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ASSESSING THE SIMDualKc MODEL FOR IRRIGATION SCHEDULING SIMULATION IN MEDITERRANEAN ENVIRONMENTS

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SUMMARY - Proper irrigation programming and irrigation scheduling require the availability of accurate, quick and easy to use tools. The SIMDualKc software application was developed with this purpose to compute crop evapotranspiration and irrigation scheduling using the dual crop coefficient approach (K_{cb} + K_e). SIMDualKc performs the soil water balance at field level, using a daily time step. This model was validated using data from several experimental fields in various Mediterranean countries: the Sorraia irrigation district, Portugal for a maize crop; the Catania plain irrigation district, Sicily, Italy, with a citrus crop; the Tel Hadya research station, Aleppo, Syria, for a wheat crop; and the Hendi Zitoun experimental station, Central Tunisia, with a winter wheat crop. In addition, the model was validated and calibrated for cotton and winter wheat in Uzbekistan, Central Asia. The validation was performed with crop, soil water field and meteorological data collected in those experimental fields by comparing the observed and simulated soil water content values using a regression through the origin. Results show a good agreement for all studied cases, which indicates that the model adequately predicts soil moisture during the growing season; particularly good results refer to the initial stages of crop development. It could be concluded that crop evapotranspiration was properly estimated. The good results obtained for the Mediterranean conditions, along with the good predictions relative to Central Asia, allow a wide-broad application of the SIMDualKc model to predict crop evapotranspiration and irrigation requirements for planning and environmental studies, as well as to support farmers' advice.

Key words: crop evapotranspiration, dual crop coefficients, irrigation scheduling, soil water balance, simulation models.

RÉSUMÉ *- La programmation et le pilotage des irrigations exige la disponibilité d' outils précis et faciles à utiliser. Le logiciel SIMDualKc a été développé avec ce but pour calculer l'évapotranspiration des cultures et appuyer la planification et le pilotage de l'irrigation en utilisant l'approche des coefficients culturaux de base (*K_{cb} *+* K_e*). Le modèle SIMDualKc exécute le bilan hydrique du sol à l'échelle de la parcelle avec un pas de temps journalier. Ce modèle a été validé en utilisant des données de divers champs expérimentaux dans différents pays méditerranéens: le périmètre irriguée du Sorraia, Portugal, avec la culture du maïs; le périmètre irriguée de Catane, Sicile, Italie, avec la culture de l'orangier; le centre de recherche de Tel Hadya, Aleppo, Syrie, avec la culture du blé ; et la station expérimentale de Hendi Zitoun en Tunisie centrale avec la culture du blé d'hiver. En plus, le modèle a été validé et calibré pour le coton et le blé en Uzbequistan, Asie Centrale. La validation a été effectuée avec des données de terrain et météorologiques observées aux parcelles expérimentales mentionnées en comparant les valeurs observées et simulées de la teneur en eau du sol par une régression forcée à l'origine. Pour tous les cas étudiés, les résultats montrent une bonne concordance ce qui indique que le modèle prévoit correctement l'évolution de l'humidité de sol pendant toute la saison, avec des résultats particulièrement bons pendant les étapes initiales du développement des cultures. On conclut que l'évapotranspiration des cultures est correctement estimée. Les bons résultats obtenus pour les conditions méditerranéennes et de l'Asie Centrale permettent une ample application du modèle SIMDualKc pour prévoir la évapotranspiration et les besoins d'irrigation des cultures tant pour la planification et des études environnementales que pour le conseil aux irrigants.*

Mots-clés*: Évapotranspiration cultural, coefficients culturaux de base, programmation de l'irrigation, bilan hydrique du sol, modèles de simulation.*

INTRODUCTION

Proper irrigation programming and irrigation scheduling require the availability of accurate, quick and easy to use tools. The SIMDualKc software application was developed with this purpose to compute crop evapotranspiration (ET_c) and irrigation scheduling using the dual crop coefficient approach (Allen *et al.*, 1998, 2005a). This approach considers separately the soil evaporation and the transpiration components of evapotranspiration, thus to analyse how water from precipitation and irrigation events is used by the crop. Computing crop evapotranspiration (ET_c) using the time averaged crop coefficients (K_c) approach provides satisfactory results for various time step calculation, including for daily ET_c estimation with appropriate accuracy for most applications (Pereira, 2004). However, for high frequency irrigations and for partial cover crops, as well as in regions with frequent rainfall, adopting the dual K_c approach may produce more accurate ET_c estimates (Allen *et al.*, 2005b). In fact partitioning the K_c into the soil evaporation coefficient (K_e) and the basal crop coefficient (K_{cb}), it is possible to better follow the impacts of wetting the soil by the rain or irrigation, as well as the impacts of keeping part of the soil dry, or using mulches for controlling soil evaporation (E).

The first applications of the dual K_c methodology as proposed by Allen *et al.* (1998) are reported by Allen (2000), applied to cotton and other crops in a study developed in Turkey for comparing several approaches to estimate ET_c, and by Liu and Pereira (2000), applied to the crop sequence winter wheat-summer maize in the North China Plain. Other successful applications to cotton, which is a partial cover crop, are reported by Howell *et al.* (2004) who not only confirm the accuracy of the approach but also its usefulness when comparing full-, deficit-irrigated and rainfed ET_c since the methodology allows partitioning ET_c into the soil evaporation and the transpiration components. The accuracy of estimates for full cover crops is recently reported by Er-Raki *et al.* (2007) for wheat in a Mediterranean environment, in Morocco. Among studies referring to the appropriate use of the approach for orchards, typically partial cover crops, are reported by Goodwin *et al.* (2006) and Paço *et al.* (2006). These studies confirm the interest in having a reliable tool that allows an easy adoption of the dual K_c methodology.

The main aim of SIMDualKc is to develop irrigation scheduling options, mainly focusing partial cover crops, including vegetables and orchard crops, and high frequency irrigation such as with microirrigation. In addition, it intends to better simulate supplemental irrigation, i.e. the conjunctive use of rainfall and irrigation water. This paper presents the model and its validation for several crops, partial and full cover crops, relative to various irrigation methods, including surface, sprinkler and microirrigation, using field data collected in various regions in the Mediterranean region and in Central Asia.

MODEL DESCRIPTION

Model structure

This application was developed in Visual Basic 6.0 and includes a database in Access 2000, in order to provide a user-friendly environment and to enable an easy visualization of the results. The SIMDualKc model was developed using a three tiers architecture approach including the following components (Fig. 1): a graphic user interface (GUI), a mathematical model and a database (Rolim *et al.*, 2006).

The GUI was developed to be user-friendly, taking into account the user requirements. The database stores information about the soil, crop, climate, irrigation systems and simulation data, which is a specific combination of the previous factors representing the field to simulate. The computational module was developed in such a manner that allows to be easily integrated in the WINISAREG (Teixeira and Pereira, 1992; Pereira *et al.*, 2003) and in the GISAREG (Fortes *et al.*, 2005) models for extending them to adopt the dual K_c approach, or to operate alone using the GUI interface (Fig. 2). This feature was achieved using two abstract interfaces: one that links the computational module with the GUI or with the selected model; the other to perform the connection between the database and the program (numerical modules) through queries that enable to adapt different databases to the data structure of SIMDualKc (Fig. 2).

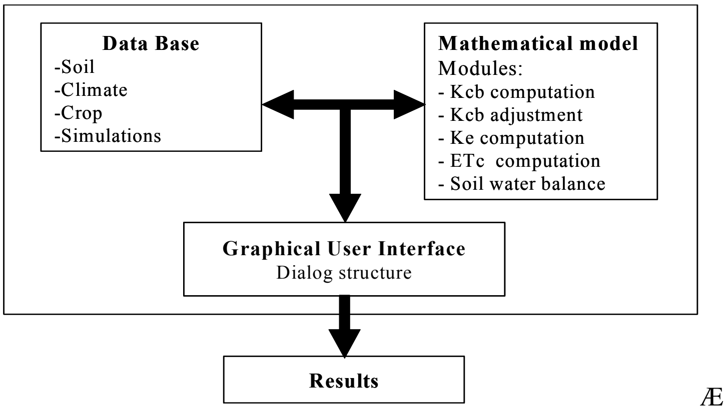

Fig. 1. Conceptual structure of SIMDualKc model.

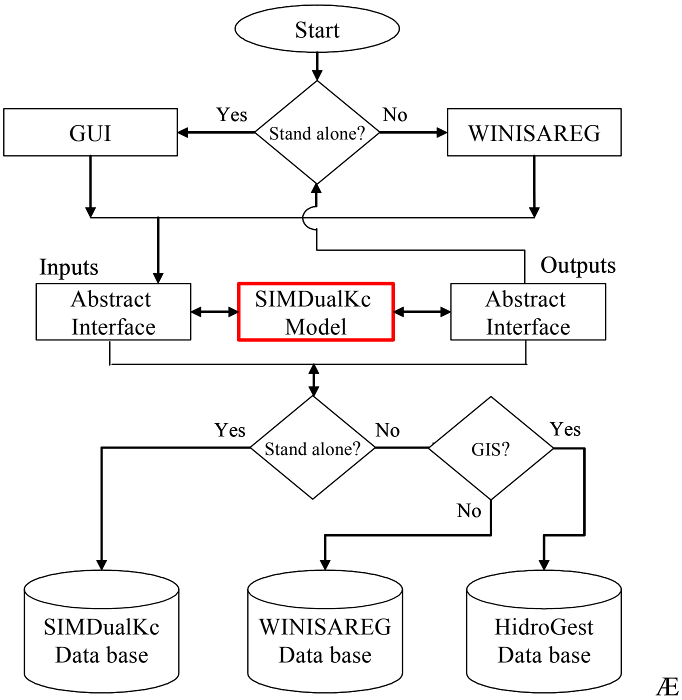

Fig. 2. SIMDualKc flowchart referring to the options of using the model alone or integrating it with the model WINISAREG.

The structure of this model, clearly separating the algorithm's procedures of the database, makes easier the connection of this application to different databases, including georeferenced databases (GIS) such as HidroGest (Mateus *et al.*, 2005), enabling the prediction of crop evapotranspiration at the irrigation project level as proposed by Allen *et al.* (2005b). It intends to incorporate the most accurate and suitable methodology as described by Allen *et al.* (1998, 2005a) to support farmer's advice in their decisions relative to crop irrigation scheduling.

Dual K_c Methodology

The methodology adopted to compute ETc follows the dual K_c approaches proposed by Allen *et al.* (1998; 2005a) which is defined by:

$$ET_c = (K_{cb} + K_e) ET_o \qquad (1)$$

where: ET_c is crop evapotranspiration [mm d^{-1}], K_{cb} is the basal crop coefficient [], K_e is the soil evaporation coefficient [], and ET_o is the reference crop evapotranspiration [mm d^{-1}]. The dual crop coefficient calculation is conducted on a daily basis and the procedure used to compute ET_c follows that proposed by (Allen *et al.*, 1998; 2005a). This procedure and the simulation of the soil water balance producing a season irrigation schedule consists of Figure 3:

1. The acquisition and gathering of the soil, climate, crop and irrigation system data. Climate data includes the estimation of ET_o, and crop data includes the identification of the locally adjusted lengths of the four crop growth stages, and the selection of the corresponding tabled K_{cb} coefficients (e.g. the K_{cb} tabled by Allen *et al.*, 1998);

2. Adjusting of the selected tabled K_{cb} to local climatic conditions and respective calculation for each day of the growing period according to the crop grow stage;

3. The calculation of daily K_e values, to estimate soil evaporation (E), uses the methodology updated by Allen *et al.* (2005a), including the estimation of soil cover (f_c), soil wetted (f_w), soil wetted and exposed fractions (f_{ew}), and the determination of evaporation reduction coefficient (K_r) and water stress coefficient (K_s);

4. The calculation of the daily ET_c (Eq. 1) with the "actual" crop coefficient ($K_{c\ act}$), and daily soil water depletion.

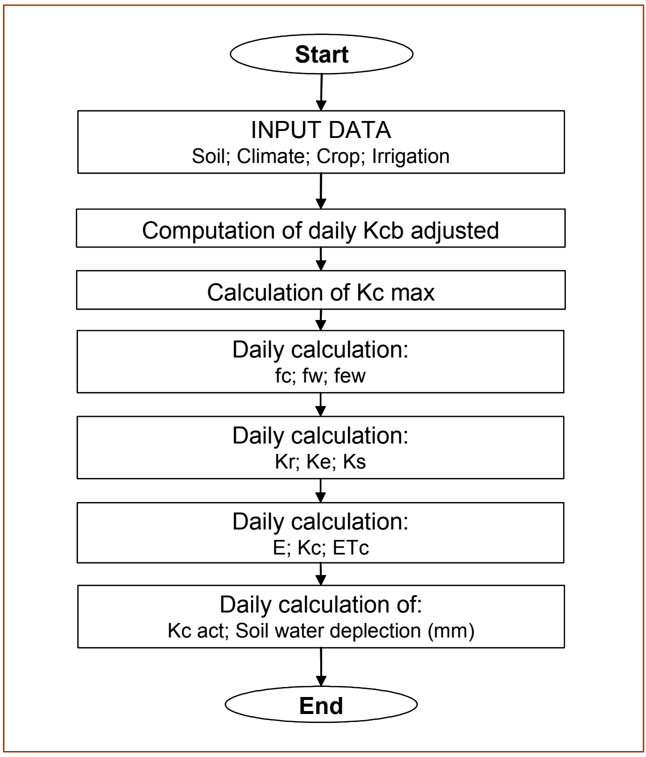

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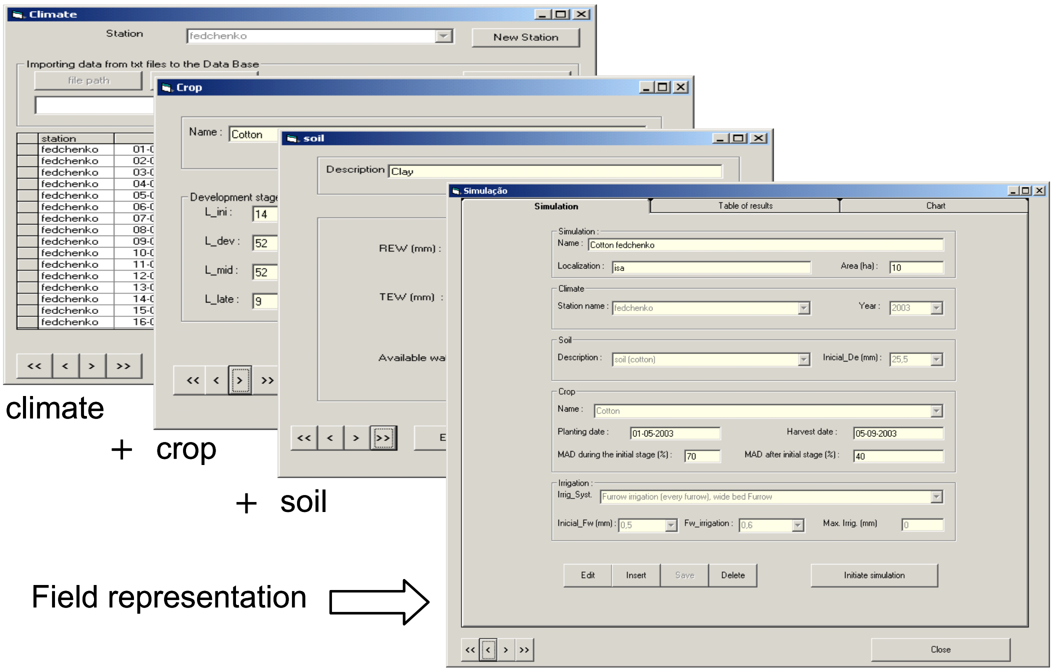
Fig. 3. Core Algorithm of SIMDualKc .

Model operation

Input data is inserted at run-time by the keyboard and through the MSaccess database (Fig. 4) and refers to:

- Meteorological data concerning minimum and maximum temperature, T_{min} and T_{max} [ºC]; wind speed , u_2 [m s^{-1}]; reference evapotranspiration, ET_o [mm]; and effective precipitation, P_e [mm];
- Crop data referring to the planting date, lengths of the crop development stages, L [days], tabled (or observed) basal crop coefficients (K_{cb}); maximum and minimum root depths Z_r [m]; plant height [m], fraction wetted by the irrigation, f_w, fraction of soil cover, f_c, fraction of soil wetted and exposed to solar radiation, few, soil water depletion fractions for no-stress (p);

- Soil data relative to, depth of the evaporation layer, d [mm], readily evaporable water, REW [mm]; total evaporable water, TEW [mm]; and total available water, TAW [mm m^{-1}].



Climate – Station: fedchenko

Crop – Name: Cotton; Development stage: L_ini: 14; L_dev: 52; L_mid: 52; L_late: 9

soil – Description: Clay; REW (mm):; TEW (mm):

Simulação – Simulation: Name: Cotton fedchenko; Localization: isa; Area (ha): 10

Climate: Station name: fedchenko; Year: 2003

Soil: Description: soil (cotton); Inicial_De (mm): 25,5

Crop: Name: Cotton; Planting date: 01-05-2003; Harvest date: 05-09-2003; MAD during the initial stage (%): 70; MAD after initial stage (%): 40

Irrigation: Irrig_Syst. Furrow irrigation (every furrow), wide bed Furrow; Inicial_Fw (mm): 0,5; Fw_irrigation: 0,6; Max. Irrig. (mm) 0

Fig. 4. Model input data windows referring to climate, crop, soil and field representation.

First, the user must enter the data relative to the soil and the crop. This information is stored in the database to be used in future simulations. The second step is to import the climatic data of the local region, with a daily time step, together with the description of the climatic station. When importing data the user can choose between importing ET_o along with other climatic variables, or to compute ET_o daily values using the SIMDualKc. After, the user creates a simulation file combining soil, climate (climatic station and data series) and crop with a given irrigation system, thus creating a field representation in the simulation window. Simulation results are shown in a table and in a graphic showing the seasonal soil water balance, as shown in Fig. 5 for cotton in Fergana. The results can be exported to a text file or to a spreadsheet.

MODEL VALIDATION

This model was validated using data from several experimental fields in various Mediterranean countries: the Sorraia irrigation district, Portugal, with surface irrigated maize crop under full and deficit irrigation (Fernando, 1993); the Catania plain irrigation district, Sicily, Italy, with citrus crop with microirrigation (Alba *et al.*, 2003); the Tel Hadya research station, Aleppo, Syria, with sprinkler irrigated wheat crop (Oweis *et al.*, 2003); and Hendi Zitoun, central Tunisia, with furrow irrigated winter wheat, (Zairi *et al.*, 2003). In addition, the model has been validated and calibrated for cotton and winter wheat in Central Asia (Uzbekistan) under various irrigation management practices with furrow irrigation. The validation was performed with soil, crop and meteorological data collected during the full irrigation seasons in those experimental plots. Soil data include basic soil hydraulic properties and soil water content observed at different depths along the crop seasons; crop data refers to the crop growth stage dates, crop cover parameters and root depths from planting to harvesting. Meteorological data from the nearest weather station were used for evapotranspiration computations using the FAO Penman-Monteith method (Allen *et al.*, 1998) and to estimate the effective precipitation.

The validations were conducted for different irrigation strategies representing several water demand scenarios, and for different levels of climatic demand. The validation was performed comparing the observed and simulated available soil water or the soil water content values using a regression forced to the origin.

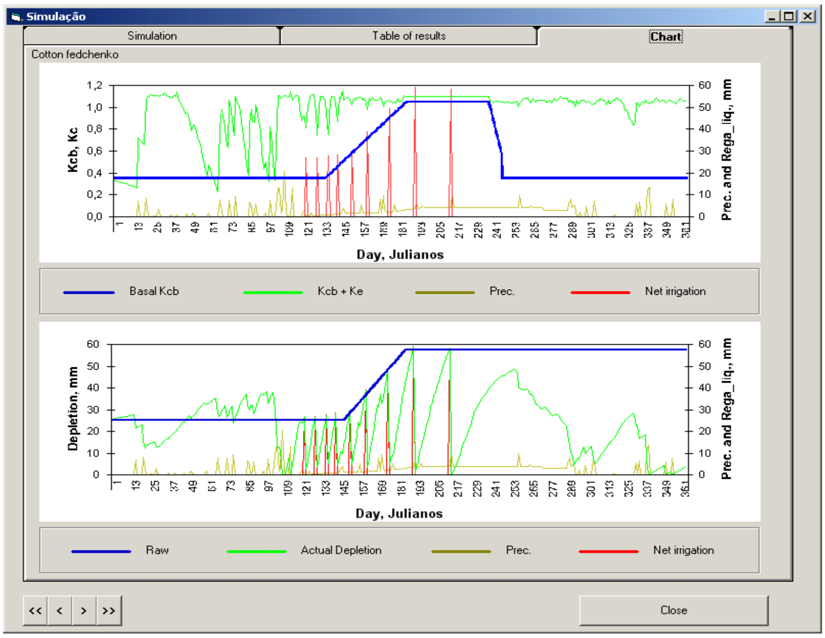


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Fig. 5. Model output window showing the K_c and soil water depletion curves.

Mediterranean basin

The irrigation scheduling data used for the simulations are given in *Table 1*.

Table 1. Irrigation dates and depths (mm) relative to the validation trials.

Irrigation events					
Trials*	day	Irrig. depth (mm)	Trials*	day	Irrig. depth (mm)
a) maize	21-07-1989	80	e) wheat	06-04-1994	40
	08-08-1989	80		20-04-1994	40
	29-08-1989	54	f) citrus	02-06-1998	20
b) maize	25-07-1989	100		19-06-1998	5
	22-08-1989	54		26-06-1998	47
c) wheat	23-11-1992	30		15-07-1998	47
	17-02-1993	40		18-07-1998	50
	05-03-1993	40		09-08-1998	80
	12-04-1993	40		19-08-1998	67
	18-04-1993	40		29-08-1998	70
	28-04-1993	40		14-10-1998	14
d) wheat	09-04-1992	40		10-11-1998	19
	30-04-1992	40			

* a) and b): Fernando, 1993; c): Zairi *et al.*, 2003; d) and e): Oweis *et al.*, 2003; f): Alba *et al.*, 2003.

Results from comparing the simulated and the observed available soil water (ASW, mm) for maize in Coruche, Portugal, are presented in Fig. 6. One trial is for fully irrigated maize (3 basin irrigation events) and the other for deficit irrigation (2 irrigation events). Both show a regression coefficient close to 1.0 and determination coefficients of 0.90 and 0.85 respectively. Values observed cover a large range of ASW values.

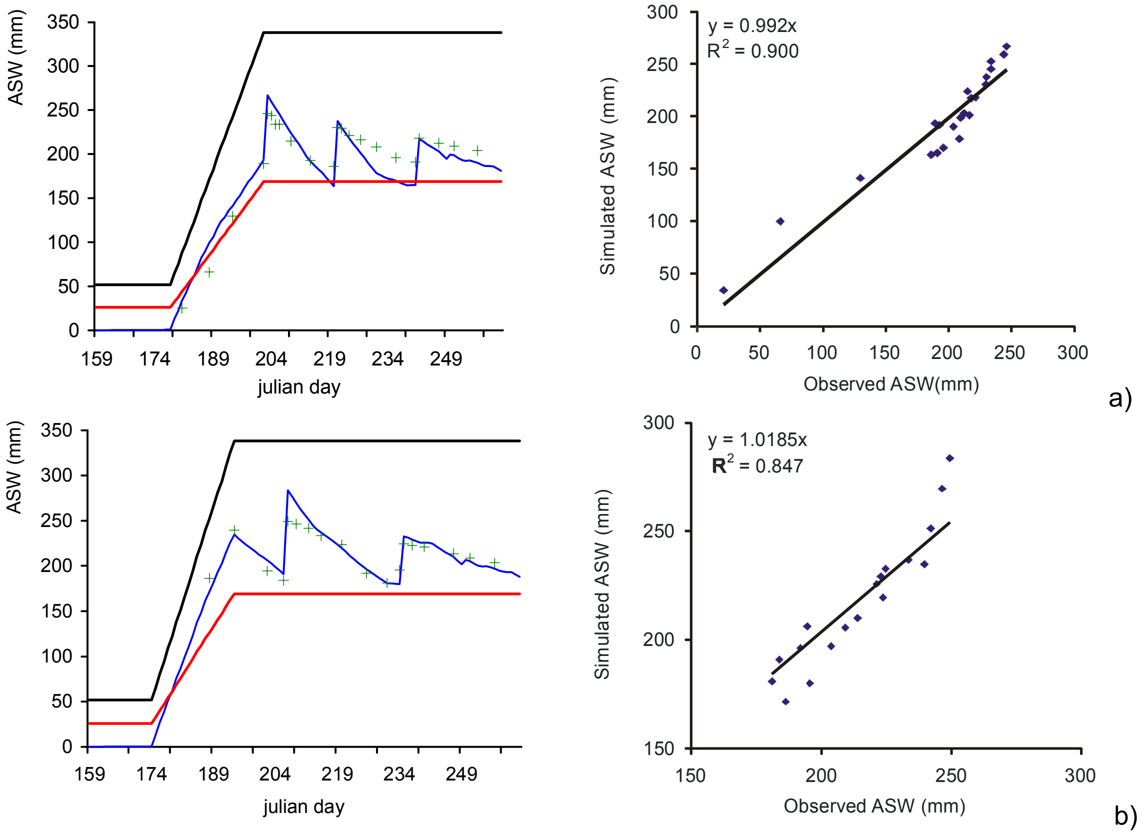

Fig. 6. Comparison between observed and simulated available soil water (ASW) for maize in Coruche Portugal: on the left, the simulated ASW curves and observed values (+) - lines represent TAW and the threshold ASW for no stress -; on the right, the regressions between simulated and observed values for two experiments (a) with 3 and (b) with 2 irrigation events.

Results for the SIMDualKc validation for furrow irrigated winter wheat in the experimental station of Hendi Zitoun, Central Tunisia (Zairi *et al.*, 2003) are shown in Fig. 7. This experiment concerns supplemental irrigation with furrow irrigation. Results show a regression coefficient close to 1.0 and a determination coefficient of 0.94 referring to a large range of values, thus a very good prediction of ASW values by the model.

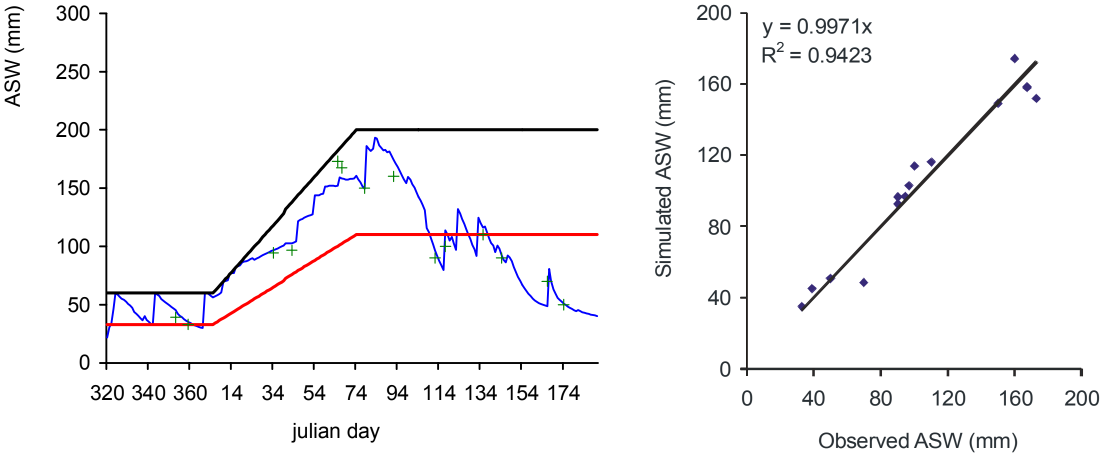

Fig. 7. Comparison between observed and simulated available soil water (ASW) for furrow irrigated winter wheat in Hendi Zitoun, Tunisia: on the left, the simulated ASW curves and the observed values (+); on the right, the regression between simulated and observed values.

SIMDualKc was also validated with data from two sprinkler irrigated wheat experiments performed at the Tel Hadya research station (Oweis *et al*., 2003). Results are shown in Figure 8. The regression coefficients are close to 1 for the first year and 0.98 for the second year. The coefficients of determination are 0.82 and 0.87 respectively for those years. As for the previous cases, the model is able to predict available soil water in a wide range of observed values.

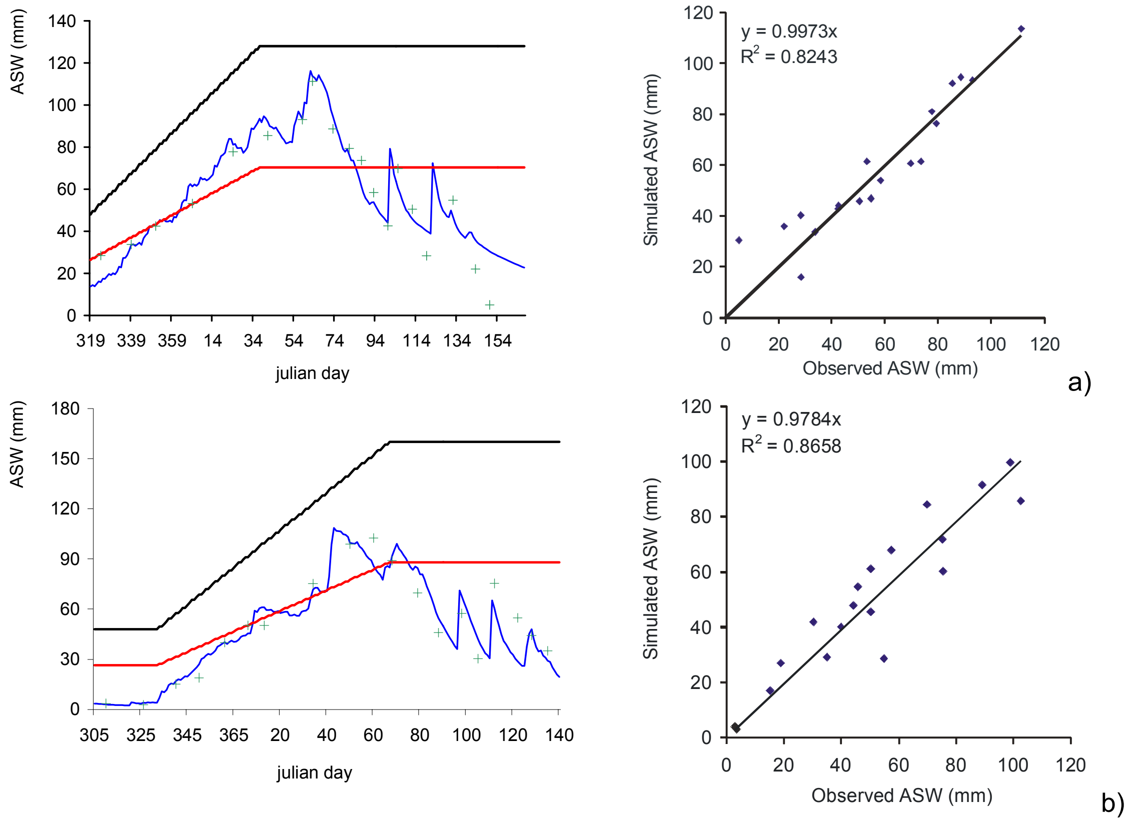

Fig. 8. Comparison between observed and simulated available soil water (ASW) for supplemental irrigation of sprinkler irrigated wheat in Tel Hadya, Syria: on the left, the simulated ASW curves and the observed values (+); on the right, the regressions between simulated and observed values.

The validation performed for a citrus orchard in the Catania Plain was the most difficult one because soil water observations were less precise as identified by Alba *et al*. (2003). The experiment was conducted during a drought year using microsprinkler irrigation and soil water was often below the non-stress threshold. Nevertheless, a coefficient of regression of 0.96 was obtained but the coefficient of determination is relatively low (0.75).

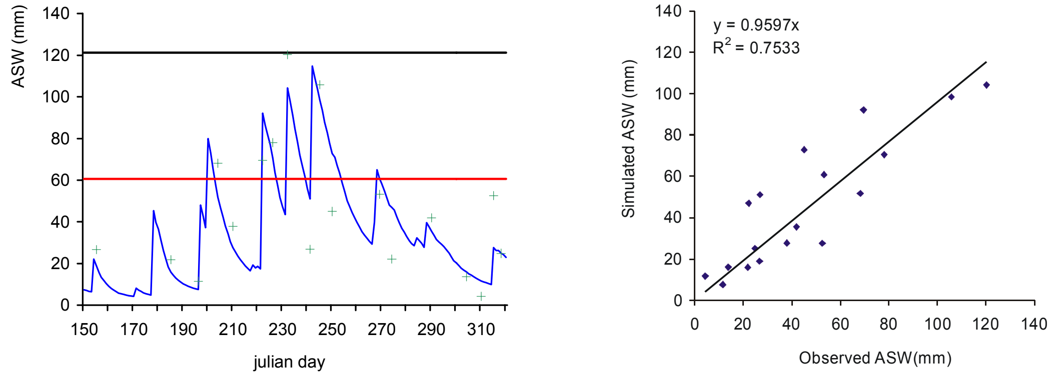

Fig. 9. Comparison between observed and simulated available soil water (ASW) for citrus in Catania Plain: on the left, the simulated ASW curves and observed values (+); on the right, the regressions between simulated and observed values.

Cotton and wheat in Central Asia

The SIMDualKc model was validated using field and meteorological data collected in Fergana Valley, Uzbekistan, for cotton and winter wheat irrigated by furrows (Cholpankulov *et al.*, 2005). Field data used for simulations is summarized in Table 2 and irrigation dates and depths are presented in Table 3 (Cholpankulov, *et al.*, 2005).

Table 2. Trials base information referring to crop, field location, soil and irrigation system.

	a)	**b)**	**c)**	**d)**	**e)**
Crop	cotton	cotton	cotton	cotton	winter wheat
Local	Fergana	Fergana	Fergana	Fedchenko	Fergana
Plantation date	06-04-2003	08-04-2001	13-04-2001	01-05-2003	3-5-2001/02
Max. height (m)	1.2	1.2	1.2	1.2	1.0
Roots length, min. (m)	0.2	0.2	0.2	0.2	0.2
Roots length, max. (m)	0.7	0.6	1.1	0.8	0.7
L_ini (day)	74	63	25	35	57
L_dev (day)	27	35	61	60	96
L_mid (day)	54	54	45	61	78
L_late (day)	28	34	39	48	26
TAW (mm/m)	160	200	230	180	250
REW (mm)	11.6	11.6	10.8	10.8	12.4
TEW (mm)	27.0	27.0	25.5	25.5	29.0
MAD, initial stage (%)	60	60	60	65	30
MAD after ini. stage (%)	70	70	70	70	80
Initial De (mm)	11.3	14.1	38.1	43.2	105
Initial f_w	1	1	1	1	1
Irrigation f_w	0.6	0.6	0.6	0.6	0.6

Table 3. Irrigation dates and depths (mm) in cotton and wheat experiments (Cholpankulov *et al.*, 2005)

Dates and depths of irrigation events					
Trials*	day	Irrig. depth (mm)	Trials*	day	Irrig. depth (mm)
a) cotton	15-06-2003	124	c) cotton	02-06-2001	127
	09-07-2003	103		25-06-2001	174
	24-07-2003	123		11-07-2001	123
	10-08-2003	114		25-07-2001	111
	26-08-2003	91		07-08-2001	86
	12-09-2003	94	d) cotton	07-05-2003	68
b) cotton	08-06-2001	119		05-06-2003	58
	04-07-2001	202		22-06-2003	55
	17-07-2001	113		13-07-2003	37
	30-07-2001	155	e) wheat	10-10-2001	163
	14-08-2001	183		16-02-2002	119
	16-09-2001	93		08-03-2002	130
				20-04-2002	137

The validation of SIMDualKc model for cotton was performed by comparing the observed and simulated available soil water values using a regression through the origin. Simulated and observed soil water content (Fig. 10) show for all cases a good agreement, with the regression coefficient close to 1.0 and coefficients of determination between 0.88 and 0.93. The observations cover a large range of soil water data. Hence, results indicate that the model adequately simulates the soil moisture for the four irrigated cotton crop experiments and, therefore, that ET_c is well estimated.

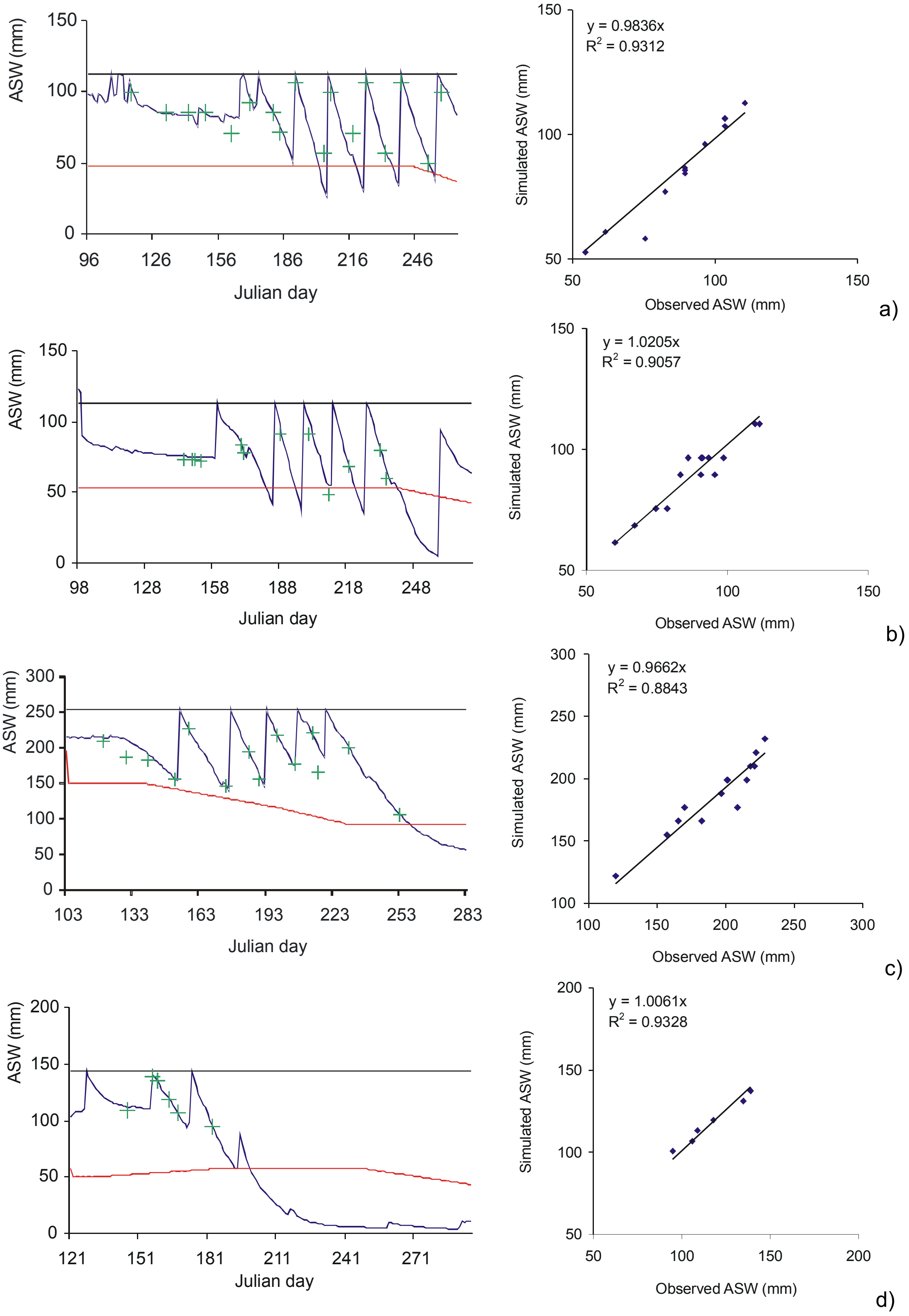

Figure 10. Comparison between observed and simulated available soil water (ASW) for cotton in Fergana Valley, Uzbekistan: on the left, the ASW curves and the observed values (+); on the right, the regressions between simulated and observed ASW values for (a) Fergana; 06-04-2003, (b) Fergana, 08-04-2001, (c) Fergana, 13-04-2001, and (d) Fedchenko, 01-05-2003.

For the winter wheat crop, results of the validation of SIMDualKc model are presented in Figure 11. The regression coefficient is close to 1.0 and the coefficient of determination is 0.80. Thus, the model adequately simulates the soil moisture for the irrigated winter wheat crop, similar to those referred above.

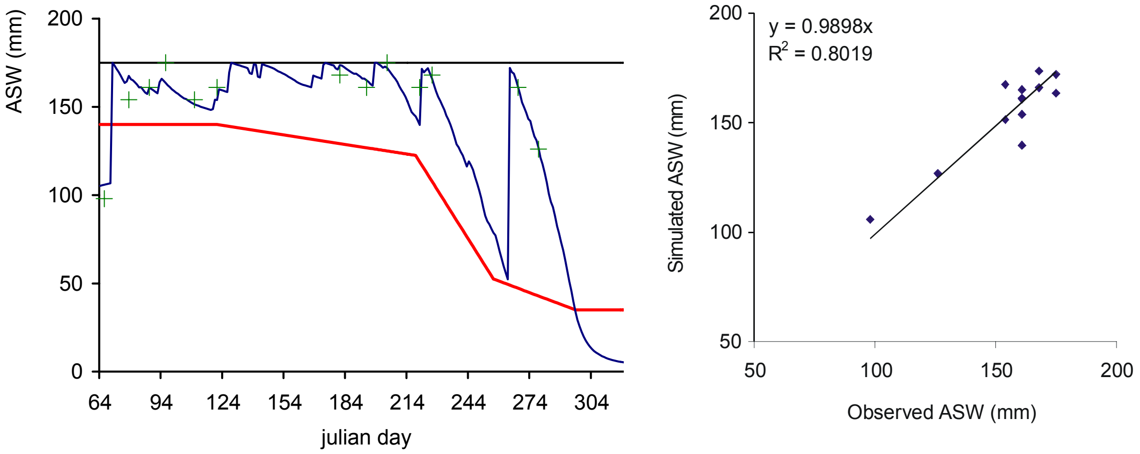

Fig. 11. Comparison between observed and simulated available soil water (ASW) for winter wheat in Fergana (2001-2002): on the left, the simulated ASW curve and the observed values (+); on the right, the regression between simulated and observed values.

Discussion

Results obtained from comparing model simulations and observations of the ASW or the soil water content are summarized in Table 4. They show for all cases regression coefficients close to the target value 1.0 which indicate that the model do not show any tendency for over-or underestimation of ASW or the soil water content. In addition, all cases refer to experiments where soil water observations covered a large range of values. The determination coefficient is close to 0.90 for all but the case of a citrus orchard where problems of soil water observations were recognized.

Table 4. Summary of indicators comparing observed and simulated soil water content values.

Crop experiment	Irrigation method	Regression coefficient	Determination coefficient
Maize, Coruche, 3 irrigations	Level basin irrigation	0.99	0.90
Maize, Coruche, 2 irrigations	Level basin irrigation	1.02	0.85
Wheat, Hendi Zitoun	Furrow irrigation	1.00	0.94
Wheat, Tel Hadya, first year	Sprinkler	1.00	0.82
Wheat, Tel Hadya, second year	Sprinkler	0.98	0.87
Citrus, Catania	Microsprinkler	0.96	0.75
Cotton, Fergana, 2003	Furrow irrigation	0.98	0.93
Cotton, Fergana, 2001 (Field 1)	Furrow irrigation	1.02	0.91
Cotton, Fergana, 2001 (Field 2)	Furrow irrigation	0.97	0.88
Cotton, Fedchenko, 2003	Furrow irrigation	1.01	0.93
Wheat, Fergana, 2001-02	Furrow irrigation	0.99	0.80

Results were obtained for various crops under different irrigation management conditions, including full and deficit irrigation, and using different irrigation methods. In addition soils were different but most of them were clay soils. This indicates a broad spectrum of experimental conditions that support the conclusions about the capability of the model to simulate the soil water balance and therefore to accurately estimate ET_c using the dual crop coefficient approach. Results not only allow to consider the accuracy of the model but also confirm the results by Allen *et al*. (2005c) indicating that the dual K_c approach is more accurate than the average K_c methodology. In fact, for all cases where the WINISAREG model was applied the resulting indicators are better for the simulations presented herein.

CONCLUSIONS

The tests performed by the SIMDualKc model against field data demonstrate a good adherence of model results to observations. The experiments used for validating the model were independently performed and concern various crops under different irrigation management conditions, including full and deficit irrigation, and using different irrigation methods. In addition soils were different but most of them were heavy soils with large clay fractions. Thus, a broad spectrum of experimental conditions has been used for model validation.

Results obtained from comparing model simulations and observations of the available soil water or the soil water content show for all cases regression coefficients close to the target value 1.0, hence indicating that the model does not show any trend to over- or underestimate the ASW or the soil water content. In addition, all cases refer to experiments where soil water observations refer to a large range of values. The determination coefficient is close to 0.90 for all but the case of a citrus orchard where problems of soil water observations were recognized. Therefore, the model proves to accurately simulate the soil water balance during all crop stages, which indicates that the estimation of the crop evapotranspiration with the dual approach is highly accurate.

Further developments consist of improving the user friendly interface of the model software, implement the integration of the model with a real time water balance model and with GIS platforms, as well as to better test the model for farmer advising, including using earth observation data.

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