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Comparison of SWAP and FAO Agro-Hydrological Models to Schedule Irrigation of Wine Grape

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Abstract

In the paper a comparison between two agro-hydrological models, used to schedule irrigation of typical Mediterranean crop, is assessed. In particular the comparison between the model proposed by FAO, using a black box schematization of the processes, and the SWAP model based on the numerical analysis of Richards' equation is showed for grapevine. The comparison carried out for irrigation season 2005 and 2006 focuses on hydrological balance components and on soil water contents. Then the ordinary scheduling parameters were identified and the performance of the two models, aimed to evaluate the seasonal water requirement and the irrigation times, assessed. In the validation phase both the models satisfactorily simulated the soil water content and allowed to obtain comparable values of cumulative evapotranspiration.

With the aim to take into account the crop water stress condition recognized in the field, the original algorithm of FAO 56 model was modified. The experience conducted evidenced how the examined agro-hydrological models, although characterized by a different approach in modeling the phenomena, showed a similar behaviour when used for scheduling irrigation under soil water deficit conditions.

Subject headings: Irrigation (NT), Crops (RT), Water Management (NT), Hydrologic Model (NT), Probe Instruments (NT), Evapotranspiration

Keywords: Agro-hydrological models, FAO 56, SWAP, Irrigation Scheduling, Wine grape.

Introduction

One of most appropriate ways to reduce water use in agriculture is to supply the exact amount of irrigation water to crops when it is required, so that water use efficiency can be maximized.

Despite the farmer experience, irrigation scheduling established on the basis of the visual observation carried out on a few plants and on the soil, often leads to water overuse, as a consequence of the low effectiveness of the empirical evaluations; otherwise, a precise assessment of irrigation depth and/or irrigation timing, can allow to optimize the water use.

The study of this issue becomes serious in the Mediterranean environment, characterized by semiarid climate (Cartabellotta et al., 1998), where the period of crops growth does not coincide with the rainy season. In these conditions the crop is subject to water stress periods that may be amplified due to the incorrect irrigation practice. The stress condition, linked to the outbreak of a soil water deficit period, can be clarified through the Taylor and Ashcroft (1972) assumption in which they define "Stress Day" when the average soil water potential was less than -7.35 kPa.

Agro-hydrological models can be considered an economic and simple tool to optimize irrigation water use, where water represents a limiting factor for crop yield. In the last two decades, agro-hydrological physically based models have been developed to simulate mass and energy exchange processes in the soil-plant-atmosphere (SPA) system (Feddes et al., 1978; Bastiaanssen et al., 2007). In particular, deterministic models have been proposed to simulate all the components of the water balance, including actual crop evapotranspiration and water and solute transport (van Dam et al., 1997; Ragab, 2002).

Unfortunately, the physically based agro-hydrological models, although very reliable, as a consequence of the high number of required variables and of the complex computational analysis, cannot often be used. Therefore, the use of simplified agro-hydrological models may represent a useful and simple tool for practical irrigation scheduling.

The main objective of the paper is to assess the suitability of two different agro-hydrological models to schedule irrigation of wine grape. Validation of the models was initially carried out on the basis of the comparison between measured and predicted soil water content. Then, the SWAP model (Soil-Water-Plant-Atmosphere, van Dam et al., 1997) and FAO 56 procedure (Allen et al., 1998) were compared to analyze the different scheduling options and to estimate irrigation water requirement for wine grape. Finally the two models, once fixed the scheduling parameter and the irrigation depth to apply, allowed to determine the number of days in which the crop is subject to water stress condition.

The real time application of the models, under the examined pedo-climatic conditions, once fixed MAD or f and the irrigation depth, can therefore allow the farmer to identify when to proceed with irrigation.

Model Description

Agro-hydrological models used for irrigation management, allow to explain the complex relations of water exchange occurring within the Soil-Plant-Atmosphere (SPA) continuum. SPA is a very complex system, not only for the high number of variables that must be defined, but especially for internal self-regulation phenomena involving the system components (Ritchie, 1981).

Whatever be the modeling approach used to study the water relations within the SPA system, it is necessary to estimate the evapotranspiration terms, depending on the combination of water evaporation from soil and plant transpiration. According to FAO the reference crop evapotranspiration, ET_0 [mm d^{-1}], can be determined on the basis of the following Penman Monteith equation:

$$ET_0 = \frac{0.408\Delta\left(R_n - G\right) + \gamma \frac{900}{T_a + 273} U_2 (e_s - e_a)}{\Delta + \gamma(1 + 0,34 U_2)} \qquad (1)$$

where Δ [kPa °C^{-1}] is the slope of saturation vapour pressure curve, $e_s(T)$ [KPa] is the saturation vapour pressure at air temperature, R_n [MJ m^{-2} d^{-1}] is the net radiation, G [MJ m^{-2} d^{-1}] is the soil heat flux, $(e_s\text{-}e_a)$ [kPa] is the vapour pressure deficit, γ [kPa °C^{-1}] is the psychometric constant at air temperature T_a [°C] and U_2 [m s^{-1}] is the wind speed measured at 2 m from the soil.

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

$$D_i = D_{i-1} - P_i - I_i + ET_{c,i} + DP_i \qquad (2)$$

where D_i [mm] and D_{i-1} [mm] are the root zone depletions at the end of day i and $i\text{-}1$ respectively, P_i (mm) is the net precipitation, $ET_{c,i}$ [mm] is the actual evapotranspiration and DP_i [mm] is the deep percolation of water moving out of the root zone.

The domain of the depletion function, D_i, is between 0, which occurs when the soil is at the field capacity, and a maximum value, corresponding to the total available water, TAW [mm], for the plant, given by the following equation:

$$TAW = 1000 * \left(\theta_{fc} - \theta_{wp}\right) * Z_r \qquad (3)$$

where θ_{fc} [cm^3 cm^{-3}] and θ_{wp} [cm^3 cm^{-3}] are the soil water contents at field capacity and wilting point respectively and Z_r [m] the depth of the root system.

In absence of water stress (potential condition), the crop potential evapotranspiration ET_c is obtained multiplying the dual crop coefficients (K_{cb} + K_e) with the Penman-Monteith reference evapotranspiration rate, ET_0, (Allen et al., 1998). In particular the “dual crop coefficients approach”, as explained in FAO 56 paper, splits the single K_c factor in two separate coefficients, a basal crop coefficient, K_{cb}, considering the plant transpiration, and a soil evaporation coefficient K_e.

When water represents a limiting condition, the dual crop coefficients (K_{cb} + K_e) have to be multiplied to a reduction factor, K_s, that can be variable between 0 and 1. The reduction factor can be express by:

$$K_s = \frac{TAW - D_i}{TAW - RAW} \qquad (4)$$

where RAW [mm] is the readily available water, that can be obtained multiplying TAW to a depletion coefficient, p, taking into account the crop water stress resistance. In particular when water the storage in the root zone is equal to RAW, the reduction coefficient K_s is equal to 1. Values of p for different crops are proposed in the original publication (Allen at al., 1996). Considered that fraction p depends of the atmospheric evaporative demand, a function for adjusting p for ET_c should be used. The following empirical equation was proposed by van Diepen *et al*. (1988) to evaluate the depletion coefficient:

$$p = \frac{1}{\alpha_p + \beta_p ET_c} - 0{,}1\left(5 - No_{cg}\right) \qquad (5)$$

where α_p [-] and β_p [d cm-^{1}] are two regression coefficients, that can be assumed equals to 0.76 and 1.5 respectively (van Diepen et al., 1988) and No_{cg} [-] is the “crop group number”, that depends on the level of crop resistance to water stress.

The soil evaporation coefficient, K_e, describes the evaporation component of ET_c. When the topsoil is wet, i.e after rainfall event or irrigation, K_e is maximum. Dryer the soil surface, lower is K_e, with a value equal to zero when the soil surface water content is θ_{wp}. In particular when the topsoil dries out, less and less water is available for evaporation: the soil evaporation reduction can be therefore considered proportional to the amount of water in the soil top layer, or:

$$K_e = MIN\left\{\begin{matrix} K_r * \left(K_{c\_\max} - K_{cb}\right) \\ \\ f_{ew} * K_{c\_\max} \end{matrix}\right\} \qquad (6)$$

where K_e is the soil evaporation coefficient, K_{cb} is the basal crop coefficient, K_r is a dimensionless evaporation reduction coefficient, depending on the cumulative depth of water evaporated from the topsoil, f_{ew} is the fraction of the soil that is both exposed and wetted, i.e. the fraction of soil surface from which most evaporation occurs and K_{c_max} is the maximum value of K_c following rain or irrigation. The term K_{c_max} represents an upper limit on the evaporation and transpiration from any cropped surface and it is introduced to reflect the natural constraints placed on available energy represented by the energy balance difference Rn-G-H; where H is sensible heat flux density. The evaporation decreases in proportion to the amount of water in the surface soil layer:

$$K_r = \frac{TEW - D_{e,i-1}}{TEW - REW} \qquad (7)$$

where $D_{e,i-1}$ is cumulative depth of evaporation (depletion) from the soil surface layer at the end of (i-1)th day [mm], TEW [mm] is the total evaporable water from an effective depth Z_e of soil surface subject to drying,, and *REW* [mm] is the readily evaporable water, representing the maximum depth of water that can evaporate from the topsoil layer without restrictions.

When not known, *TEW* is estimated from the soil water retention characteristics of the upper soil layer as $TEW = 1000*(\theta_{fc}-\theta_{wp})*Z_e$, with a depth Z_e equal to 0.10-0.15 m, and *REW* is estimated from the soil textural characteristics (Allen et al., 1998).

In FAO 56 procedure, the irrigation timing can be evaluated on the basis of the management allowed depletion (*MAD*, Merriam, 1966), defined 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 necessary to irrigate. The values for *MAD* are influenced by management and economic factors in addition to the eco-physiological factors influencing *p*. When irrigation is scheduled in absence of crop water stress, the *MAD* parameter can be assumed equal to the *p* coefficient. On the contrary, when irrigation is managed under water deficit conditions the *MAD* parameter is higher than *p*. This last circumstance is typical of the semi-arid Mediterranean environments.

The algorithm proposed in the FAO 56 paper (Appendix 8: Spreadsheet for applying the dual K_c procedure in irrigation scheduling) enables to schedule only full irrigation ($MAD=p$); not considering crops under water stress conditions. The absence of water stress cannot be assumed in Mediterranean environment, where water is often a limiting factor for crop production. Therefore, as will be better specified, it was necessary to modify the FAO 56 model, in order to schedule irrigation under water deficit conditions ($MAD>p$).

SWAP (Soil-Water-Atmosphere-Plant) is a one-dimensional physically based model for water flow in saturated and unsaturated soil (van Dam at al., 1997) and simulates the vertical soil water flow and solute transport by considering the crop growth. Richards' equation (Richards, 1931), including root water extraction, is applied to compute transient soil water flow under specified upper and lower boundary conditions.

$$\frac{\partial\theta}{\partial t} = C(\psi)\frac{\partial\psi}{\partial t} = \frac{\partial}{\partial z}\left[K\left(\psi\right)\left(\frac{\partial\psi}{\partial z}+1\right)\right] - S_a\left(\psi\right) \tag{9}$$

In equation (9), *z* [cm] is the vertical coordinate, assumed positive upwards, *t* [d] is the time, *C* [cm^{-1}] is the differential moisture capacity ($\partial\theta/\partial\psi$), $K(\psi)$ [cm d^{-1}] is the soil hydraulic conductivity function and S_a [d^{-1}] is the root uptake term that, for uniform root distribution, is defined by the following equations:

$$S_a\left(\psi\right) = \alpha_w\left(\psi\right)\frac{T_p}{z_r} \tag{10}$$

$$T_p = K_c ET_0\left[1 - \exp\left(-k_{gr} LAI\right)\right] \tag{11}$$

in which T_p [cm d^{-1}] is the potential transpiration, Z_r [cm] the rooting depth, α_w [-] is a ψ-dependant reduction factor accounting 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 (9), (10) and (11) is possible after specifying initial, upper and lower boundary conditions as well as the soil hydraulic properties, i.e. the soil water retention curve, $\theta(\psi)$, and the soil hydraulic conductivity function, $K(\psi)$; detailed field and/or laboratory investigations are therefore necessary.

Different options are available in SWAP to schedule irrigation. In particular the timing criteria include allowable daily stress (as expressed by the reduction of potential crop transpiration), allowable depletion of readily available water in the root zone, allowable depletion of totally available water in the root zone and critical soil water pressure head or soil water content at a certain depth. The irrigation amounts can be prescribed, or can be calculated by SWAP as the difference between actual water storage in the root zone and water storage at field capacity. In this study, only the irrigation timing was assessed after defining an allowable depletion fraction, *f*, of readily available water in the root zone:

$$f = \frac{\sum_{i=1}^{n}\left(\theta_{fc_i} - \theta_{\lim_i}\right)_i}{\sum_{i=1}^{n}\left(\theta_{fc_i} - \theta_{wp_i}\right)_i} \qquad (12)$$

in which θ_{lim} is the minimum soil water content below which it is necessary to irrigate, and *n* is the number of layers of homogeneous soil, as defined in the model.

The *f* factor as well as the *MAD* and the irrigation depth define the farmers' irrigation strategy. Naturally, the farmer's irrigation strategy is influenced by two components: the first is deterministically linked to the physical process, depending on the spatial and temporal variability of eco-physiological variables; the second stochastic component is represented by the farmer's behavior for irrigation practice. Therefore, both parameters, to a certain extent, are site-specific, in the sense that they reflect the average perception of farmers to the soil water dynamics as well as the farmer's attitude to induce or not crop water stress in order to improve qualitatively or quantitatively the production. The correct evaluation of *f* and *MAD* has a particular relevance for vineyard irrigation scheduling, when in particular crop water stress is controlled during fruit ripening, in order to reach specific wine quality objectives.

Materials and methods

The study area and data collection

Investigation was carried out during irrigation seasons 2005 and 2006 in an experimental farm (fig.1) located in Castelvetrano (UTM EST: 310050, NORD: 4168561), where land use is mainly characterized by arboreal crops (olives and wine grapes). The study area is included within "Agrigento 3" irrigation district.

Fig. 1 - Geographic location and Google earth image of test area. The description of land use and the position of instruments are showed. S: agrometeorological station; P1: soil moisture measurement

The data set for the validation of SWAP and FAO models includes the following information: (i) soil hydraulics parameters; (ii) groundwater data for the lower boundary condition; (iii) vegetation parameters for the upper boundary condition; (iv) irrigation calendar, defined with irrigation depth and timing.

Fig. 2 shows the daily and cumulative values of rainfall during the investigated years.

Fig. 2 – Daily and cumulate rainfall data collected during 2005 and 2006 years

In the same period soil hydraulic characteristics were determined and the main agro–hydrological and physiological variables monitored. Traditional laboratory methods were used to evaluate the soil hydraulic properties of undisturbed soil cores, representative of four different depths of a soil profile. Hydraulic conductivity of saturated and near saturated conditions was measured with a tension infiltrometer at the soil surface and at depths of 0.3 m, 0.6 m and 1.0 m. At each depth two soil samples 0.05 m height and 0.08 m diameter were collected in order to determine some points of the water retention curve, in the range of potential between –0.05 and -153 m. Hanging water column apparatus (Burke et al., 1986) was used to evaluate soil water contents corresponding to matric potential values ranging from -0.05 to -1.5 m; pressure plate apparatus (Dane and Hopmans, 2002) with sieved soil samples 0.05 m diameter and 0.01 m height, was used to measure soil water contents corresponding to matric potentials of -3.37 m, -10.2 m, -30.6 m and -153.0 m. For each undisturbed soil sample, dry bulk density was also determined.

Soil texture was measured by the hydrometer method on the same soil samples used for the water retention curves. Soil textural class, according USDA classification, is silty clay loam.

The Leaf Area Index (LAI) was monitored by means of the optical sensor *Li-Cor LAI 2000*. The root density distribution in the soil profile was estimated through an indirect methodology based on roots interference on the shape of soil moisture profile around the plant, when compared to the shape profile under bare soil condition (Cavazza, 1981).

Temporal and spatial variability of soil water contents in the plot was measured, at several depths in the range between 0 and 1.0 m, using the Diviner 2000 capacitance probe (Sentek Environmental Technologies, 2000). The probe containing the sensor, if inserted in an access tube installed in the field, can measure the soil water content at different depths. In order to obtain the average water content in the soil profile, the measured values were initially averaged at each depth and then weighted for the root density. In order to proceed to an homogeneous comparison between the soil water contents estimated by the two models, the humidity profiles obtained by SWAP were integrated in the root domain, taking also into account the root density distribution.

Irrigation water is applied by means of a trickle irrigation plant, with 8 l h^{-1} emitters spaced 1.0 m. Two irrigations, 30 and 50 mm depth, were supplied on August 3 and 17, 2005, whereas three watering with depths of 77, 61 and 27 mm were provided on July 3, July 27 and September 1 respectively.

Three access tubes having a length of 1.2 m were installed at distances of 0.10, 0.30 and 0.50 m from the point of falling water drops, following an axis-symmetric scheme, as shown in fig. 3.

Fig. 3 – Position of the Diviner access tubes. Distances are measured from the point of falling water drops

The van Genuchten-Mualem parameters of soil hydraulic characteristics, showed in tab. 1, were determined with the $\theta_i(\psi_i)$ and $K_i(\psi_i)$ experimentally obtained, by using the RETention curve computer Code, RETC, (van Genuchten et al., 1991, Mualem, 1976).

Tab. 1 - Soil parameters used in SWAP simulations. α, n and λ are the parameters of van Genuchten-Mualem equations

The farm where experiments were carried out is specialized in the cultivation of grape wine (*Cv*. Ansonica). Grape vines are planted in rows with distance between the rows equal to 2,40 m and between the plants of 1.0 m with a density of 4166 plants per 10.000 m^2.

The values of the variables used as input for simulations with SWAP and FAO 56 are showed in tabs. 2 and 3 respectively. The values of θ_{fc} and θ_{wp} used in FAO 56 simulations were obtained as average of the correspondent values measured in the four investigated soil layers, as considered in SWAP simulations. For both the irrigation seasons, the initial soil water content profile was assumed according to the measured values. In order to evaluate the “ordinary” irrigation scheduling parameters (*MAD* and *f*) a preliminary simulation was carried out, considering the irrigation timing and the water volumes derived from observed data.

Tab. 2 -Variables used for SWAP model simulations

Tab. 3 –Variables used for FAO 56 model simulations. Value between brackets are assumed for the 2006 season

Performance of the models

The performance of the models was evaluated by calculating the root mean square error (RMSE), and the mean bias error (MBE), defined as:

$$RMSE = \sqrt{\left(\frac{1}{N}\sum_{i=1}^{N} d_i^{\,2}\right)} \qquad (13)$$

$$MBE = \frac{1}{N}\sum_{i=1}^{N} d_i \qquad (14)$$

where N is the number of measured data, d_i is the difference between the predicted and the measured values (Kennedy and Neville, 1986).

An additional Student t-test was used, as proposed by Kennedy and Neville (1986):

$$t = \sqrt{\frac{(N-1)MBE^2}{RMSE^2 - MBE^2}} \qquad (15)$$

To determine if the difference between measured and simulated soil water content are statistically significant, the absolute value of the calculated t must be less than the critical t value (t_{crit}), for the fixed significance level. A significance level α=0.05 was assumed and, for N-1 degrees of freedom, the value of t_{crit} is equal to 2.05.

The performance evaluation of irrigation scheduling of the two models was carried out by analysing different irrigation scenarios, implemented by varying both the timing irrigation factors (*MAD* and *f*) and the water depth within domains chosen from ordinary parameters. In particular *f* and *MAD* were considered variables in the range 10-50 and 50-80 respectively, whereas irrigation water depth was assumed equal to 30, 40, 50 and 60 mm.

Each single scenario was then assessed through a frequency analysis of the stress days occurring in the period between the crop vegetative recovery and the harvest. In particular a "Stress Day” was defined as the day in which the average value of simulated soil water potential is less than -7.35 kPa (Taylor and Ashcroft, 1972).

Other performance indicator irrigation scheduling was the number of irrigation supply suggested by the models in respect of each scenario.

Results and discussion

Model validation

Fig. 4a,b shows the average soil water content in the root zone simulated by SWAP (dark lines) and FAO 56 model (light lines), for the considered irrigation seasons. The average water contents measured in the soil profile (white circles), as well as the rainfalls and the irrigation amounts (dashed lines) are also showed.

Fig. 4c,d illustrates the cumulative soil evaporation and tree transpiration simulated with the two models.

Fig. 4a-d. – Comparison between daily average soil water content simulated by the models for the 2005 (a) and 2006 (b) seasons with the measured values (white circles); cumulative soil evaporation and tree transpiration fluxes are showed below (c-d)

As can be observed in the fig. 4a,b both the models predict quite well the average soil water contents during the considered irrigation seasons. Differences between the two models are mainly observed at the begin of the first irrigation season (2005), when simulated values of soil water content obtained with the FAO 56 model are lower than those evaluated with the SWAP model, due to the higher simulated evaporation and transpiration fluxes, as showed in fig. 4c. The higher transpiration fluxes, partially counterbalanced by the lower soil evaporation obtained with FAO 56 (fig. 4d), justify the minor difference on soil water contents observed at the begin of 2006 season (fig. 4b). Unfortunately, the absence of soil water content measurements observed during the initial phases of the considered period, does not allow to verify which model performs better.

Fig. 5 shows the comparison between measured and estimate values of soil water content θ [cm^3 cm^{-3}].

Fig. 5 – Estimated soil water content vs. measured values

For both the models a substantial agreement between measured and estimated soil water contents is observed, especially for soil water contents lower than 20%.

For each model, coefficient of determination (R^2), root mean square error (*RMSE*), mean bias error (M*BE*) and *t*-statistic, calculated with measured and simulated soil water contents are shown in tab. 4.

Tab. 4 – Statistics of the comparison between measured and simulated soil water contents

As can be observed in tab. 4, R^2 and *RMSE* values for both the considered models are similar, according to the observed agreement between simulated and measured soil water contents. According to the *t-statistic*, SWAP model performs slightly better than FAO 56. Both the models can therefore be considered suitable to predict the dynamic of the average water contents in the soil profile and probably to provide a good approximation of the actual crop evapotranspiration fluxes.

Model scheduling performance analysis

In order to assess the scheduling performance of the models, different scenarios were considered, and compared to the ordinary farmer irrigation strategy. Firstly, the values of *MAD* and *f* were evaluated with eq. (8) and (12), in order to obtain the “ordinary” scheduling parameters for the investigated area. Tab. 5 shows *MAD* and *f* obtained immediately before irrigation for the investigated seasons. The average values, MAD_{av} and f_{av}, were identified as the “ordinary” scheduling parameters for the investigated area.

Tab. 5. Values of MAD and f obtained for each irrigation practiced by the farmer and corresponding average values

Both the models were then runned in order to verify if the assumption of MAD_{av} and f_{av} allowed to reproduce the actual dynamic of soil water contents and evapotranspiration fluxes. Relatively to SWAP model, fig. 6a,b shows, for the two investigated seasons, the comparison between simulated water contents, obtained by considering irrigation scheduled by the model (case A), with those simulated when the ordinary scheduling parameter f_{av} is assumed (case B). On the other side fig. 6c, d shows simulated cumulative evapotranspiration fluxes obtained for both the considered cases.

The analysis shows that SWAP model allows to identify the first irrigation as well as the distribution of water application during both the crop seasons. The actual cumulative evapotranspiration fluxes, showed in fig. 6c,d, obtained in case A are very similar to those estimated by considering the ordinary scheduling parameter (case B).

Fig. 6 a-d. Daily average soil water content and watering distribution simulated by SWAP model in 2005 (a) and 2006 (b) seasons, for irrigation scheduled by the model (case A) or by using ordinary parameters (case B). The cumulated evapotranspiration fluxes (c-d) are shown below

A similar analysis was performed with FAO 56 model. With the aim to take into account the crop water stress condition recognized in the field, the original algorithm of FAO 56 model was modified. In particular in the *MAD* factor, hereafter indicated by the acronym *MAD**, the eco-physiological parameter, p, was separated from the component related to economic management factors. This amendment was carried out in the original spreadsheet suggested in the FAO 56 paper (Annex 8; BOX 8.1: Spreadsheet formulas and corresponding equations for Excel spreadsheet programs), as indicated in Tab. 6.

Tab. 6 – Amendment of the FAO 56 algorithm

Fig. 7a,c shows the soil water contents estimated by the modified FAO 56 model for case A and for case B.

The modified model allows to evaluate three water application in 2005 and four in 2006, distributed within each crop cycle. fig. 7c,d shows the cumulative simulated evapotranspiration fluxes for case A and B.

Fig. 7a-d. Daily average soil water content and watering distribution simulated by FAO 56 modified model in 2005 (a) and 2006 (b) seasons, for irrigation scheduled by the model (Case A) or by using ordinary parameters (Case B). The cumulated evapotranspiration fluxes (c-d) are shown below

Moreover when the scheduling parameters MAD_{av} and f_{av} are considered, the actual cumulative evapotranspiration fluxes estimated by SWAP and modified FAO 56 models are similar. Scientifically higher cumulative *ET* fluxes are obtained if the original FAO 56 model is considered. In the latter case in fact the crop water stress conditions cannot be taken into account and the “full irrigation” management is allowed.

With reference to the analysis of performance of the two models examined, fig. 8a-d shows the relative frequency of stress day as a function of f or MAD, for different values of the irrigation depth.

Fig. 8a-d. Scheduling irrigation scenarios. Values of the number of stress days for different scheduling parameters (MAD and f) and for several irrigation depth

For each model, fig. 8a-d, highlights how the farmer’ irrigation strategy, characterized by 50 mm of water depth and f_{av} and MAD_{av} equal respectively to 50 and 80%, maintained the crop at the water stress condition close to the maximum admissible. The upper limit of stress days relative frequency depends on the soil water status at the vegetation recovery (start model simulation), that is consequent to the previous rainfall regime. In 2006, when limited rainfall characterized by the initial period of the growing season a higher relative frequency of stress days was observed for both the models compared. Furthermore, the relative frequency of stress day estimated by two models for both season resulted in general different, with lower values obtained with SWAP (Fig 8a,b and 8c,d)

The higher relative frequency of stress days, obtained with FAO 56 model, is due to the higher water consumptions at the begin of the simulations, and consequently to the fast reduction of soil water content, determining the occurrence of water stress.

It has to be noticed that for a fixed f or MAD values the relative frequency of stress day increase with decreasing irrigation depth. The higher number of watering consequent to the lower amount in FAO 56 determines in fact higher soil evaporation losses, considered that after irrigation soil surface is wet and the soil evaporation coefficient, K_e, is often close to 1. Despite the different approach to evaluate soil evaporation used by SWAP, the runned simulations showed that the relative frequency of stress days for a fixed f, increase at decreasing of the amount of irrigation depth and consequently at increasing of the number of watering. However, such behaviour cannot be generalized, considered that SWAP model evaluates evaporative losses according to the pressure head gradient between the atmosphere and the first soil layer. For these reasons a high values of hydraulic conductivity and/or root density in the soil surface layer could lead to a different result.

The performed analysis allows a practical application that can help the farmer in scheduling regulated deficit irrigation (RDI) as well as during the day-to-day operations. Under the investigated conditions in fact, after establishing the irrigation depth to apply, the farmer can evaluate the scheduling parameters (MAD or f) according to the relative frequency of stress days he wants to tolerate according to the adopted RDI management.

The real time application of the models, under the examined pedo-climatic conditions, once fixed MAD or f and the irrigation depth, can finally allow the farmer to identify when to proceed with irrigation.

Fig. 9a-d shows, for each considered water depth, the number of irrigations suggested by the two models as function of *f* and *MAD*.

Fig. 9a-d. Scheduling irrigation scenarios. Number of watering for different scheduling parameters (MAD and f) and irrigation depth

For both the considered seasons the number of watering suggested by FAO 56 model is always higher than that obtained by SWAP for a fixed stress conditions. For example in 2005, for a fixed irrigation depth of 40 mm and a relative frequency of stress day equal to 0.30, *f* and *MAD* resulted approximately equal to 30 and 60% (fig. 8a, d) and the numbers of watering equal to 9 and 4 respectively for FAO 56 and SWAP model. A higher number of watering can also be observed in 2006, even if with lower differences between the models. The low differences we think are due at the different initial water content and rainfall distribution during the start simulation period.

In fact, in the season 2006, characterized by a lower amount of precipitation, it is possible to observe that the differences in the number of water applications suggested by the two models are negligible.

The examined models therefore, although characterized by a different modelling of the phenomena, showed a similar behaviour when used for scheduling irrigation under water stress conditions.

Conclusions

The paper shows the comparison between SWAP and FAO 56 agro-hydrological models applied to a vineyard.

Both the models simulated with a satisfactory approximation the measured values of average soil water content in the root zone, with error of estimation equal to about 2.0%. Both the models provided similar results also in terms of estimation actual evapotranspiration fluxes.

The models were then compared in order to verify their suitability for irrigation scheduling. In order to take into account the crop water stress conditions, the original algorithm of FAO 56 model was modified. Firstly the average scheduling parameters, f_{av} and MAD_{av}, for the considered irrigation seasons were determined in order to characterize the “ordinary” irrigation management practised in the area. Then the modified FAO 56 and SWAP outputs (scheduled volumes and irrigation timing) were compared.

Modified FAO 56 simulates reliable values of average soil water content, even if, compared with the SWAP model, a certain overestimation of evapotranspiration fluxes is observed. Moreover for the examined crop, the modified FAO 56 model suggests to anticipate of some days the first irrigation and to supply slightly higher seasonal water volumes compared to the ordinary management.

A performance analysis on different irrigation scenarios was finally implemented. The analysis showed that the models give similar outputs when seasons are characterized by low precipitation amount and therefore soil water content at the begin of growing season is lower.

Despite the models are characterized by a different modelling approach of the phenomena, they showed a similar behaviour when used for scheduling irrigation under soil water deficit conditions.

Acknowledgements

The research was carried out in the frame of PRIN 2008 (Provenzano), co-financed by Ministero dell'Istruzione, dell'Università e della Ricerca (MIUR) and Università degli Studi di Palermo.

Author’s Contribution

The contribution to the paper has to be shared between authors as following indicated.
Field and laboratory data collection was cared by M. Minacapilli and G. Rallo. Contributes to set-up the experiments, data processing and text revision have to be equally divided between authors. Text was written by G. Rallo.

Notation

The following symbols are used in the paper:

APW = Available plant water [mm/m]

$C = (\partial\theta/\partial\psi)$ Differential moisture capacity , [cm^{-1}]

D_e = Cumulative depth of evaporation (depletion) from the soil surface layer [mm]

D = Cumulative depth of evapotranspiration (depletion) from the root zone [mm]

DP = Deep percolation [mm]

e_s = Saturation vapour pressure for a given time period [kPa]

e_a = Actual vapour pressure [kPa]

$e_s - e_a$ = Saturation vapour pressure deficit

ET_o = Reference crop evapotranspiration [mm day^{-1}]

ET_c = Crop evapotranspiration under standard conditions [mm day^{-1}]

f = Timing irrigation factor used in SWAP model

f_{ew} = Fraction of soil that is both exposed and wetted (from which most evaporation occurs) [-]

f_w = Fraction of soil surface wetted by rain or irrigation [-]

G = Soil heat flux [MJ m^{-2} day^{-1}]

H = Maximum crop height, [m]

I = Irrigation depth [mm]

J_{plant} = Number of day of the year at time of planting [-]

J_{dev} = Number of day of the year at beginning of the development period [-]

J_{mid} = Number of day of the year at beginning of midseason period [-]

J_{harv} = Number of day of the year at time of harvest or death [-]

J_{late} = Number of day of the year at beginning of late season period [-]

K_c = Crop coefficient [-]

$K_{c\ max}$ = Maximum value of crop coefficient (following rain or irrigation) [-]

K_{cb} = Basal crop coefficient [-]
$K_{cb\ ini}$ = Basal crop coefficient during the initial growth stage [-]
$K_{cb\ mid}$ = Basal crop coefficient during the mid-season growth stage [-]

$K_{cb\ end}$ = Basal crop coefficient at end of the late season growth stage [-]

K_e = Soil evaporation coefficient [-]

K_r = Soil evaporation reduction coefficient [-]

K_s = Water stress coefficient [-]

$K(\psi)$ = Soil hydraulic conductivity [cm d^{-1}]

LAI = Leaf area index [m^2 (leaf area) m^{-2} (soil surface)]

MAD = Management allowed depletion [mm]

No_{cg} = Crop group number, depending on the level of crop resistance to water stress

P = Rainfall [mm]

p = Evapotranspiration depletion factor [-]

R_n = Net radiation [MJ m^{-2} day^{-1}]

RAW = Readily available soil water in the root zone [mm]

REW = Readily evaporable water (i.e., maximum depth of water that can evaporate from the soil surface layer without restriction) [mm]

RH_{min} = Daily minimum relative humidity [%]

S_a = Root water uptake term [d^{-1}]

T_a = Air temperature [°C]

T_p = Potential transpiration [cm d^{-1}]

TAW = Total available soil water in the root zone [mm]

TEW = Total evaporable water (i.e., maximum depth of water that can evaporate from the soil surface layer) [mm]

U_2 = Wind speed at 2 m above ground surface [m s^{-1}]

Z_e = Depth of surface soil layer subjected to drying by evaporation [cm]

Z_r = Rooting depth [cm]

z= Vertical coordinate [cm]

α_{w} = Reduction factor accounting for water deficit stress

α_p [-] = Regression coefficient [d cm-^{1}]

β_p = Regression coefficient [d cm-^{1}]

γ = Psychrometric constant [kPa °C^{-1}]

Δ = Slope of saturation vapour pressure curve [kPa °C^{-1}]

θ = Volumetric soil water content [cm^3 cm^{-3}]

θ_{fc} = Soil water content at field capacity [m^3 (water) m^{-3} (soil)]

θ_{lim} = Average soil water content below which it is necessary to irrigate [cm^3 cm^{-3}]

θ_{wp} = Soil water content at wilting point [m^3 (water) m^{-3} (soil)]

k_{gr} = Extinction coefficient for global solar radiation [-]

ψ = Soil matric potential [cm]

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Tab. 1 - Soil parameters used in SWAP simulations. α, n and λ are the parameters of the van Genuchten-Mualem equations

	Layers			
Parameters	**I 0-20 cm**	**II 20-40 cm**	**III 40-60 cm**	**IV 60-80 cm**
θ_r	0.030	0.139	0.103	0.119
θ_s	0.400	0.444	0.400	0.410
K_s	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

Table 2
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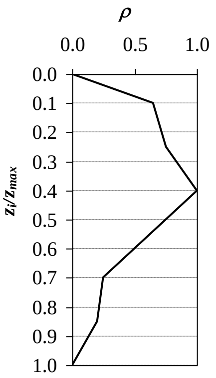
Tab. 2 -Variables used for SWAP model simulations

<table>
<tr><th colspan="2">Variables</th><th>Value</th></tr>
<tr><td colspan="2">Length of the crop cycle [d]</td><td>153</td></tr>
<tr><td colspan="2">Extinction coeff. for diffuse visible light, κ_{df} [-]</td><td>0.45</td></tr>
<tr><td colspan="2">Extinction coeff. For direct visible light, κ_{dir} [-]</td><td>1.0</td></tr>
<tr><td colspan="2">Minimum canopy resistance [s/m]</td><td>70.0</td></tr>
<tr><td colspan="2">Precipitation interception coefficient</td><td>0.25</td></tr>
<tr><td rowspan="5">Critical soil water pressure head [cm.c.a] (Taylor e Ashcroft, 1972)</td><td>ψ_{sat}.:</td><td>-10</td></tr>
<tr><td>ψ_{fc}:</td><td>-25</td></tr>
<tr><td>ψ_{p_high}:</td><td>-750</td></tr>
<tr><td>ψ_{p_low}:</td><td>-1000</td></tr>
<tr><td>ψ_{wp}:</td><td>-10000</td></tr>
<tr><td colspan="2">Threshold level high atm. demand [cm]</td><td>0.5</td></tr>
<tr><td colspan="2">Threshold level low atm. demand [cm]</td><td>0.2</td></tr>
<tr><td colspan="2">Crop Factor Bare Soil, K_{soil}</td><td>1</td></tr>
<tr><td colspan="2">Max. rooting depth [cm], Z_r</td><td>100</td></tr>
<tr><td colspan="2">Root density, ρ</td><td>
</td></tr>
<tr><td colspan="2">Leaf Area Index, <i>LAI</i>
Crop coefficient, <i>Kc</i></td><td><table>
<tr><th>DVS*</th><th>LAI</th><th>Kc</th></tr>
<tr><td>0.00</td><td>0.5</td><td>0.50</td></tr>
<tr><td>0.65</td><td>2.0</td><td>0.75</td></tr>
<tr><td>1.88</td><td>2.0</td><td>0.75</td></tr>
<tr><td>2.00</td><td>2.0</td><td>0.63</td></tr>
</table></td></tr>
<tr><td colspan="2">Irrigation Timing, <i>f</i></td><td>0,48</td></tr>
</table>

**DVS, Development Stage, is 0 or 2 when the crop stands in the initial or end cycle respectively*

Table 3
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Tab. 3 –Variables used for FAO 56 model simulations. Value between brackets are assumed for the 2006 season

Variables		**Value**
θ_{fc} [cm^3/cm^3]		0.32
θ_{wp} [cm^3/cm^3]		0.13
APW [mm/m]		187.6
TEW [mm]		32.2
REW [mm]		9
f_w		0.53
Development stage [J]	J_{plant}	105 (116)
	J_{dev}	110 (120)
	J_{mid}	160 (162)
	J_{late}	247 (249)
	J_{harv}	258 (258)
Basal crop coefficients	$K_{cb\ ini}$	0,15
	$K_{cb\ mid}$	0,65
	$K_{cb\ end}$	0,40
Maximum crop height, *H* [m]		1.5
Minimum rooting depth [cm]		80.0
Midseason, Average, Wind Speed [m/s]		1.1 (1.2)
Midseason, Average, RH_{min} [%]		47.7 (55.9)
Management Allowed Depletion, *MAD*		0.83

Tab. 4 – Statistics of the comparison between measured and simulated soil water contents

Statistic	**SWAP**	**FAO 56**
R^2	0.69	0.74
RMSE **[% vol.]**	2.09	2.14
MBE **[% vol.]**	-0.41	-0.83
t **value**	1.04	2.18
$t_{crit}(\alpha=0.05)$	2.05	2.05

Tab. 5. Values of MAD and f obtained for each irrigation practiced by the farmer and corresponding average values

Irrigation	**Date**	**DOY**	***MAD***	***f***
1	03-08-05	215	0.90	0.48
2	16-08-05	228	0.72	0.34
3	02-07-06	183	0.92	0.50
4	29-07-06	207	0.79	0.47
5	31-08-06	243	0.85	0.59
	average		**0.83**	**0.48**

Table 6
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Tab. 6 – Amendment of the FAO 56 algorithm

Cell	**Original Algorithm Test, Value or Formula**	**Modified Algorithm Test, Value or Formula**
AE2	empty	Nocg
AF2	empty	value
AO2	empty	MAD*
AP2	empty	value
AH3	MAD during Initial Stage	empty
AK3	value	empty
AH4	MAD after Initial Stage	empty
AK4	value	empty
AM13	empty	Depletion fraction, p
AM14	empty	=((1/(0,76+(1,5*H14/10)))-(0,1*(5-AF2)))*100
AF14	=MAX(IF(D14<Q$4;AK$3;AK$4)/100*AE14*$AF$5;AF13)	=AM14/100*AF5*AF3
AH14	=IF(D14>=Q$3;IF(D14<(Q$6+Q$7)/2;IF(AG14>AF14;AG14;0);0);0)	=IF(D14>=Q$3;IF(D14<(Q$6+Q$7)/2;IF(AG14>$AP$2;AG14;0);0);0)

Figure 1

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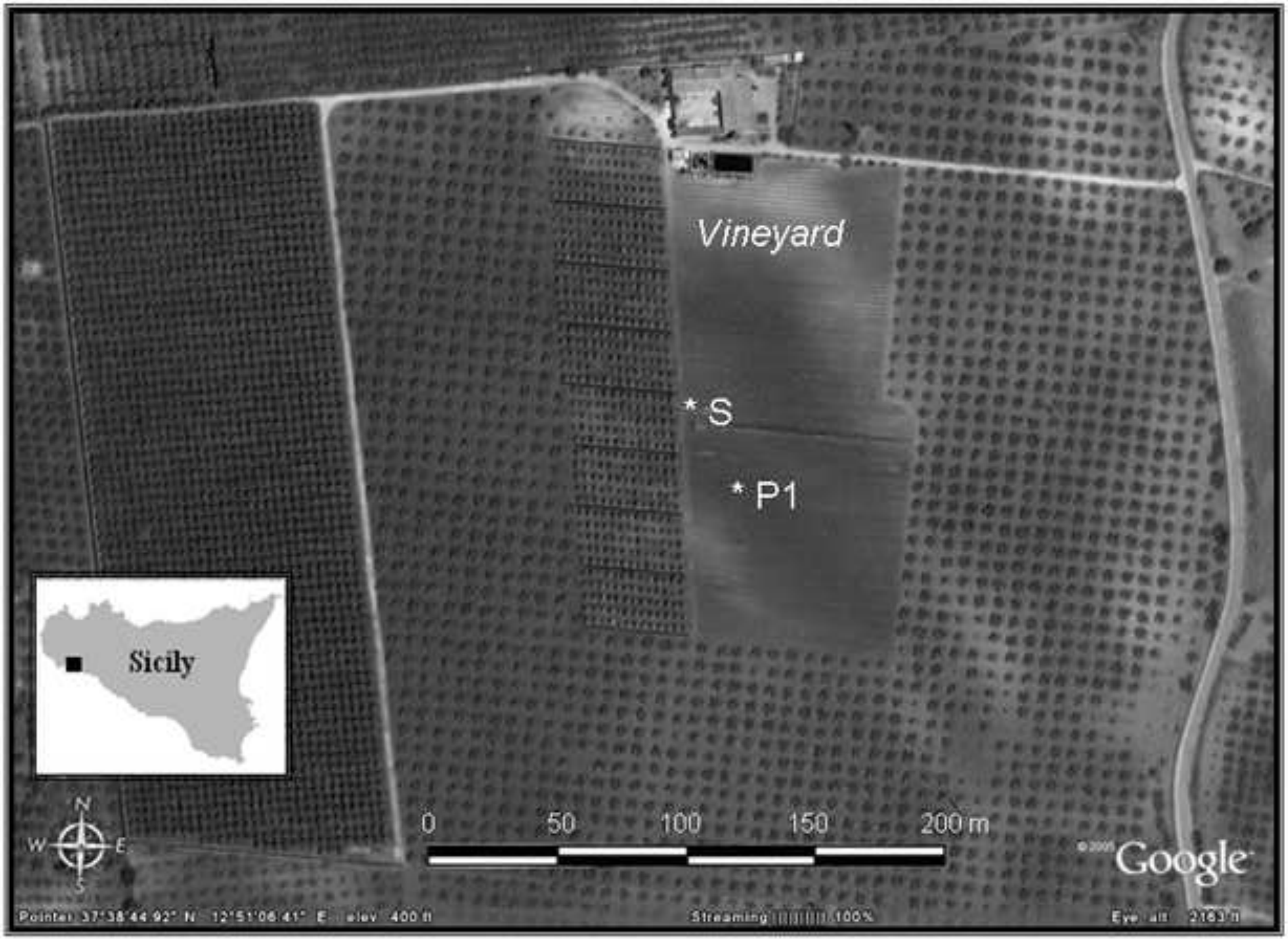

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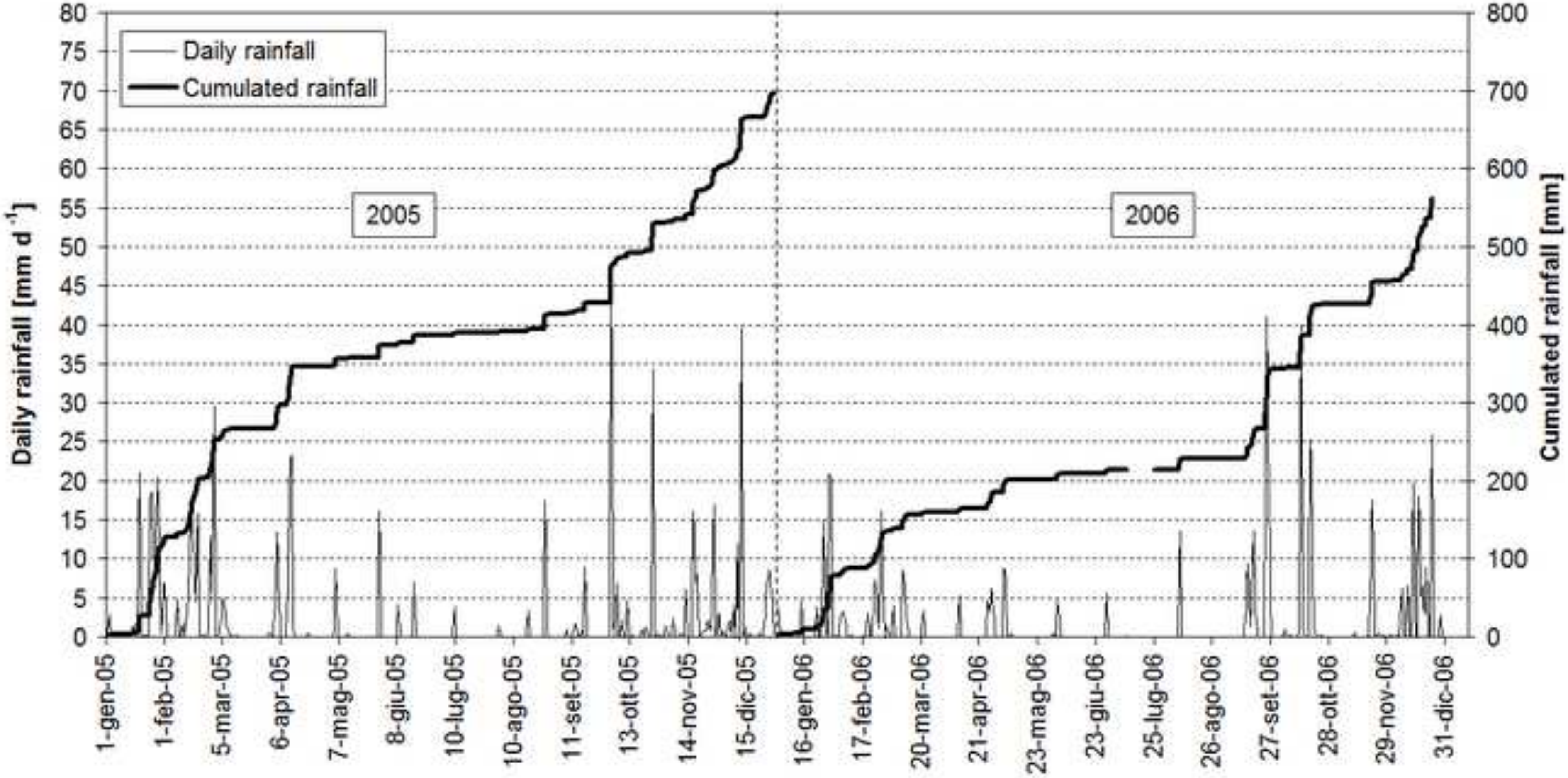

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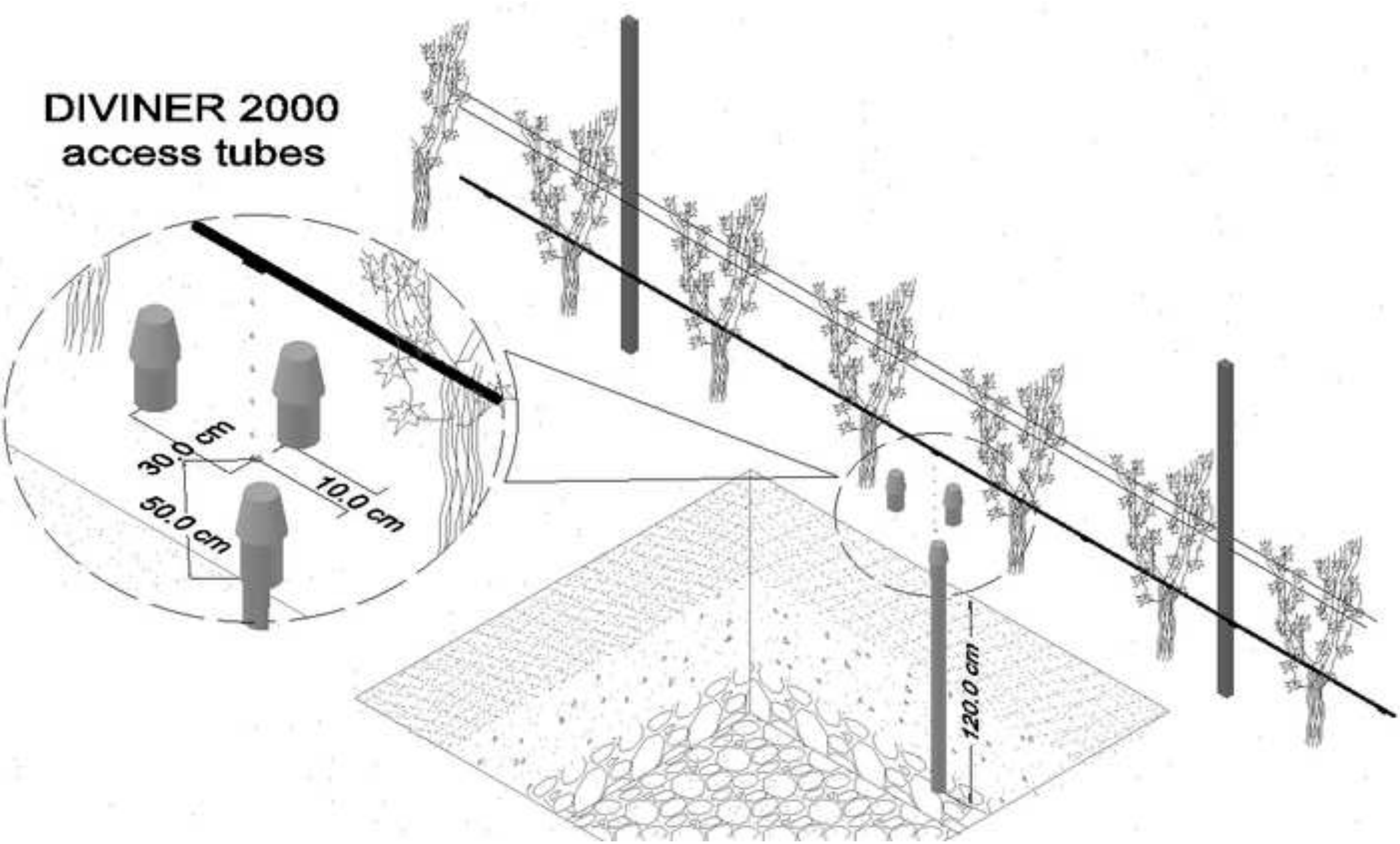

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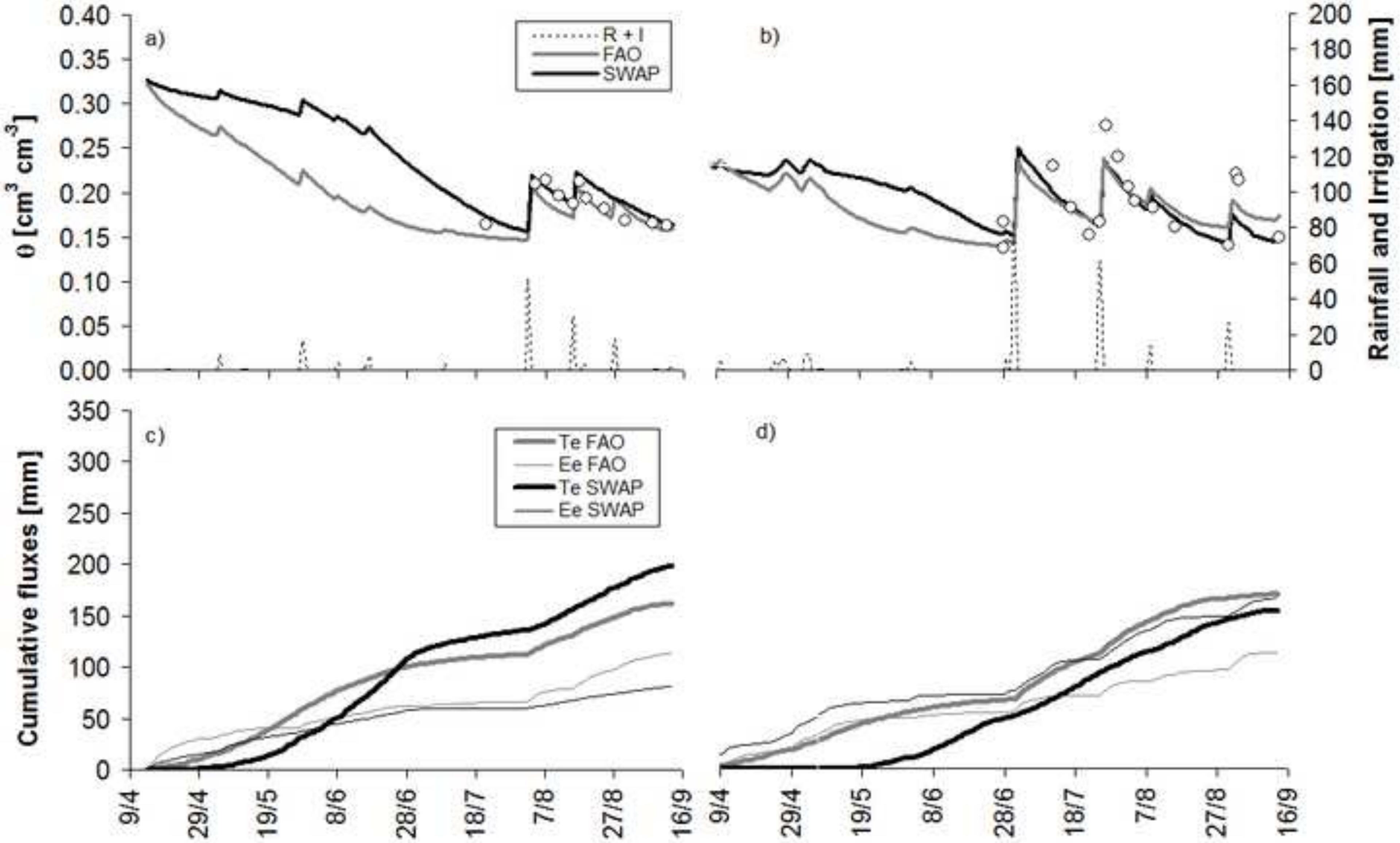

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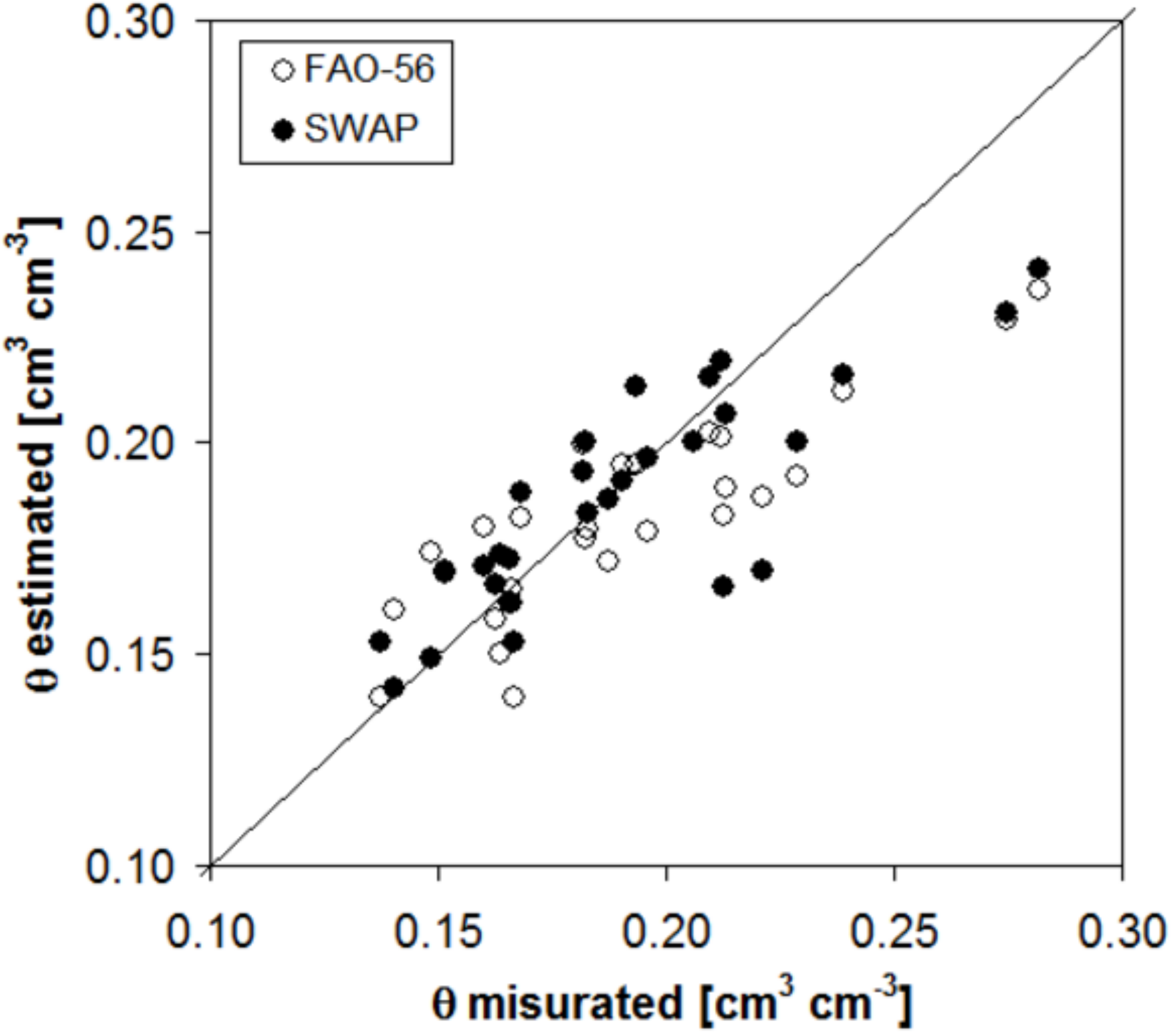

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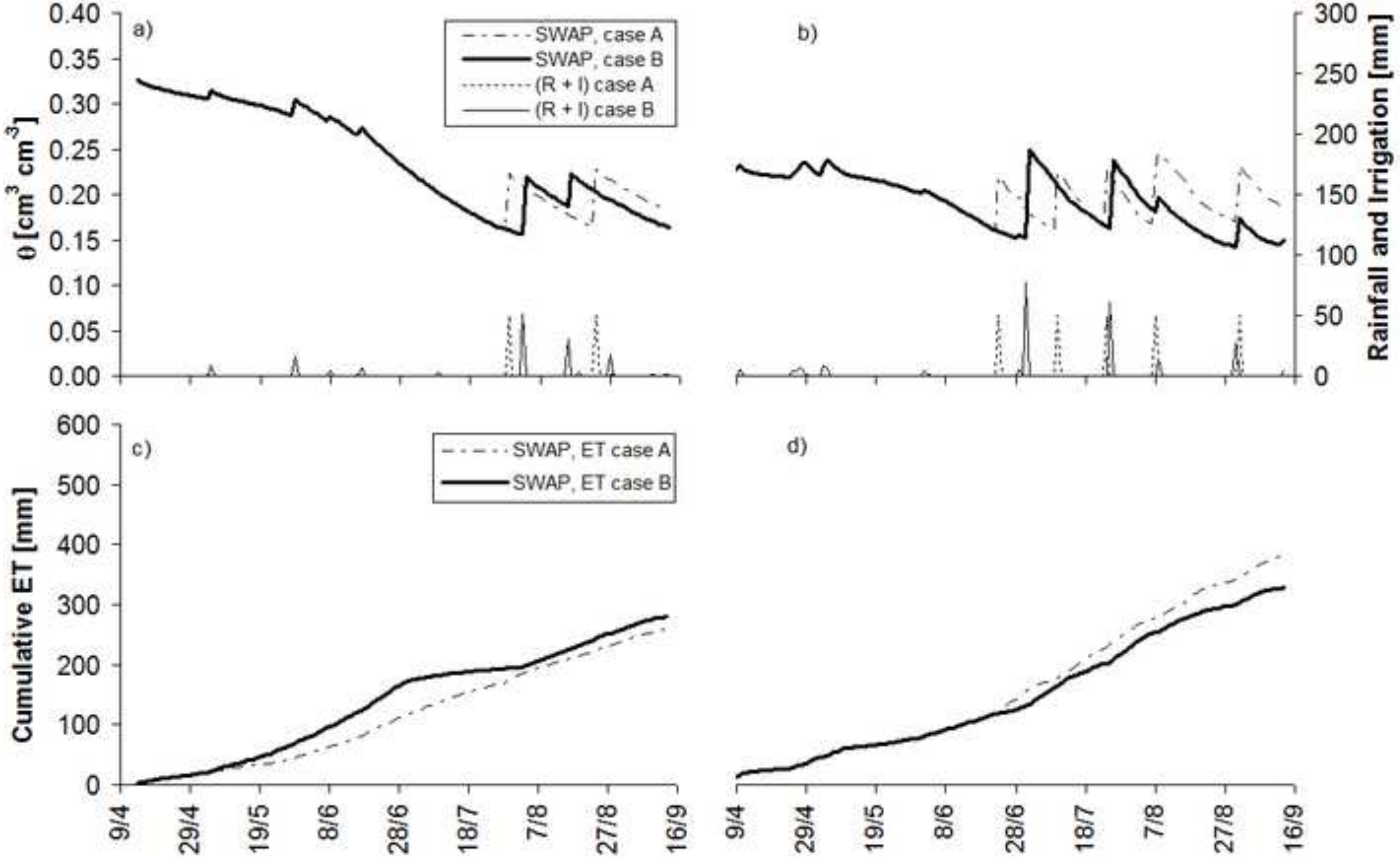

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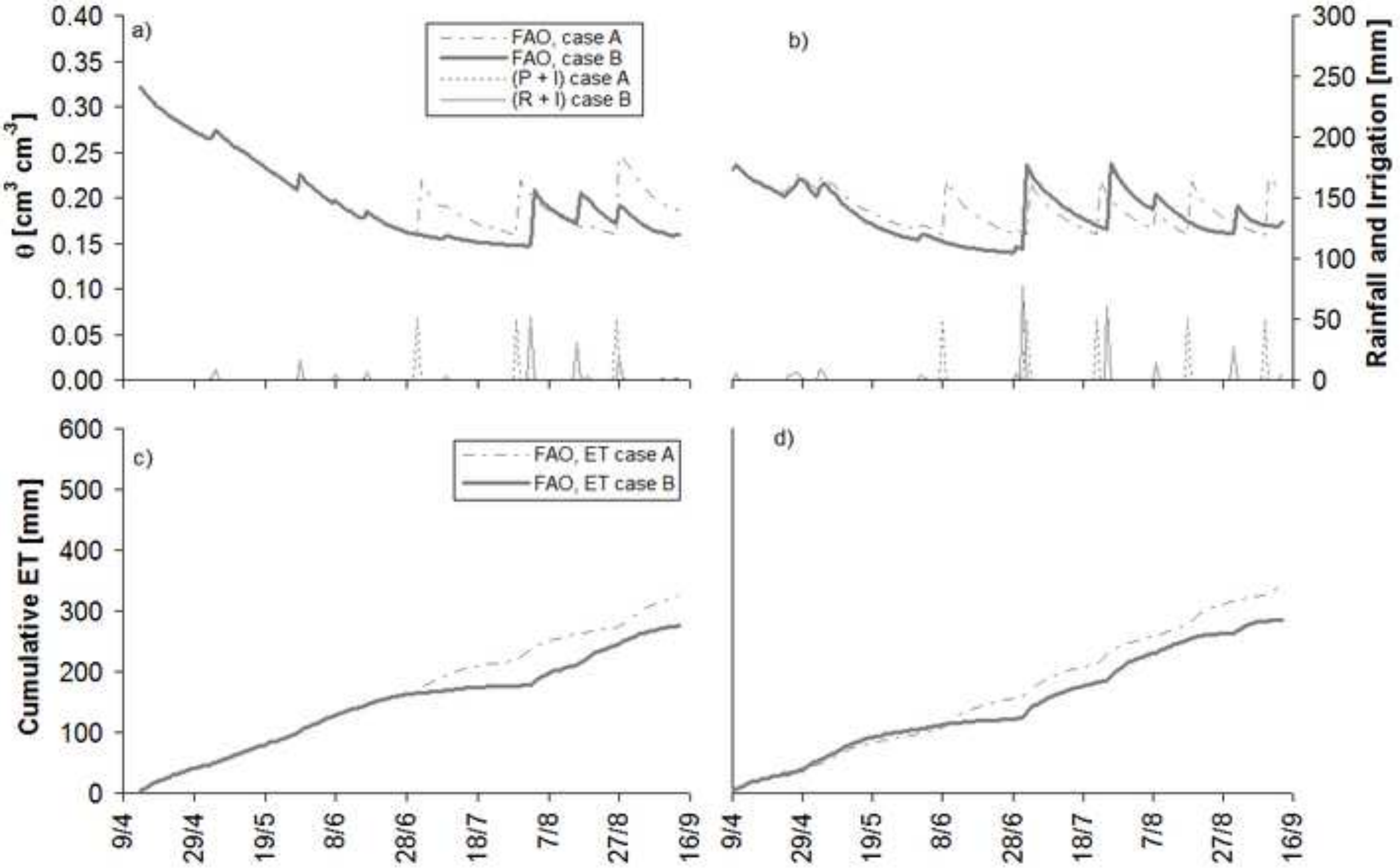

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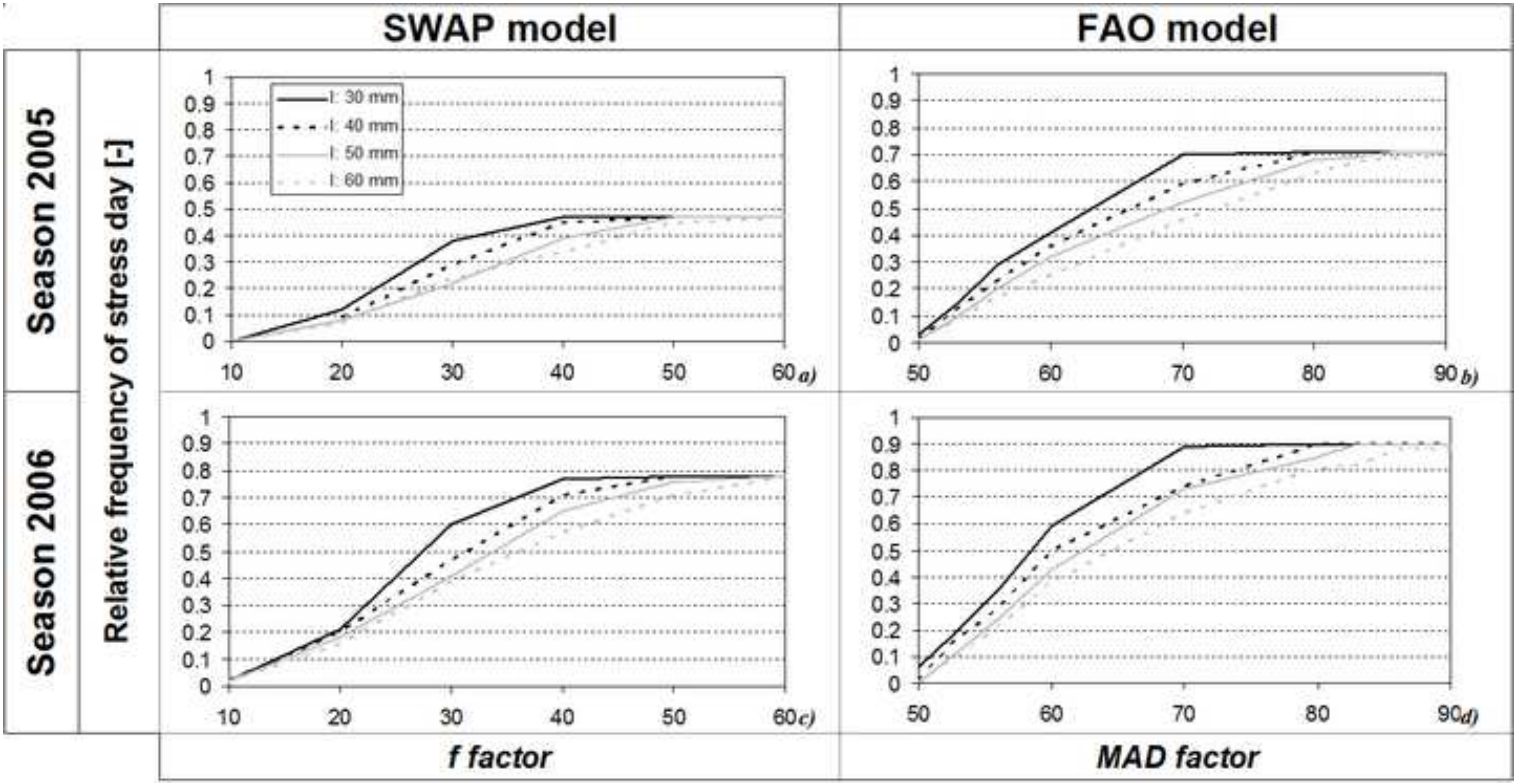

Figure 9

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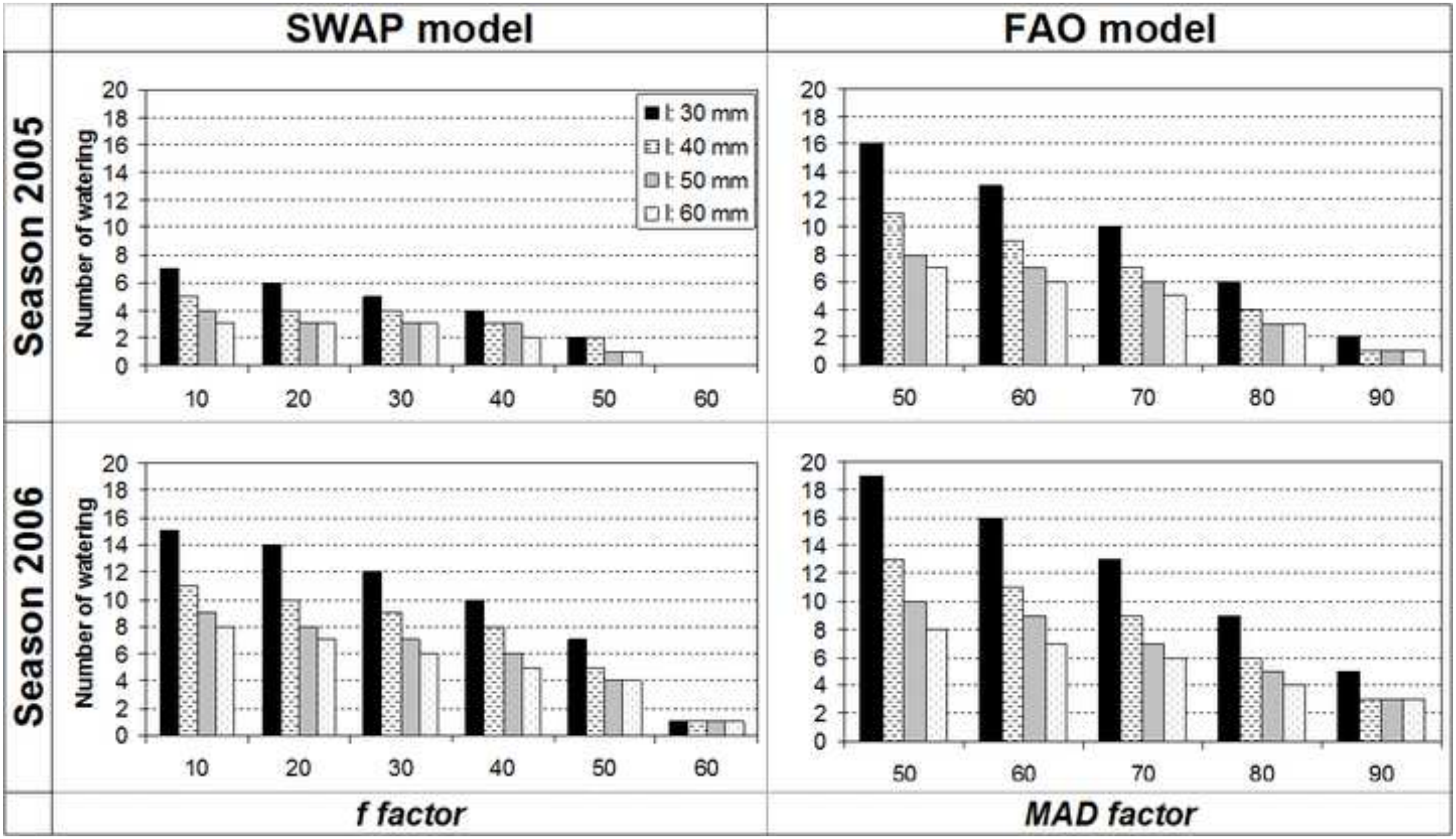

Figure Caption List

Fig. 1 - Geographic location and Google earth image of test area. The description of landuse and the position of instruments is showed. S: agrometeorological station; P1: soil moisture measurement

Fig. 2 – Daily and cumulate rainfall data collected during 2005 and 2006 years

Fig. 3 – Position of the Diviner access tubes. Distances are measured from the point of falling water drops

Fig. 4a-d. – Comparison between daily average soil water content simulated by the models for the 2005 (a) and 2006 (b) seasons with the measured values (white circles); cumulative soil evaporation and tree transpiration fluxes are showed below (c-d)

Fig. 5 – Estimated soil water content vs. measured values

Fig. 6 a-d. Daily average soil water content and watering distribution simulated by SWAP model in 2005 (a) and 2006 (b) seasons, for irrigation scheduled by the model (case A) or by using ordinary parameters (case B). The cumulated evapotranspiration fluxes (c-d) are shown below

Fig. 7a-d. Daily average soil water content and watering distribution simulated by FAO 56 modified model in 2005 (a) and 2006 (b) seasons, for irrigation scheduled by the model (Case A) or by using ordinary parameters (Case B). The cumulated evapotranspiration fluxes (c-d) are shown below

Fig. 8a-d. Scheduling irrigation scenarios. Values of the number of stress days for different scheduling parameters (MAD and f) and for several irrigation depth

Fig. 9a-d. Scheduling irrigation scenarios. Number of watering for different scheduling parameters (MAD and f) and irrigation depth