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Assessing agro-hydrological models to schedule irrigation for crops of Mediterranean environment

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Abstract. Despite in Mediterranean environment water resources for irrigation are limited, water management for agriculture is often practiced ignoring principles of environmental sustainability.
Objective of the paper is to asses the possibility of using agro-hydrological models for irrigation scheduling, in order to optimize the water use efficiency.
The results of a comparison between the numerical SWAP model and the functional model proposed by FAO to estimate water requirements in two typical arboreal Mediterranean Crops (grapevine and olive) are showed.
In the initial phase of the research, involving both irrigation seasons 2005 and 2006, after a preliminary analysis of soil hydraulic and biophysical plant parameters, two intensive field measurements campaigns were carried out to measure the soil water content at different depths, to proceed to the validation of both the models.
Validation of the model was carried out by means of the comparison between measured and predicted soil water content.
Finally different irrigation scheduling options were examined, in order to compare the scheduled irrigation times with those planned by the farmers.
The results of investigations evidenced that FAO model simulates reliably the values of average water content of the soil profile, even if a certain overestimation of evapotranspiration fluxes can be observed with the FAO 56 model compared with SWAP. Consequently, the FAO model anticipates the starting date for irrigation obtained with SWAP, but, in terms of seasonal water requirements, the estimates determined by the two modes did not result significantly different.

Keywords. SWAP – FAO – Scheduling irrigation.

Evaluation de modèles agro-hydrologiques pour la programmation de l'irrigation des cultures en environnement méditerranéen

Résumé. *Malgré la rareté des ressources hydriques pour l'irrigation dans la zone méditerranéenne, la gestion de l'eau dans l'agriculture est souvent pratiquée tout en ignorant les principes de durabilité de l'environnement. L'objectif de cet article est d'évaluer la possibilité d'utiliser des modèles agro-hydrologiques pour la programmation de l'irrigation, afin d'optimiser l'efficience de l'utilisation de l'eau. Les résultats de la comparaison du modèle SWAP avec le modèle proposé par la FAO pour évaluer les besoins en eau, sont présentés pour deux cultures arboricoles (vigne et olive) typiques de la Méditerranée. En phase initiale de la recherche où les deux saisons d'irrigation 2005 et 2006 ont été considérées, deux sessions intensives de mesure de l'humidité du sol à différentes profondeurs ont été effectuées, tenant compte d'une analyse préliminaire des paramètres hydrauliques du sol et biophysiques de la plante, afin de valider les deux modèles. La validation des modèles a été effectuée en comparant la teneur en eau eau du sol mesurée et prédite. Enfin, différentes options pour la programmation de l'irrigation ont été examinées, afin de comparer les dates d'irrigation conseillées par le modèle avec celles envisagées par les agriculteurs. Les résultats ont montré que le modèle de la FAO simule bien les valeurs de la teneur moyenne d'eau du profil du sol, même si une certaine surestimation des flux d'évapotranspiration a été observée par rapport à SWAP. Par conséquent, le modèle de la FAO 56 a anticipé la date de partance de l'irrigation par rapport à SWAP, mais, du point de vue des besoins saisonniers d'eau, les estimations déterminées par les deux modèles ne différent pas significativement.*

Mots clés. *SWAP – FAO – Programmation de l'irrigation.*

I – Introduction

The question related to the efficient water use in irrigated areas has a fundamental importance in Mediterranean regions, where the water scarcity and the semi-arid climate often cause fragility and severe damages in the agro-ecosystems. In the last two decades, this evidence has induced the development of several models to simulate the mass and energy exchange processes in the Soil-Plant-Atmosphere system (SPA) (Feddes *et al.*, 1978; Bastiaanssen *et al.*, 2007). Some of these models are physically based and allow to simulate in great detail all the components of the water and energy balance, including crop growth, irrigation and solute transport (van Dam *et al.*, 1997; Vanclooster *et al.*, 1994; Ragab, 2002). Others models using simplified schematizations, focusing on the possibility to simulate only the main terms of soil water balance allowing to schedule irrigations, have also been proposed.

Objective of the work is to assess the suitability of two different agro-hydrological models for irrigation scheduling. In particular a comparison between the physically based SWAP model (Soil-Water-Plant-Atmosphere, van Dam *et al.*, 1997) and the simplified FAO procedure (Allen *et al.*, 1998) to estimate water requirements for two typical arboreal Mediterranean crops (grapevine and olive) is showed.

For the study area, located in the south-western cost of Sicily, agro-hydrological and micro–climatic parameters, were monitored during two irrigation seasons. A temporal series of measured soil water content at different depth and observed irrigation volumes were used to validate both the models.

II – Study area description

Investigation was carried out during irrigation seasons 2005 and 2006 in an experimental farm (Figure 1) near Castelvetrano (TP), where land use is characterized by arboreal crops (mainly olives, grapes and citrus) and soil textural class, according to USDA classification, is silty clay loam.

During the considered years the most important micro–climatic parameters, such us precipitation, wind speed and direction, global radiation and air humidity were monitored. Furthermore agro–hydrological and physiological parameters were observed in two experimental plots (a vineyard and an olive grove).

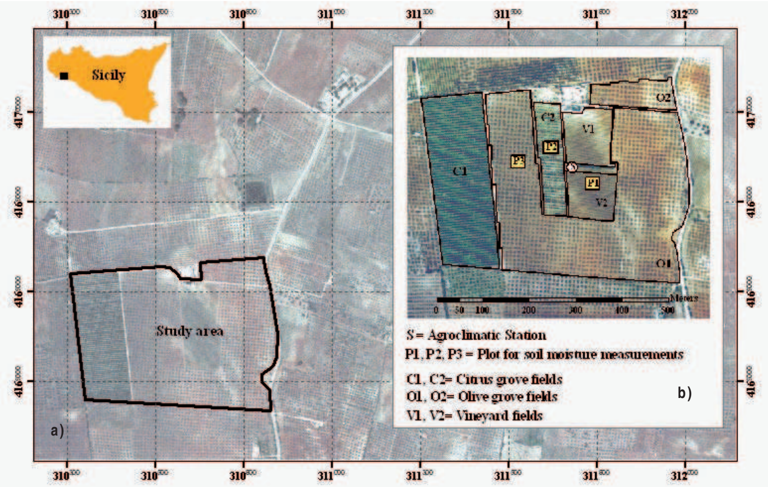

Figure 1. Geografic location with a) subset of study area and b) the description of landuse and field facilities.

III – Materials and methods

1. Soil hydraulic characterization

Traditional laboratory methods were used to evaluate soil hydraulic properties of undisturbed soil cores representative of four different depths of a soil profile. Soil texture, bulk density, hydraulic conductivity of saturated and near saturated soil conditions, as well as some points of the water retention curve in the potential range between –5 and -15300 cm were deduced for each depth. The van Genuchten-Mualem parameters of soil hydraulic characteristics, showed in Table 1, were then deduced by using the RETC code (van Genuchten *et al.* 1991) to the experimental values θ_i-h_i and k_i-h_i, being θ_i-h_i the volumetric soil water content and the matric potential at the generic depth, and k_i the soil hydraulic conductivity measured at the same depth.

Table 1. van Genuchten-Mualem parameters for the investigated soil layers (θ_r=residual water content, θ_s= saturated water content, K_0=saturated hydraulic conductivity; α, n and λ= fitting parameters)

Parameters	Layers			
	1 0-20 cm	2 20-40 cm	3 40-60 cm	4 60-80 cm
θ_r	0.030	0.139	0.103	0.119
θ_s	0.400	0.444	0.400	0.410
K_0 [cm/day]	10.00	3.00	30.00	0.24
α	0.0104	0.0118	0.0159	0.046
n	1.838	2.128	1.548	1.487
λ	0.5	0.5	0.5	0.5

2. Soil moisture content measurements

Temporal variability of soil water contents in two different plots were measured, at several depths, using Diviner 2000 Sentek capacitance sensor. The probe containing the sensor can measure the soil water content at different depth, when inserted in an preliminarily installed access tube. In the vineyard three access tubes were installed at 10, 30 and 50 cm from the source point where the emitter was located, with an axis-symmetric scheme, as shown in Figure 2. In the olive plot, where irrigation water is supplied with a micro-sprinkler system, a single access tube was installed at the border of wetted zone.

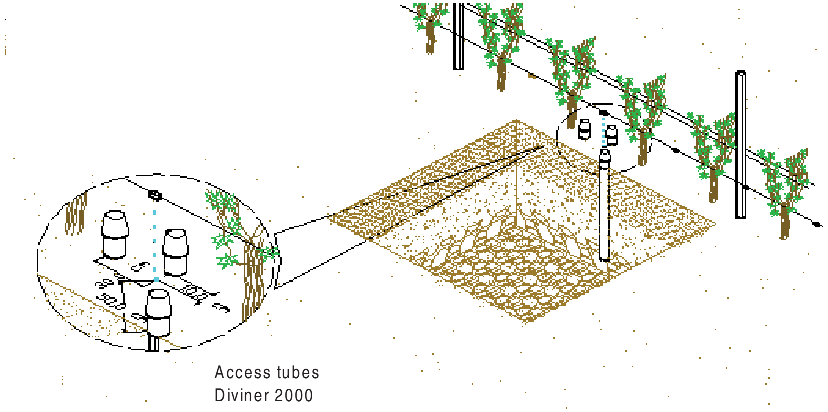

Figure 2. Set-up of DIVINER access tubes in the vineyard.

IV – Agro-hydrological models

SWAP model aims to simulate all the water processes in the soil-plant-atmosphere continuum. The model includes detailed sub-models for soil water flow, soil evaporation, crop growth, irrigation practice and can operate on fixed temporal interval from daily to seasonal cycle.

The Bucket model "FAO 56" solves the water balance equation in terms of soil water depletion. The actual water fluxes terms are obtained from the potential fluxes, using the approach based on a "dual crop K_c coefficients" taking into account the crop water stress by means of a transpiration reduction coefficient, K_s, and a evaporation reduction coefficient, K_e.

1. SWAP Basic equations

SWAP (Soil-Water-Atmosphere-Plant) is a one-dimensional physically based model for water flow in saturated and unsaturated soil (Kroes *et al.*, 2000) and simulates the vertical soil water flow and solute transport in close interaction with crop growth. Richards' equation (Richards, 1931), including root water extraction, is applied to compute transient soil water flow:

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

under specified upper and lower boundary conditions. In eq. (1), z (cm) is the vertical coordinate, assumed positive upwards, t (d) is time, C (cm^{-1}) is the differential moisture capacity, K(h) (cm d^{-1}) is the soil hydraulic conductivity function and S (d^{-1}) is the root uptake term that, for uniform root distribution, is defined by the following equations:

$$S(h) = \alpha_w(h)\frac{T_p}{|z_r|} \qquad (2)$$

$$T_p = K_c \times ET_0\left[1 - \exp(-K_{gr}LAI)\right] \qquad (3)$$

in which T_p (cm d^{-1}) is the potential transpiration, z_r (cm) the rooting depth, α_w (-) is a h-dependant reduction factor which accounts for water deficit and oxygen stress (Feddes *et al.*, 1978), K_c (-) is the crop coefficient, ET_0 (cm d^{-1}) is the reference evapotranspiration, K_{gr} (-) is an extinction coefficient for global solar radiation and finally LAI (-) is the leaf area index.

The numerical solution of eqs. (1), (2) and (3) is possible when initial, upper and lower boundary conditions and the soil hydraulic properties, i.e. the soil water retention curve, θ(h), and the soil hydraulic conductivity function, K(h), are specified; detailed field and/or laboratory investigations are therefore needed.

Different options are available in SWAP to schedule irrigation (i.e. determining irrigation times and water requirements); for the purpose of this study, only the irrigation time parameter, defined as an allowable depletion fraction, f, of readily available water in the root zone, was defined:

$$f = \frac{\sum_{i=1}^{n}\left(\theta_{fc_i} - \theta_{lim_i}\right)_i}{\sum_{i=1}^{n}\left(\theta_{fc_i} - \theta_{wp_i}\right)_i} \tag{4}$$

in which θ_{lim} is the soil water content below which it is necessary to irrigate, θ_{fc} and θ_{wp} are the soil water content at field capacity and at wilting point respectively, and n is the number of layers of homogeneous soil, as defined in the model.

2. The FAO 56 procedure

In the FAO 56 procedure the root zone depletion is calculated daily, with a water balance model based on a simple tipping Bucket approach:

$$D_{r,i} = D_{r,i-1} - P_i + ET_i + DP_i \tag{5}$$

where $D_{r,i}$ (mm) and $D_{r,i-1}$ (mm) are the root zone depletion at the end of day i and i-1 respectively, P_i (mm) is the precipitation, ET_i (mm) is the actual evapotranspiration and DP_i (mm) is the deep percolation of water moving out of the root zone.

In absence of water stress (potential condition), the actual evapotranspiration ET is obtained multiplying the crop coefficient K_c (-) to the Penman-Monteith reference evapotranspiration rate, ET_0, (Allen *et al.*, 1998). FAO 56 paper proposed a new “dual crop coefficients approach” that splits the K_c factor in two separate coefficients, a basal crop coefficient, K_{cb}, for transpiration and a soil evaporation coefficient, K_e. The actual evapotranspiration ET can therefore be evaluated as:

$$ET = (K_{cb} + K_e)\ ET_0 \tag{6}$$

When water represents a limiting conditions, the coefficients of Eq. (6) are multiplied by a reduction factors, K_s, that can be variable between 0 and 1; the last value have to be used when soil water storage in the root zone has been depleted under a threshold value (mm), RAW, corresponding to the readily available water.

The reduction coefficients, K_s, is expressed by:

$$K_s = \frac{TAW - D_{r,i}}{TAW - RAW} \tag{7}$$

where TAW (mm) is the total available water (i.e. water stored in the root zone between field capacity and permanent wilting point), $D_{r,i}$ (mm) the root zone depletion, and RAW (mm) is the readily available water. RAW values can be obtained multiplying the TAW values by a depletion coefficient, p, taking into account the crop water stress resistance.

A completed description to calculate TAW, RAW and p, for numerous crops, can be found in FAO 56 paper (Allen *et al.*, 1998).

The irrigation times in the FAO 56 procedure is based on the management allowed depletion, MAD, of the available water that can be stored in the root zone, obtained as

$$MAD = \frac{\left(\theta_{fc} - \theta_{lim}\right)}{\left(\theta_{fc} - \theta_{wp}\right)} \tag{8}$$

in which θ_{lim} is the average soil water content below which it is time to irrigate.

When irrigation is scheduled in absence of crop water stress, the MAD parameter can be assumed equal to the p coefficient.

V – Results and discussions

In order to evaluate the values of the irrigation scheduling parameters, a preliminary simulation was carried out on both vineyard and olive grove plots, by using, as input, the observed irrigation times and water volumes. Table 2a,b, summarizes the values of the main measured parameters used in the simulations. The values of other parameters necessary to run the simulations have been estimated according to the procedures suggested by the FAO 56 paper (Allen *et al.*, 1998). Since SWAP uses the "single K_c" schematization, the values of crop coefficients, showed in Table 2.b as deduced from FAO 56 paper, differs respect to the "dual approach" values indicated in Table 2.a. The values of soil moisture at field capacity, θ_{fc}, and at wilting point, $\theta_{wp,}$ used in the FAO 56 simulations are obtained averaging the correspondent values measured in the four different soil layers, as considered in the SWAP simulations. For both the irrigation seasons, the initial soil water content assumed in the simulations was fixed according to the corresponding values measured in the soil profile.

Table 2a. Main parameters used in the FAO 56 simulations (in parenthesis are indicated the values used for 2006).

PARAMETERS		Grapevine	Olive
θ_{fc}, Soil moisture at field capacity [cm³/cm³]		0.42	0.42
$\theta_{wp,}$ Soil moisture at wilting point [cm³/cm³]		0.13	0.13
TAW, Total Available Water [mm/m]		187.6	187.6
Development stage and main crop parameters	$DOY_{plant.}$ K_{cb}	105 (116), 0.15	105 (95), 0.65
	$DOY_{dev.}$ K_{cb}	110 (120), 0.15	105 (95), 0.65
	$DOY_{mid.}$ K_{cb}	160 (162), 0.65	105 (95), 0.65
	$DOY_{late.}$ K_{cb}	247 (249), 0.65	258 (258), 0.65
	$DOY_{harv.}$ K_{cb}	258 (258), 0.40	258(258), 0.65

Table 2b. Main parameters used in the SWAP simulations (in parenthesis are indicated the values used for 2006).

PARAMETERS		Grapevine	Olive
Critical pressure heads (cm)			
h_2 (h below which optimum water uptake starts in the root zone)		-25	-25
h_{3h} (h below which optimum water uptake reduction starts in the root zone in case of high atmospheric demand)		-750	-1500
h_{3l} (h below which optimum water uptake reduction starts in the root zone in case of low atmospheric demand)		-1500	-1500
h_4 (wilting point, no water uptake at lower pressure heads)		-10000	-16000
k_{gr} (extinction coefficient) (-)		0.45	0.50
Development stage and main crop parameters	$DOY_{plant.}$ K_c	105 (116), 0.30	105 (95), 0.7
	$DOY_{dev.}$ K_c	110 (120), 0.30	105 (95), 0.7
	$DOY_{mid.}$ K_c	160 (162), 0.75	105 (95), 0.7
	$DOY_{late.}$ K_c	247 (249), 0.75	258 (258), 0.7
	$DOY_{harv.}$ K_c	258 (258), 0.60	258(258), 0.7

1. Models validation and assessment of scheduling parameters

For the considered irrigation seasons Figure 3 a,b shows the simulated daily average soil water content in the root zone, obtained for the vineyard field, and the volumes of each water supply. The average water contents measured in the soil profile (white dots) as well as the rainfalls and irrigation amounts are also plotted.

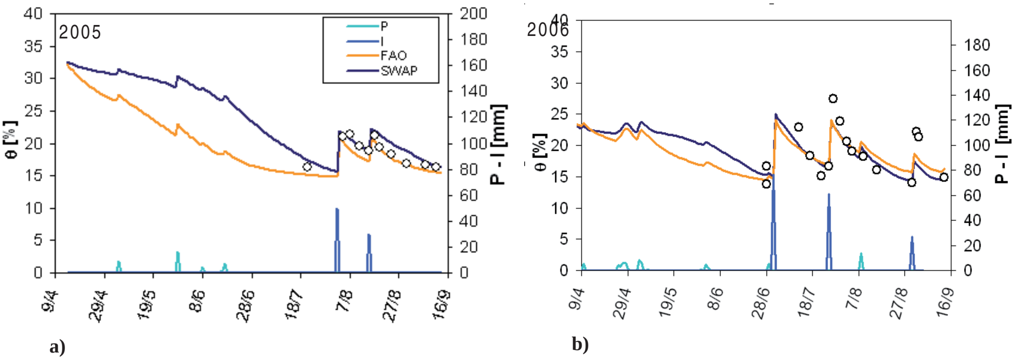

Figure 3. a,b. Measured (white dots) and simulated (continuous lines) average soil water content in the root zone for grapevine. In the secondary axes the irrigation volumes and the rainfall amounts for the two considered irrigation seasons are plotted.

As can be observed in the figure both the model are able to predict quite well the values of average soil water contents. Differences between the two models can be observed mainly at the beginning of the 2005 simulation period, during which the simulated values of soil water content obtained with the FAO 56 model are lower than those obtained with the SWAP model. This behavior can be justified by higher evapotranspiration rates simulated from the FAO 56 model (Agnese *et al.*, 2008). Unfortunately, the absence of measured water content values during the initial phase of simulation, does not allow to verify which model performs better.

Similar results are obtained for the olive crop, as illustrated in figure 4 a,b for both the simulation years.

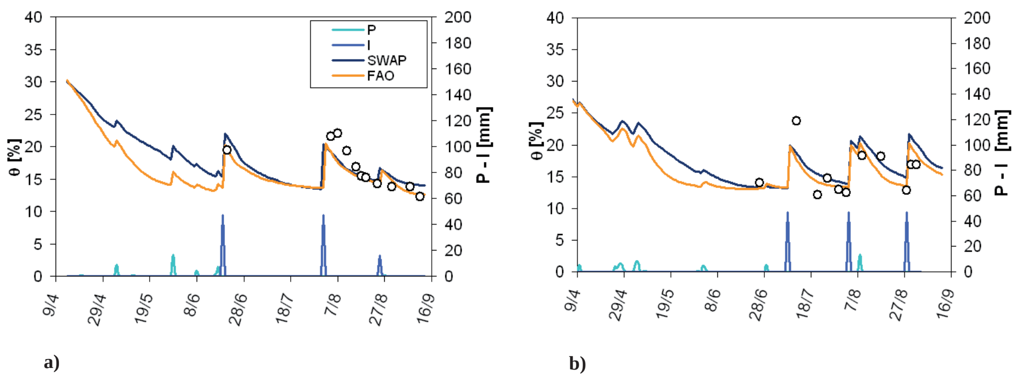

Figure 4. a,b. Measured (white dots) and simulated (continuous lines) average soil water content in the root zone for olive crops. In the secondary axes the irrigation volumes and the rainfall amounts for the two considered irrigation seasons are showed.

The outputs of the two models allowed to assess the farmer strategy for irrigation. Ordinary scheduling parameters f and MAD were therefore calculated as the average values obtained during the two years. In particular the values of f and MAD parameters corresponding to each irrigation practiced by the farmer were evaluated according to equations (4) and (6), as results of the simulations carried out by using SWAP and FAO 56 model respectively. Table 3 shows the values of f and MAD obtained for both the considered crops and irrigation seasons as well as the calculated average values. Lately the average values indicated in Table 3 have been used as input parameters in further simulations, in order to evaluate the simulated irrigation times, that were then compared to the observed ones.

Table 3. Values of f and MAD obtained for both vineyard and olive grove for each irrigation practised by the farmer (average values in bold characters).

Date	Irrig.	Date	DOY	*f*	*MAD*
vinegrape	1	03-08-05	215	0.48	0.90
	2	16-08-05	228	0.34	0.72
	3	02-07-06	183	0.50	0.92
	4	29-07-06	207	0.47	0.79
	5	31-08-06	243	0.59	0.85
		average		**0.48**	**0.83**
Olive crops	1	20-06-05	171	0.45	0.96
	2	02-08-05	213	0.54	0.96
	3	26-08-05	237	0.50	0.92
	4	09-07-06	190	0.55	0.98
	5	04-08-06	216	0.53	0.98
	6	29-08-06	241	0.50	0.97
		average		**0.51**	**0.96**

2. Results of model application for irrigation scheduling

The models were run in order to obtain the irrigation time, whereas the water supply was fixed to 50 mm, corresponding approximately to the average depth provided by the farmer. The scheduling MAD and f parameters were fixed equal to the average values of table 3.

Figure 5 a,b shows the evolution of soil water content during the irrigation seasons for the vineyeard, obtained by FAO 56 and SWAP models. As can be observed in figure 5 a,b, for both the seasons, FAO 56 model generally anticipates the irrigation times respect to SWAP. The observed circumstance, as described in the previous paragraph, is essentially due to the higher evapotranspiration fluxes simulated by the FAO 56 model during the initial phase of simulations. Similar results were obtained for the Olive grove, as can be observed in figure 5 c,d.

Table 4 shows, for both the considered crops the amount of the water supplied according with the farmer strategy as well as those obtained with the simulations. Despite some differences between the simulated irrigation time and in terms of seasonal water requirements, the corresponding values obtained with the two models are not significantly different.

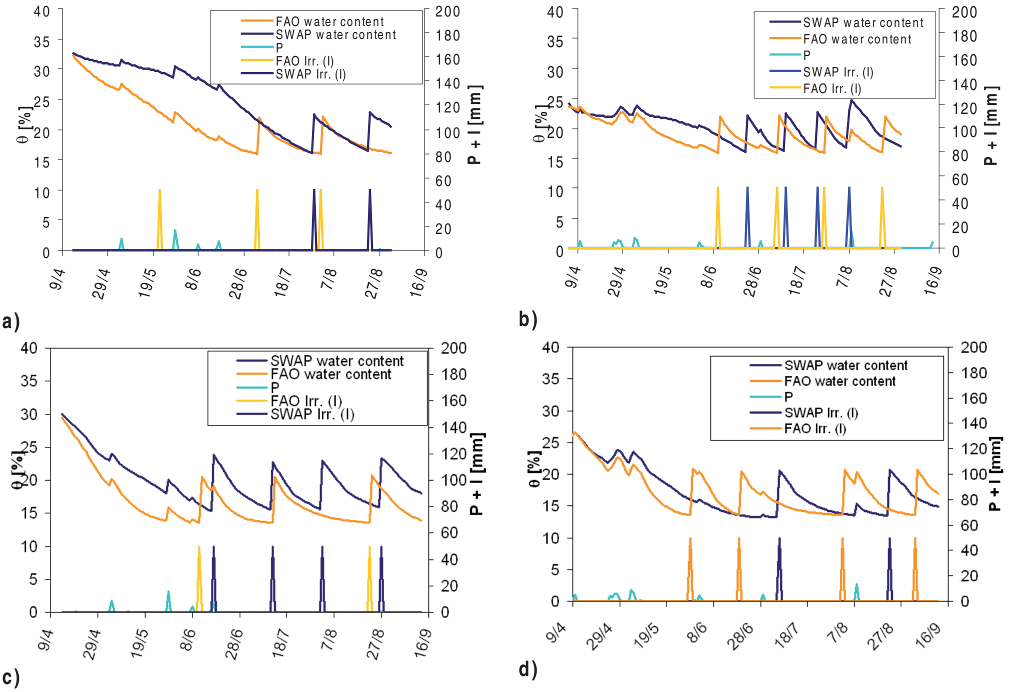

Figure 5. Comparison between simulated SWAP and FAO 56 daily soil water contents in the root zone and irrigation volumes during irrigation season 2005 and 2006 for the vineyard (a,b) and olive grove (c,d).

IV – Conclusion

First of all the time scheduling parameters f and MAD were evaluated as result of models' validation, considering fixed irrigations actually observed in the field.

Then the FAO 56 and SWAP soil water balance outputs i.e. the scheduling time and seasonal water requirements are compared.

FAO 56 model simulates reliable values of average water content of soil profile when a modification of stress function K_s is used, even if, compared with SWAP, a certain overestimation of evapotranspiration fluxes is observed.

Consequently the FAO 56 model anticipated the starting irrigation time evaluated with SWAP even if, in terms of seasonal water requirements, the estimates obtained by the two modes does not evidence significant differences.

Table 4. Observed irrigation volumes and times for vineyard and olive grove in both the irrigation seasons and scheduled values obtained with SWAP and FAO 56.

			Season 2005					Season 2006				
		Irrig.	**I**	**II**	**III**	**IV**	**TOT**	**I**	**II**	**III**	**IV**	**TOT**
Vineyard	**Ordinary Irrigation**	**DOY**	215	228				183	207	243		
		Irrig. depth [mm]	50	30			80	77	61	27		165
	SWAP Scheduled Irrigation	**DOY**	211	236				175	192	206	220	
		Irrig. depth [mm]	50	50			100	50	50	50	50	200
	FAO 56 Scheduled Irrigation	**DOY**	186	214				162	188	209	235	
		Irrig. depth [mm]	50	50			100	50	50	50	50	200
Olive grove	**Ordinary Irrigation**	**DOY**	171	215				190	216	241		
		Irrig. depth [mm]	47	50			97	47	47	47		141
	SWAP Scheduled Irrigation	**DOY**	169	194	215	240		188	235			
		Irrig. depth [mm]	50	50	50	50	200	50	50			100
	FAO 56 Scheduled Irrigation	**DOY**	163	194	235			150	171	215	246	
		Irrig. depth [mm]	50	50	50		150	50	50	50	50	200

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