for depths of 0.15, 0.25, 0.35, and 0.45 m

Irrigation, crop coefficient, and potential evapotranspiration

Irrigation. Irrigation of the plantation amounted to 994.3 mm · year^{-1}, an average of 2.72 mm · day^{-1}; doses are traditionally calculated using an average annual crop coefficient $Ea/ET_0 = 0.78$ (a minimum of 0.58 in January and a maximum of 1.27 in July); soils are irrigated all year, with the minimum during January–March, November, and December, and the maximum during May–August (Table 2*a*). The annual irrigation doses applied to the orange grove are very similar to those cited in the work of Castel and Buj [1990], Martin et al. [2001] and García Petillo and Castel [2004, 2007]. During our measurements, root uptake occurred preferentially in the first layer of soil, from 0.00 to 0.15 m (Fig. 4); the underlying strata, 0.15–0.25, 0.25–0.35, and 0.35–0.45 m, were maintained at field capacity. In April, irrigation is applied at a level near $Ea_{simulated}$ from our model (±9 m^3 of water ha^{-1} · month^{-1}, 0.3 m^3 of water ha^{-1} · day^{-1}; this difference represents 1.25%; Fig. 5*abc*; Table 2*b*). We believe that the irrigation used May through August causes drainage out of the root zone of the orange grove (Table 2*c*), which is not true in other months. In cases of excess water irrigation supply, with consequent draining out of the soil profile, the runoff which would have been caused by minimal infiltrability has never occurred: in fact, we estimated the hydraulic conductivity coefficient of saturated soil at $k_s > 500$ mm · day^{-1}. Knowing that the average annual rainfall is $Pi =$ 95.4 mm · year^{-1} and the maximum irrigation dose is 10 mm · day^{-1}, we can assume that our soil infiltrability has never actually been minimal.

Potential evapotranspiration. Mean annual and mean daily ET_0 calculated over the period 2005–2010 is 1271.5 mm · year^{-1} (3.48 mm · day^{-1}); with an average minimum ET_0 in January of 2.74 mm · day^{-1} and in December of 2.70 mm · day^{-1} and a mean maximal ET_0 in July of 4.26 mm · day^{-1} and in August of 4.20 mm · day^{-1}.

Table 2. Simulated average monthly values of actual evapotranspiration and average monthly values of the irrigation of the orange grove in the study plot over the period 1 January 1 2005 to 31 December 2010 (constant values over the period 1 June 2005 to 26 April 2013):

(a) Comparison between $Ea_{simulated}$ and irrigation (Ea vs I_{mean})

	$Ea_{simulated}$	I_{mean}	Pi $m^3 \cdot month^{-1}$	$I_{mean} + Pi$ $m^3 \cdot month^{-1}$	$I_{mean} + Ps$ $m^3 \cdot month^{-1}$
January	54 527	39 680	17 376	57 056	54 971
February	54 273	40 320	11 683	52 003	50 601
March	60 905	54 560	5 045	59 605	59 000
April	64 356	62 400	3 080	65 480	65 110
May	67 892	71 920	13 987	85 907	84 228
June	76 663	84 000	0	84 000	84 000
July	84 526	133 920	0	133 920	133 920
August	83 412	104 160	0	104 160	104 160
September	80 429	72 000	0	72 000	72 000
October	72 889	49 600	13 480	63 080	61 462
November	60 747	43 200	1 761	44 961	44 750
December	53 518	39 680	9 924	49 604	48 413
January–December	**814 137**	**795 440**	**76 336**	**871 776**	**862 616**

(b) Comparison between $Ea_{simulated}$ and irrigation with gross precipitation (Pi) (Ea vs I_{mean} + Pi);

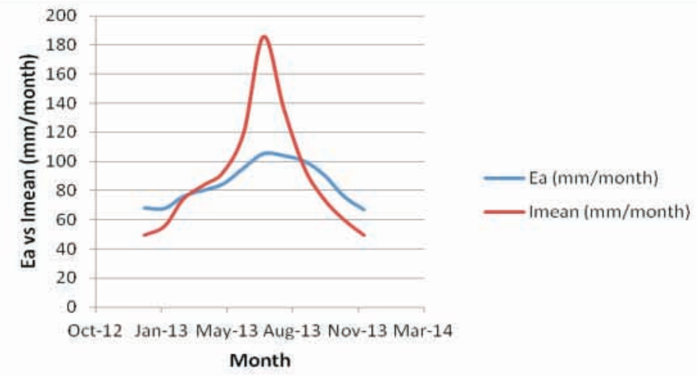
	$I_{mean} - Ea_{simulated}$ $m^3 \cdot ha^{-1} \cdot month^{-1}$	$(I_{mean} + Pi) - Ea_{simulated}$ $m^3 \cdot ha^{-1} \cdot month^{-1}$	$(I_{mean} + Ps) - Ea_{simulated}$ $m^3 \cdot ha^{-1} \cdot month^{-1}$
January	–180	32	6
February	–174	–28	–46
March	–79	–16	–24
April	–24	14	9
May	50	225	204
June	92	92	92
July	617	617	617
August	259	250	259
September	–105	–105	–105
October	–291	–123	–143
November	–219	–197	–200
December	–179	–49	–64
January–December	**–234**	**720**	**606**
Excess of water	1019	1239	1188
Deficit of water	–1253	–519	–476
Water balamce	**–234**	**721**	**711**

Table 2. cont.

(c) Comparison between $Ea_{simulated}$ and irrigation with throughfall, Ps (Ps = gross precipitation minus net interception) (Ea vs $I_{mean} + Ps$)

	$(I_{mean} + Pi) - Ea_{simulated}$ $m^3 \cdot ha^{-1} \cdot month^{-1}$	$(I_{mean} + Ps) - Ea_{simulated}$ $m^3 \cdot ha^{-1} \cdot month^{-1}$	$(I_{mean} + Ps) - Ea_{simulated}$ $m^3 \cdot 80\ ha^{-1} \cdot month^{-1}$	$I_{mean} - Ea_{simulated}$ $m^3 \cdot 80\ ha^{-1} \cdot month^{-1}$
June	14	9	754	–24
July	225	204	16336	50
August	92	92	7337	92
September	617	617	49394	617
October	259	259	20748	259
June–October	**1208**	**1182**	**94570**	**994**

(a) Comparison between $Ea_{simulated}$ and irrigation (Ea vs I_{mean})



(b) Comparison between $Ea_{simulated}$ and irrigation with gross precipitation (Pi) (Ea vs $I_{mean} + Pi$)

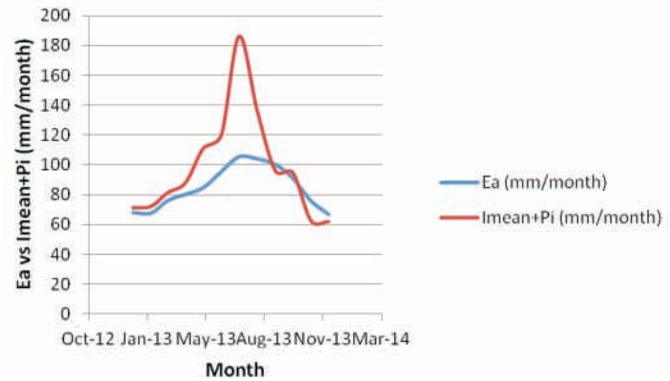


Fig. 5ab. Simulated average monthly values of actual evapotranspiration (Ea) and average monthly values of irrigation (I_{mean}) of the orange grove in the studied plot over the period 1 January 2005 to 31 December 2010 (constant values during the period 1 June 2005 to 26 April 2013)

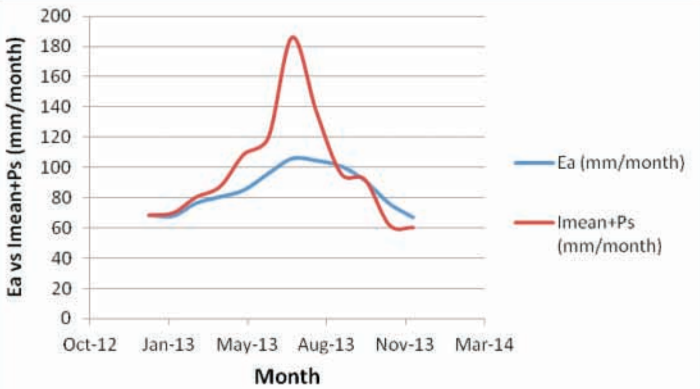


Fig. 5c. Simulated average monthly values of actual evapotranspiration (*Ea*) and average monthly values of irrigation (I_{mean}) of the orange grove in the studied plot over the period 1 January 2005 to 31 December 2010 (constant values during the period 1 June 2005 to 26 April 2013)

Simulation of the actual evapotranspiration of the orange orchard and accurate irrigation

A simulation of the actual evapotranspiration of the orange orchard was carried out from 1 January 2005 to 31 December 2010, using the model parameterisation from our measurements. The average annual actual evapotranspiration calculated over the six years we studied was 1,017.2 mm · year^{-1} (2.79 mm · day^{-1}), which was very close to the annual irrigation dose applied to the orange grove: I_{mean} = 994.3 mm · year^{-1} (2.72 mm · day^{-1}), or 102.3% of I_{mean}. These values are comparable to those obtained by Castel and Buj [1990], Martin et al. [2001] and García Petillo and Castel [2004, 2007], which were obtained for the same types of orchards. We analysed the distribution of monthly irrigation during an average year, averaged from six years of simulation. As we did not know the details of the calculations that led to the irrigation doses, we analysed $Ea_{simulated}$ three ways:

(1) $Ea_{simulated}$ comparison with irrigation ($Ea_{simulated}$ vs I_{mean}) (Table 2*b*; Fig. 5*a*): over an entire year, $Ea_{simulated}$ exceeds the applied irrigation doses of 18,697 m^3 · month^{-1}, or 233 m^3 · month^{-1} · ha^{-1}. Irrigation values for January are 25 to 30% lower than those of $Ea_{simulated}$; values for April and May are very close; values for June, July, and August are markedly higher (10 to 60%); values for September to December are lower by 11 to 25%. These calculations do not account for water input due to gross precipitation (*Pi*).

(2) $Ea_{simulated}$ comparison with irrigation to which gross precipitation (*Pi*) is added ($Ea_{simulated}$ *vs* I_{mean} + *Pi*) (Table 2*b*; Fig. 5*b*): to monthly doses, we added intake due to monthly gross precipitation (with Pi_{annual} of 95.4 mm · year^{-1}). Over an entire year, $Ea_{simulated}$ is lower than the applied irrigation doses of 57,639 m^3 · month^{-1}, or 720 m^3 · month^{-1} · ha^{-1}. The values of irrigation for January to April are very close (2–5%) to $Ea_{simulated}$; values for June and July were considerably higher and for August much higher (10–60%); values for September to December were lower by 11 to 15%. This approach is not accurate enough, because it does not take into

account the phenomenon of net interception in the plantation; it is necessary to deduct the fraction of gross precipitation that evaporates without reaching the soil and which thus should not be taken into account in the calculation of transpiration.

(3) $Ea_{simulated}$ comparison with irrigation to which throughfall Ps ($Pi - In$) is added ($Ea_{simulated}$ vs $I_{moy} + Ps$) (Table 2b; Fig. 5c): we estimated throughfall (Ps) from the Nizinski and Saugier [1988] interception model; it follows that, given the rainfall distribution (brief but intense showers) and the type of vegetation (planting in rows), throughfall averages out at 88% of gross precipitation (Pi). We added the inputs due to throughfall (with Ps_{annual} of 83.9 mm · year^{-1}) to the monthly doses of irrigation. Over an entire year, $Ea_{simulated}$ is less than the applied irrigation doses of 56,908 m^3 · month^{-1}, or 711 m^3 · month^{-1} · ha^{-1}. The values of irrigation for December to April are very close (2–5%) to those of $Ea_{simulated}$; the values for June, July, and August significantly higher (10 to 60%); the values for September to November are lower by 11 to 15%.

No matter which approach is used, comparing $Ea_{simulated}$ with irrigation ($Ea_{simulated}$ vs $I_{mean} + Pi$) or irrigation to which throughfall is added ($Ea_{simulated}$ vs $I_{mean} + Ps$) yielded adequate irrigation doses for December to May, but substantially overestimated doses for June to October (Table 2c), which results in drainage outside the root zone of the orange grove, equalling 94,570 m^3 per water · year^{-1} for the entire plantation of 80 ha, or 1,182 m^3 of water ha^{-1} · month^{-1}. This constituted 11.9% of the total volume of water used in irrigation (792,266 m^3 per water · year^{-1} for the entire plantation of 80 ha).

Excess irrigation in May–August (months of maturation and harvesting of fruit) is motivated by a project to increase the tonnage of fruit harvest, which is based on the assumption that temporary congestion will induce additional absorption. This seems questionable because, given the type of soil (sandy soil, reduced available water reserve) and actual soil-water content (soil-water content close to field capacity reserve), excess water doses are drained almost instantly from the root zone. It would be desirable to make a comparative study of the evolution of the weight of the irrigated fruit trees by means of varying the crop coefficient Ea/ET_0, from unequal values (lower than 0.80) to higher values (up to 1.0). In addition, an economic analysis is required: the drip system of irrigation is associated with higher costs, due to the cost of water.

According to Bouazzama and Bahri [2009] (Maroc Late; gravitational irrigation; type of soil and method of calculating the crop coefficient unspecified), the final yield with a crop coefficient $Ea/ET_0 = 0.80$ would be 74 kg · tree^{-1}, while with a crop coefficient $Ea/ET_0 = 1.10$, the yield would be 117 kg · tree^{-1}, an increase of 43 kg · tree^{-1}. These results can be considered in the economic balance: hypothetical gains from higher fruit yield due to excess irrigation as described by Bouazzama and Bahri [2009] compensate for the overall cost of irrigation (high cost of the water supplied). It is therefore reasonable to retain water losses of 94,570 m^3 per water year^{-1} for the entire plantation of 80 ha, or 1,182 m^3 per water ha^{-1} · year^{-1} (Table 2*c*).

CONCLUSION

We constructed a model of actual evapotranspiration with a time step resolution of one day, using the Penman-Monteith approach (inputting standard data from the meteorological stations of the national network), taking into account the specificity of the plant cover (cover resistance and, in particular, the relationship of stomatal resistance to leaf water potential). We compared the irrigation doses applied to the orange orchard with the water requirements of the model: this comparison enables us to propose a scheme of daily management of irrigation that saves water. It is reasonable to retain water losses of 94,570 m^3 per water $year^{-1}$ for planting of the entire 80 hectares, or 1,182 m^3 per water $year^{-1} \cdot ha^{-1}$.

This model is a reliable tool for the management of accurate irrigation for any crop (wheat, sugar beets, beans, clover, peas, rice, cotton, watermelons, sunflowers, or maize) across the Nile Delta. The model parameters *cover resistance* and *stomatal resistance*, derived from the Bowen ratio method during the period 9 to 24 April 2013, can be improved: in fact the approach of Monteith [1965] (Jarvis-Stewart model [Stewart 1988]) does not account for the evolution of stomata (*minimal stomatal resistance*) during the lifetime of the leaves evolution which controls the regulation of transpiration flux (*minimal stomatal resistance* or *maximal stomatal conductance*): 1) the evolution of the morphology of the epidermis of orange-tree leaves from budburst to senescence, as well as during different phases (if they exist); it will be possible to study leaves (here persistent) and, thereby, 2) the evolution of minimal stomatal resistance depending on the age of the leaf (Fig. 6abc).

(a) One year old

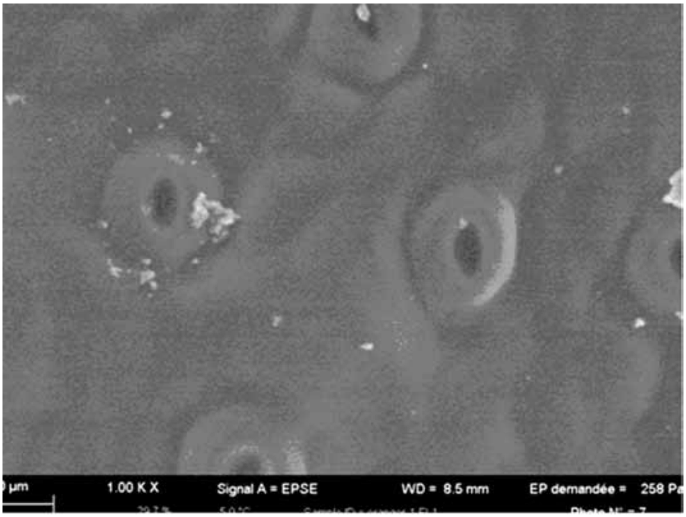
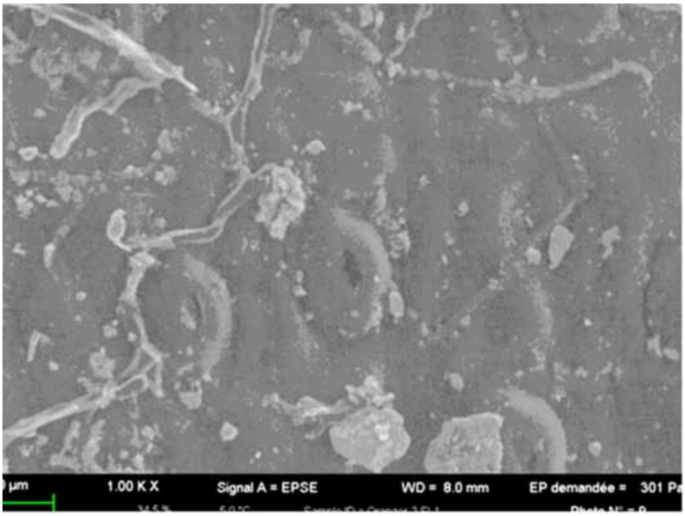
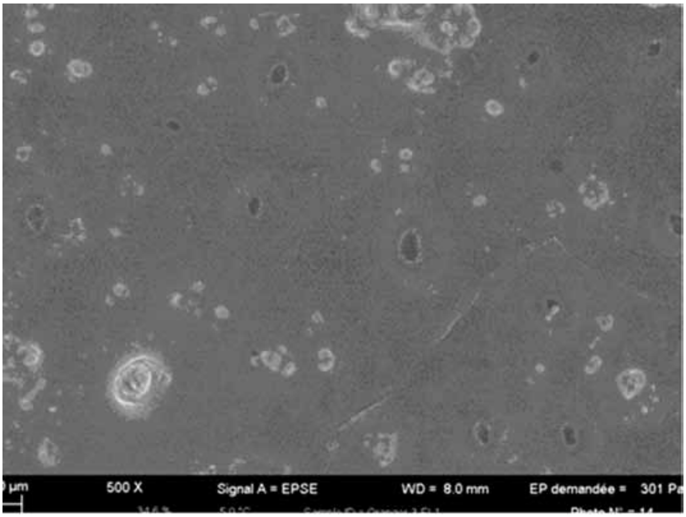


Fig. 6a. Surface quality of the leaves in the orange grove in the study plot: scanning electron microscopy (SEM) epidermal photographs of studied Valencia Late leaves (*Citrus sinensis late*): choice of the leaves for a of $LAI_{max} = 4.24$ with a mean stomatal resistance $r_{stomatal\text{-}min} = 176.01\ s \cdot m^{-1}$ (±91.397; N = 615) over the period 9 to 24 April 2013

(b) Two years old



(c) Three years old



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MODELOWANIE JAKO NARZĘDZIE ZARZĄDZANIA NAWODNIENIAMI KROPLOWYMI – PRZYKŁAD SADU POMARAŃCZOWEGO EL-SALAM, PÓŁNOCNY SYNAJ, EGIPT

Streszczenie. Badania nad gospodarką wodną w delcie Nilu i Północnego Synaju przeprowadzono w latach 2011–2013 w „Institut de Recherche pour le Développement" (Francja). Sad pomarańczowy El-Salam został wybrany jako „standardowa" stacja badawcza. Badania dotyczą zarządzania nawodnieniami. Celem pracy jest opracowanie modelu, który można wykorzystać do nawadniania innych upraw w delcie Nilu. Proponowany model ewapotranspiracji rzeczywistej działa z jednodniowym rozkładem czasowym i wykorzystuje podejście Penmana-Monteith, które uwzględnia specyfikę szaty roślinnej (opór powierzchniowy). Zmiennymi wejściowymi modelu są standardowe dane meteorologiczne ze stacji meteorologicznych sieci krajowej. Porównano dawki irygacyjne zastosowane w sadzie pomarańczowym (I_{mean} = 994,30 mm · rok^{-1}, 2,72 mm · dzień$^{-1}$, współczynnik kulturowy $Ea/ET_0 = 0,78$) z dawkami irigacyjnymi wyliczonymi z modelu ($Ea_{simulated}$): to porównanie pozwala zaproponować zarządzanie nawodnieniami precyzyjnymi uwzględniając optymalne użycie wody. W aktualnym zarządzaniu nawodnieniami straty wody (drenaż, poza strefę korzeniową) wynoszą 94570 m^3 wody rocznie dla całej plantacji o powierzchni 80 ha lub 1182 m^3 wody rok^{-1} · ha^{-1}.

Słowa kluczowe: nawadnianie kroplowe, współczynnik Bowena, ewapotranspiracja, sad pomarańczowy, delta Nilu, Egipt

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