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Implementing the dual crop coefficient approach in interactive software: 2. Model testing

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ABSTRACT

This paper is the second of a two-part series, with the first part describing the SIMDualKc model, an irrigation scheduling simulation tool that employs the dual crop coefficient approach for calculating daily crop *ET* and then performs a water balance for a cropped soil. The model was applied, calibrated and validated for rainfed and basin irrigated maize (Coruche, Portugal), rainfed and surface irrigated wheat (Aleppo, Syria), and furrow irrigated cotton (Fergana, Central Asia). Results show good agreement between available soil water content observed in the field and that predicted by the model. Results indicate that the calibrated model does not tend to over- or underestimate available soil water over the course of a season, and that the model, prior to calibration, and using standard values for many parameters, also performed relatively well. After calibration, the average growing season maximum estimation errors were 10 mm for maize, 8 mm for winter wheat and 9 mm for cotton, i.e., respectively 3.6, 2.9 and 5.0% of total available water. Results indicate that the separation between evaporation and transpiration and the water balance calculation procedures are accurate enough for use in operational water management. The indicators used for assessing model performance show the model to accurately simulate the water balance of several crops subjected to a variety of irrigation management practices and various climate conditions. In addition, the model was applied to alternative irrigation management scenarios and related results are discussed aiming at assessing the model's ability to support the development of alternative active water management strategies.

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1. Introduction

Most irrigation simulation models that compute crop evapotranspiration (ET_c) use time averaged crop coefficients (K_c), which provide satisfactory results for various time step calculations, including for daily ET_c estimation, with appropriate accuracy for most applications. However, for high frequency irrigation and for partial cover crops, as well as when frequent rainfall events occur, the adoption of the dual K_c approach may produce more accurate ET_c estimates (Allen et al., 2005a). Partitioning the K_c into the soil evaporation component (K_e) and the basal crop *ET* component (K_{cb}) makes it possible to better assess the impacts of soil wetting by rain or irrigation, as well as the impacts of keeping part of the soil dry or using mulches for controlling soil evaporation (*E*). The SIMDualKc model, described in the companion paper (Rosa et al., 2012), was developed to compute crop *ET* using many recent refinements and extensions to the dual *Kc* approach (Allen et al., 1998, 2005b, 2007; Allen and Pereira, 2009) and to perform soil water balance simulations for irrigation scheduling.

The SIMDualKc model was applied to various data sets representing field experiments with maize, winter wheat, and cotton with the purpose of testing its accuracy and flexibility in describing local conditions and cultural practices. The model was calibrated and validated for those crops where different irrigation methods and water management approaches were used by comparing the observed and the simulated soil water content. This paper presents the application of the SIMDualKc model for those crops using standard and calibrated crop and soil evaporation parameters and analyzing the respective performance. The application of the model to alternative management scenarios is also presented and results are discussed aiming at analyzing the model ability to support the development of alternative water management strategies.

2. Materials and methods

The SIMDualKc model (Rosa et al., 2012) uses the dual crop coefficient approach (Allen et al., 1998, 2005b) to calculate crop

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evapotranspiration (ET_c), with separate consideration of the soil evaporation and crop transpiration components. It allows for more precise analysis of how water from precipitation and irrigation is used by the crop. The actual crop evapotranspiration, which differs from ET_c when water stress occurs, is defined as:

$$ET_a = (K_s K_{cb} + K_e) ET_o \quad (1)$$

where ET_a is the actual crop evapotranspiration [mm d^{-1}], K_{cb} the basal crop coefficient [], K_s the water stress coefficient [], K_e the soil evaporation coefficient [] and ET_o the reference crop evapotranspiration [mm d^{-1}]. A complete description of the model is presented in the companion paper by Rosa et al. (2012).

The model was evaluated by comparing observed and simulated available soil water values, over time, for several field experiments involving maize, wheat, and cotton. The simulations were performed using soil, crop, irrigation, and weather data collected during complete crop seasons. Other information needed for running the model that was not collected in the field was estimated or taken from standard tables; this was the case for the basal crop coefficients (K_{cb}), depletion fraction for non-stress (p), total evaporable water (*TEW*), readily evaporable water (*REW*), thickness of the evaporation soil layer (Z_e) (Allen et al., 1998, 2007) and, in some cases, the parameter values used to estimate deep percolation and groundwater contribution in the presence of a shallow water table (Liu et al., 2006). All of the standard parameters are designed to be transferred for use in different climates, but they may need to be calibrated according to specific cropping conditions and soil characteristics.

Data from several field experiments were used: (1) at Sorraia irrigation district, Coruche, Portugal, with maize cropped under full and deficit surface irrigation, and rainfed conditions (Fernando, 1993); (2) at Aleppo, Syria, for wheat under rainfed conditions and surface supplemental irrigation (Oweis et al., 2003); and (3) in Fergana Valley, Uzbekistan, for cotton cropped under various furrow irrigation management practices (Cholpankulov et al., 2008).

Soil data collected at the experimental sites included basic soil hydraulic properties and soil water content measured at different depths within effective rooting zones throughout the crop seasons. Crop data included observed crop growth stage dates, crop cover parameters, crop height and root depths from planting to harvesting. Meteorological data from the nearest weather station were used to input precipitation and reference evapotranspiration, which was computed using the FAO Penman–Monteith method (Allen et al., 1998). The capillary rise from a shallow water table was estimated using the parametric equations from Liu et al. (2006) in Coruche (Portugal) and Fergana Valley (Central Asia). For this latter case study, parametric equations of Liu et al. (2006) were also used to estimate deep percolation fluxes caused by the application of large irrigation depths.

The calibration procedure consisted of adjusting the non-observed (i.e., standard) parameters (K_{cb}, p, *TEW*, *REW*, initial soil water content, capillary rise and deep percolation parameters) to minimize differences between observed and simulated available soil water values relative to the entire root depth profile (Popova and Pereira, 2011). A first set of soil parameters was estimated according to Rosa et al. (2012). Then a trial and error procedure was initiated for selecting values for K_{cb} and p, starting with the standard tabled values. When K_{cb} and p values were in an acceptable range, trial and error was then applied to the soil parameters and again for crop parameters, until differences between observed and simulated values were approximately minimized and stabilized. The validation of the model consisted of using the calibrated values to simulate other local field experiments. When the results for validation were not appropriate, the process of calibration was repeated as noted. For Coruche, experimental data on rainfed maize were used for calibration and data from the deficit and full irrigation experiments were used for validation. At Aleppo, data from a rainfed wheat experiment were taken for calibration, and supplemental irrigation data were used for validation. For cotton in Fergana, the model was first calibrated for 2001 observations and validated with 2003 data. For all cases, the model was also applied using standard parameters proposed by Allen et al. (1998, 2007) to assess how well the daily time step model performed using general crop coefficients and soil parameters based on soil texture.

Both qualitative and statistical means were used to assess the goodness of fit of SIMDualKc model predictions to observations. The qualitative strategy consisted of graphically presenting soil water content values observed in the field versus those simulated by the model. This strategy provided a good perspective on trends and/or biases in modeling and when they occurred. The second assessment strategy used linear regression forced through the origin between observed and predicted soil water content data. Generally, the observed soil water data were collected on a daily to weekly interval, depending on the time during the growing season and proximity to irrigation events. A regression coefficient (b) is close to 1.0 when the covariance was close to the variance of the observed values, indicating that predicted and observed values were statistically similar; a coefficient of determination (R^2) close to 1.0 indicated that most of the total variance of the observed values was explained by the model. Additionally, a set of indicators describing residual estimation errors was used, as employed in previous studies and applications (Green and Stephenson, 1986; Loague and Green, 1991; Liu et al., 1998; Legates and McCabe, 1999; Cholpankulov et al., 2008; Moriasi et al., 2007; Popova and Pereira, 2011).

The goodness of fit was assessed through the indicators listed below, where O_i and P_i ($i = 1, 2, \ldots, n$) represent pairs of observed and predicted values for a given variable, and $\overline{O}$ and $\overline{P}$ are the respective mean values:

- The coefficients of regression and determination relating observed and simulated data, b and R^2 respectively, are defined as:

$$b = \frac{\sum_{i=1}^{n} O_i P_i}{\sum_{i=1}^{n} O_i^2} \quad (2)$$

$$R2 = \left\{ \frac{\sum_{i=1}^{n} (O_i - \bar{O})(P_i - \bar{P})}{\left[\sum_{i=1}^{n} (O_i - \bar{O})^2\right]^{0.5} \left[\sum_{i=1}^{n} (P_i - \bar{P})^2\right]^{0.5}} \right\}^2 \quad (3)$$

- The root mean square error, *RMSE*, which characterizes the variance of the estimation error:

$$RMSE = \left[\frac{\sum_{i=1}^{n} (P_i - O_i)^2}{n} \right]^{0.5} \quad (4)$$

- The average absolute error, *AAE*, which expresses the mean size of estimation error:

$$AAE = \frac{1}{n} \sum_{i=1}^{n} |O_i - P_i| \quad (5)$$

- The average relative error, *ARE* [%], that expresses the size of error in relative terms:

$$ARE = \frac{100}{n} \sum_{i=1}^{n} \left| \frac{O_i - P_i}{O_i} \right| \quad (6)$$

Table 1
Textural and basic soil hydraulic properties of the maize experimental site, Coruche, Portugal (Fernando, 1993).

Soil layer (m)	Sand (%)	Silt (%)	Clay (%)	θ_{FC} ($m^3\ m^{-3}$)	θ_{WP} ($m^3\ m^{-3}$)
0.0–0.20	53.3	30.5	16.2	0.36	0.10
0.20–0.40	53.7	31.1	15.3	0.35	0.09
0.40–0.60	66.2	21.0	12.8	0.36	0.09
0.60–0.80	62.8	22.5	14.8	0.35	0.10
0.80–1.10	60.9	24.3	14.8	0.34	0.10

θ_{FC} and θ_{WP} represent the soil water content at field capacity and the wilting point.

- The modeling efficiency, *EF*, that is the ratio of the mean square error to the variance in the observed data, subtracted from unity:

$$EF = 1.0 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - \overline{O})^2} \quad (7)$$

  As suggested by Legates and McCabe (1999), if the square of the differences between model simulations and observations is as large as the variability in the observed data, then *EF* tends toward 0.0 and the observed mean, $\overline{O}$, is as good a predictor as the model, while negative values indicate that $\overline{O}$ is an even better predictor than the model. *EF* can vary between $-\infty$ and 1.
- The index of agreement (non-dimensional):

$$d_{IA} = 1 - \frac{\sum_{i=1}^{N}(O_i - P_i)^2}{\sum_{i=1}^{N}(|P_i - \overline{O}| + |O_i - \overline{O}|)^2} \quad (8)$$

  This index corresponds to the ratio between the mean square error and the "potential error" defined as the sum of the square of summed absolute differences between P_i and O_i to $\overline{O}$. d_{IA} represents the largest relative value that can occur from each observation-model simulation pair of values (Legates and McCabe, 1999; Moriasi et al., 2007). The maximum and best value for d_{IA} is 1.0.

3. Case study on maize

3.1. Site characteristics

Field data were collected at the António Teixeira Experimental Station, Coruche, which is located inside a 15,000 ha irrigation project in the Sorraia Valley of southern Portugal. The meteorological station is located inside the experimental site (38.57° N, 8.31° W, altitude 30 m) over clipped grass. The maximum and minimum temperatures (°C), minimum relative humidity (%), reference evapotranspiration (mm), and precipitation (mm) observed at Coruche during the year of the experiments (1989) are shown in Fig. 1. The area has a typical Mediterranean climate, with little precipitation during summer.

Soil types in the experimental area are silty loam of recent alluvial origin. Main characteristics are presented in Table 1. Total available soil water (*TAW*) averaged 260 mm m^{-1}. Measured maximum rooting depth for the maize crop was 1.40–1.65 m, based on the collection of soil samples with an Eldeman type probe and visually checking the existence of roots. Because the water table was close to these depths, a steady soil moisture profile near saturation was observed below 1.1 m (Fernando, 1993). These conditions induced little root water uptake from depths deeper than 1.1 m. Therefore, model computations were performed using an average maximum effective rooting depth of 1.1 m. A FAO 600 maize variety was grown, whose crop development stages are given in Table 2. Plant density was 85,000 plants/ha. The crop was harvested (chopped) for animal feed when the grain reached a milky stage, so that the foliage was still green and actively transpiring. Basin irrigation was used. Irrigation water was metered with a modified broad crested weir (Replogle and Bos, 1982). Root growth was

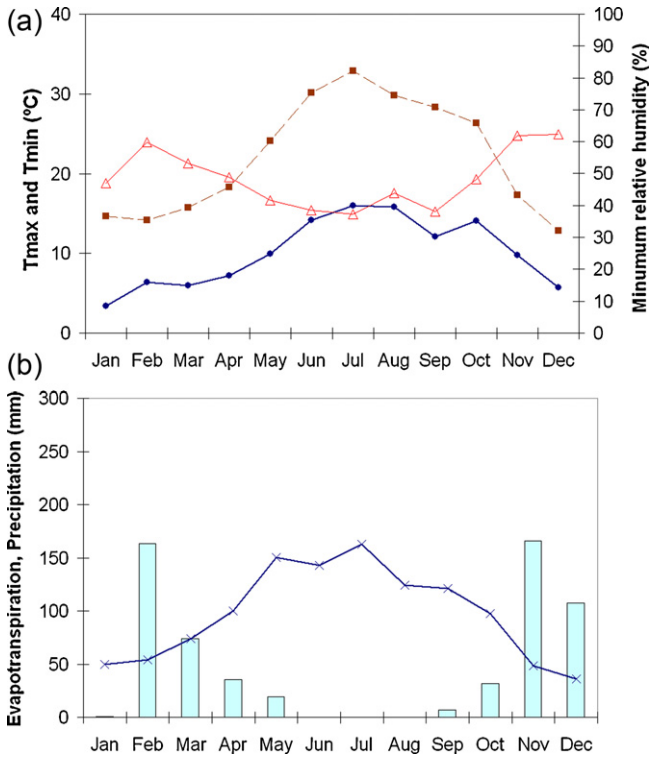

Fig. 1. Climatic data from Coruche meteorological station, 1989: (a) average monthly maximum ( ) and minimum ( ) air temperature, and minimum ( ) relative humidity; and (b) monthly precipitation ( ) and monthly reference evapotranspiration (ET_o) ( ).

Table 2
Maize crop development stages (Fernando, 1993).

Crop growth stages	Dates
Planting/initiation	08 June
Start rapid growth	24 June
Start mid-season	18 July
Start senescence/maturity	25 August
End-season/harvesting	20 September

simulated assuming a constant value of 0.25 m for the initial stage and using a linear interpolation for the crop growth period, from 0.25 to 1.1 m at the start of midseason. Root depth was assumed constant thereafter (see item 2.5 of the companion paper).

Soil water content was observed using a gravimetric method for the surface layer (0–0.10 m) and neutron scattering from 0.20 to 1.40 m at intervals of 0.1 m. Measurements were performed once per week during the period before irrigation; after irrigation began, observations were made daily or on a 2-day interval, with progressively decreasing frequency until the next irrigation event. Measurements were also performed on the days before and after each scheduled irrigation event (Fernando, 1993). The full irrigation and deficit irrigation schedules are presented in Table 3.

Table 3
Irrigation dates and depths (mm) relative to the maize trials (Fernando, 1993).

Irrigation strategy	Date	Net irrigation depth (mm)
Full irrigation	21 July	80
	08 August	80
	29 August	54
Deficit irrigation	25 July	100
	22 August	54

Table 4
Standard (initial) and calibrated basal crop coefficients, p depletion fractions, soil evaporation parameters and capillary rise parameters for simulation of the maize experiments at Coruche.

	Standard[a]	Calibrated
$K_{cb\ ini}$	0.15	0.15
$K_{cb\ mid}$	1.15	1.05
$K_{cb\ end}$	0.50	0.55
p_{ini}	0.55	0.65
p_{dev}	0.55	0.65
p_{mid}	0.55	0.65
p_{end}	0.55	0.65
REW (mm)	10	11
TEW (mm)	31	46
Z_e (m)	0.10	0.15
a_1	360	360
b_1	−0.17	−0.17
a_2	240	240
b_2	−0.27	−0.27
a_3	−1.3	−1.6
b_3	6.6	6.6
a_4	4.6	3.0
b_4	−0.65	−0.65

[a] From Allen et al. (1998, 2005b) and Liu et al. (2006).

A brief report on this experiment was provided by Fernando et al. (1988).

Continuous observation of water table depth showed an almost monotonic increase from 1.45 m, at planting, to 1.80 m, at harvesting. Water tables in the area were relatively shallow due to rice cultivation.

3.2. Results

3.2.1. Calibration, validation and model fitting

The base, standard values of K_{cb} and p proposed in FAO-56 (Allen et al., 1998) for the maize crop were applied in initial model simulations: $K_{cb\ ini}$ = 0.15, $K_{c\ mid}$ = 1.15, $K_{cb\ end}$ = 0.50, p = 0.55. The adopted value for $K_{cb\ end}$ resulted from the early harvest for animal feed. Recommended values for *REW* and *TEW* for silty loam soils by FAO-56 were initially used, 10 and 31 mm, respectively, with Z_e = 0.10 m (Table 4). The initial depletion in the evaporable layer was set for the 3 cases at 0% of *TEW* for the initial runs and for the calibration. Based on soil water observation, the initial depletion for the entire effective root zone (1.1 m) was set at 2, 3 and 10% of *TAW* for rainfed, deficit irrigation, and full irrigation experiments, respectively, indicating relatively moist initial conditions.

Groundwater contribution was computed using the parametric equations proposed by Liu et al. (2006). The initial parameters, based on soil characteristics, were those proposed by Liu et al. (2006) for silty loam soils (Table 4). The fraction of the soil wetted by irrigation (f_w), needed for the computation of K_e together with the fraction of soil covered (f_c), was f_w = 1.0. The observed values of f_c at days 21-06, 18-07, 01-08, 10-08, 25-08 and 20-09 were 0.01, 0.50, 0.75, 0.80, 0.80 and 0.70 for both irrigated plots, and 0.01, 0.50, 0.70, 0.70, 0.65 and 0.50 for the rainfed crop.

Simulated and observed available soil water (*ASW*, mm) during calibration and validation are presented in Fig. 2. The figure shows observed soil water content had a wide range, and that the model simulated the three cases well. The computed total capillary rise was 131, 94 and 86 mm for the rainfed, deficit and full irrigation experiments, respectively, and was supplied by the high water table throughout the season.

The crop parameters (K_{cb} and p), soil evaporation parameters (Z_e, TEW and REW) and parameters of the equations used to estimate the groundwater contribution obtained through calibration and used during validation are presented in Table 4. The $K_{cb\ ini}$ and

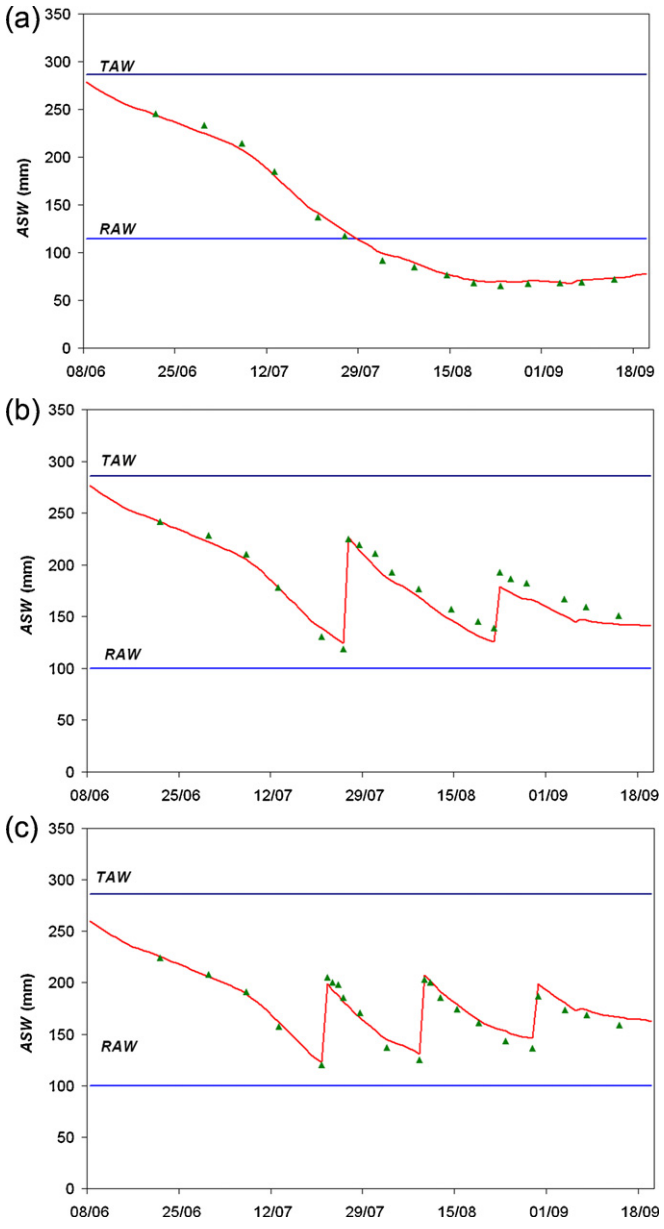

Fig. 2. Comparison between observed (▲) and simulated (▬) available soil water (ASW) curves for maize in Coruche, Portugal: (a) rainfed (calibration); (b) under deficit irrigation (validation); and (c) under full irrigation (validation). TAW and RAW are respectively the total and readily available soil water.

$K_{cb\ mid}$ parameters, as well as the p parameters, are not far from the standard values presented in Allen et al. (1998, 2007); $K_{cb\ end}$ reflect the early cut of the crop for silage. The larger value for p indicates that higher than normal depletions of water could be tolerated by the maize crop before stress. Some of this could be an artifact of the shallow water table and the use of averaged *ASW* over the total root zone even though the soil water content profile was wetter toward the water table. The $K_{cb\ mid}$ values are slightly smaller than those obtained by Zhao and Nan (2007), Jiang et al. (2008), Greenwood et al. (2009) and Liu and Luo (2010).

The computed goodness of fit indicators are summarized in Table 5. The regression coefficient was close to 1.0 for all three experimental conditions, thus showing that predicted soil water was close to observed values. The coefficients of determination ranged from 0.96 to 0.99, indicating that most of the variance was explained by the model. The *RMSE* values were lower than 11 mm, representing less than about 4% of *TAW*; the *AAE* were less than

Table 5
Indicators of goodness of fit relative to the model tests for the maize crop, when using crop, soil evaporation, and capillary rise calibrated values parameters.[a]

Goodness of fit indicators	*b*	R^2	*RMSE* (mm)	*RMSE*/*TAW* (%)	*ARE* (%)	*AAE* (mm)	*EF*	d_{IA}
Calibration (rainfed)	1.00	0.99	4.5	1.6	3.5	3.8	1.00	1.00
Validation (deficit irrigation)	0.96	0.96	10.2	3.6	5.3	8.9	0.91	0.98
Validation (full irrigation)	1.01	0.96	6.4	2.2	3.4	5.6	0.95	0.99
All experiments	0.99	0.98	7.6	2.6	4.1	6.3	0.98	0.99

[a] Parameter values presented in Table 4.

9 mm and the *ARE* values were below 6% with *EF* ranging from 0.91 to 1.00 and d_{IA} greater than 0.98 for all three conditions. All of these statistics suggest good model performance and agreement between simulated and observed *ASW*. When analyzing the experiments together, $b = 0.99$ and $R^2 = 0.98$ (Fig. 3), indicating good model prediction of *ASW* for full, deficit and no irrigation conditions. Values obtained for combined *RMSE* and *AAE* were low, 7.6 and 6.3 mm, respectively, and values for *EF* and d_{IA}, 0.98 and 0.99, respectively, were quite high (Table 5). In summary, results indicate that the model was able to perform well in simulating soil water balances for a maize crop using the dual crop coefficient approach under irrigated and rainfed conditions, taking into account groundwater contributions.

An evaluation was made on model behavior when measured soil water data are not available for model calibration, so that the model is applied using: (a) standard data for *REW*, *TEW*, Z_e, K_{cb} and *p* from Allen et al. (1998, 2007), but calibrated parameters for the capillary rise computation (Table 4); and (b) standard data for *REW*, *TEW*, Z_e, K_{cb} and *p*, and standard capillary rise data as tabled in Liu et al. (2006). For both cases, the dates of crop stages as observed in the field were adopted, which is recommended practice. The dates are different from the general values in FAO-56. The resulting indicators of goodness of fit are shown in Table 6. These indicators show lower, but still acceptable, accuracy relative to the use of calibrated values for the above parameters. When using calibrated parameters for capillary rise computation and standard values for *REW*, *TEW*, Z_e, K_{cb} and *p* (case a), the results for the rainfed experiment had a *RMSE* of 9.3 mm as compared to 4.5 mm when these parameters were calibrated. These *RMSE* values represent about 5 and 2% of *TAW*. When using standard values for the capillary rise estimation (case b) results become less accurate, with *RMSE* of 23.1 mm for the rainfed experiment, thus indicating the importance for careful calibration of these capillary rise parameters. Overall, results show that the model, when used without calibration/validation of soil and crop parameters, provided acceptable results, but users should exercise caution, especially if textbook crop stage dates are used that substantially deviate from actual ones. When standard values for *REW*, *TEW*, Z_e, K_{cb} and *p* were used together with standard values for the capillary rise parameters, *ASW* was overestimated by 2%, on average, which is probably within tolerance for useful irrigation scheduling.

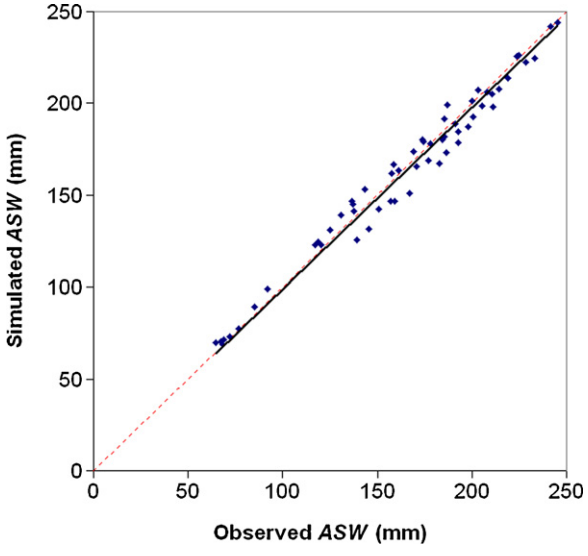

Fig. 3. Comparison between observed and simulated available soil water (*ASW*) using calibrated parameters and all maize experiments data, Coruche, Portugal.

3.2.2. Evaporation and transpiration components

The SIMDualKc model provides computations for both ET_a components, soil evaporation (*E*, mm) and plant transpiration (*T*, mm), where the basal K_{cb} can be assumed to represent primarily *T*, with a small amount of baseline *E* (Wright, 1982); however, during the initial crop growth stage, baseline (diffusive) *E* may be more important than *T*, thus caution is needed when referring to K_{cb} ET_o as plant transpiration during this stage. Results for *E* and *T* relative to crop growth stages are presented in Table 7. Seasonal *E* was 12, 14, and 16% of the seasonal ET_a for the rainfed, deficit, and full irrigation experiments respectively; these values are slightly lower than those observed (Fernando, 1993). Evaporation was the primary ET_a component during the initial crop growth stage, representing about 81% of ET_a for that period. The large *E* component resulted from high water content in the soil evaporation layer and a low fraction of soil covered by the vegetation (f_c) during the initial stage. During the crop development stage, which is the transition stage between the initial period and the midseason period, there was no precipitation or irrigation, thus the upper soil layer remained dry and estimated *E* (mm) decreased to about 6% of ET_a. During the midseason period the fraction of wet soil exposed to radiation was low, thus the evaporation during this period was essentially zero for the rainfed treatment and very low for both irrigation treatments. During the late season, because f_c decreased as the crop dried out and lost leaves, the proportion of *E* relative to ET_a increased relative to the mid-season period, supplied by a small rain. As expected, *E* was smaller for the rainfed crop because the soil evaporation layer was dry during much of the crop season. However ET_a was not very different from the other cases because capillary rise was high, 131 mm, as indicated above.

Estimates for E/ET_c of irrigated treatments, 14% and 16% respectively for 2 and 3 irrigation applications, are comparable with those published by several authors: Bethenod et al. (2000) reported E/ET_a of about 10–12%; Allen et al. (2005b) estimated E/ET_a of 24% for irrigated maize (sweet corn) at Kimberly, Idaho; Grassini et al. (2009) reported E/ET_c ranging from 7 to 34% in the Corn Belt of the USA, with lower values for irrigated maize; Katerji et al. (2010) indicated values of 17–34%, where the lower ratio corresponds to well-irrigated maize. Observations by Zhao et al. (2009) for monsoon rainfed maize reported E/ET_c of 27.4%, and Jiang et al. (2008) have found E/ET_c ranging 18–23% for a maize–wheat crop sequence. Results for the rainfed crop, $E/ET_c = 13\%$, are lower than values reported in literature because rain was extremely low in the Mediterranean climate during most of the growing season and because the ET from the crop was essentially supplied by capillary rise; hence the upper soil layer, from where evaporation originates, was dry during much of the crop season.

Table 6
Indicators of goodness of fit relative to the model tests for the maize crop, Coruche, when using: (a) standard values for crop and soil evaporation parameters and calibrated capillary rise parameters; and (b) standard values for crop, soil evaporation and capillary rise parameters.[a]

Goodness of fit indicators	*b*	R^2	*RMSE* (mm)	*RMSE*/*TAW*(%)	*ARE* (%)	*AAE* (mm)	*EF*	d_{IA}
Rainfed[(a)]	1.04	0.99	9.3	3.2	10.4	8.4	0.98	0.99
Deficit irrigation[(a)]	0.96	0.92	13.7	4.8	7.2	12.1	0.84	0.96
Full irrigation[(a)]	1.03	0.98	6.3	2.2	3.4	5.5	0.95	0.99
All experiments[(a)]	1.00	0.96	10.2	3.5	6.5	8.5	0.96	0.99
Rainfed[(b)]	1.05	0.98	23.1	8.1	25.3	19.2	0.87	0.96
Deficit irrigation[(b)]	0.98	0.99	4.8	1.7	2.5	4.3	0.98	0.99
Full irrigation[(b)]	1.05	0.88	14.0	4.9	7.0	11.5	0.75	0.93
All experiments[(b)]	1.02	0.95	14.9	5.2	10.2	11.0	0.91	0.97

[a] Parameter values presented in Table 4.

Table 7
Evaporation (*E*) and transpiration (*T*) for each development stage of the maize crop, Coruche.

	Initial stage		Vegetative growth		Mid season		Late season		Full crop season		
	E (mm)	*T* (mm)	*E* (mm)	*T* (mm)	*E* (mm)	*T* (mm)	*E* (mm)	*T* (mm)	*E* (mm)	*T* (mm)	*E*/*ET* (%)
Rainfed	34	8	5	75	0	165	3	52	42	300	12
Deficit irrigation	34	8	5	75	9	185	9	74	57	342	14
Full irrigation	34	8	5	75	14	185	12	74	65	342	16

Results for the evaporation and basal crop coefficients, K_e and K_{cb}, for the water stress adjusted K_{cb} ($K_{cb\ adj} = K_s\ K_{cb}$), as well as for the groundwater contribution (*GWc*) and precipitation are shown in Fig. 4 for the rainfed and deficit irrigated maize. These results show that daily K_e was only significant during the earlier stages of the crop and remained quite low or null until a few small rains occurred near the end of the season. Differences in K_e between treatments were small. Values for K_e were constrained during the midseason period for the irrigated crop by high K_{cb} coupled with the total constraint imposed by $K_{c\ max}$. The non-stressed K_{cb} values were the same for both treatments but the $K_{cb\ adj}$ values were different, with the rainfed treatment showing a large deviation from K_{cb} due to some late season stress. The rainfed crop was only sustained because the groundwater contribution was quite high after soil water was depleted from the root zone. Peak values for GW_c were caused by variation in the water table depth, which occurred during water management of surrounding fields, mainly paddies. Results illustrate the use of the model to improve the understanding of differences in water use among irrigation treatments.

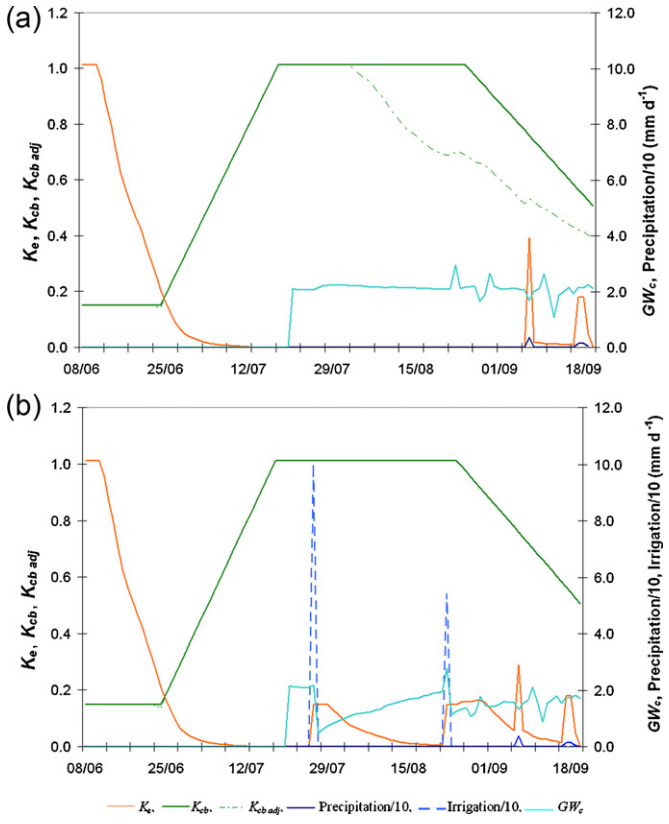

Fig. 4. Variation of the evaporation and basal crop coefficients K_e, K_{cb}, and $K_{cb\ adj}$, precipitation/10, irrigation/10 and groundwater contribution (GW_c) for: (a) rainfed and (b) deficit irrigated maize in Coruche, PT (for easier reading of the figure, irrigation and precipitation are divided by 10).

3.2.3. *Assessing an alternative irrigation management strategy*

Surface irrigation in the Sorraia Valley has been progressively replaced by sprinkler irrigation, mainly with center-pivot laterals. Thus, once calibrated, the model was applied for this alternative irrigation method to assess differences in water use caused by changes in irrigation management. The model was used with the previously calibrated parameters (Table 4) and with the same climatic, soil and crop data. Irrigation data were modified to reflect net application depths (*D*) of 20 mm and an irrigation schedule aimed at producing no stress. As observed by Klepper (1991), crop roots may not grow the same when large irrigation depths are infrequently applied, 2 or 3 times in the crop season as under surface irrigation, as compared to where smaller and frequent irrigations are applied as under center pivot irrigation, where the effective rooting depth may be less. In this application, the groundwater table was feeding the crop in conditions similar to surface irrigation, which may suppose a similar root growth until the first sprinkler irrigation by 14-07, when root depth was estimated at 0.9 m. Because frequent irrigation were considered thereafter, root growth was assumed smaller than for surface irrigation, hence the effective rooting depth was set at 1.0 m.

Fig. 5 compares impacts of using center pivot sprinkler on total ET, along with the basin full irrigation case in terms of the time variation in coefficients K_{cb}, $K_{cb\ adj}$ and K_e, as well as of the water balance terms GW_c, *I*, *P*, *E*, *T* and the seasonal variation of soil water, ΔSW. Results show that adopting high frequency center pivot sprinkler irrigation when the water table remains high leads to maintaining soil evaporation relative to basin irrigation despite increasing the number of irrigation events. This negligible change in *E* is also

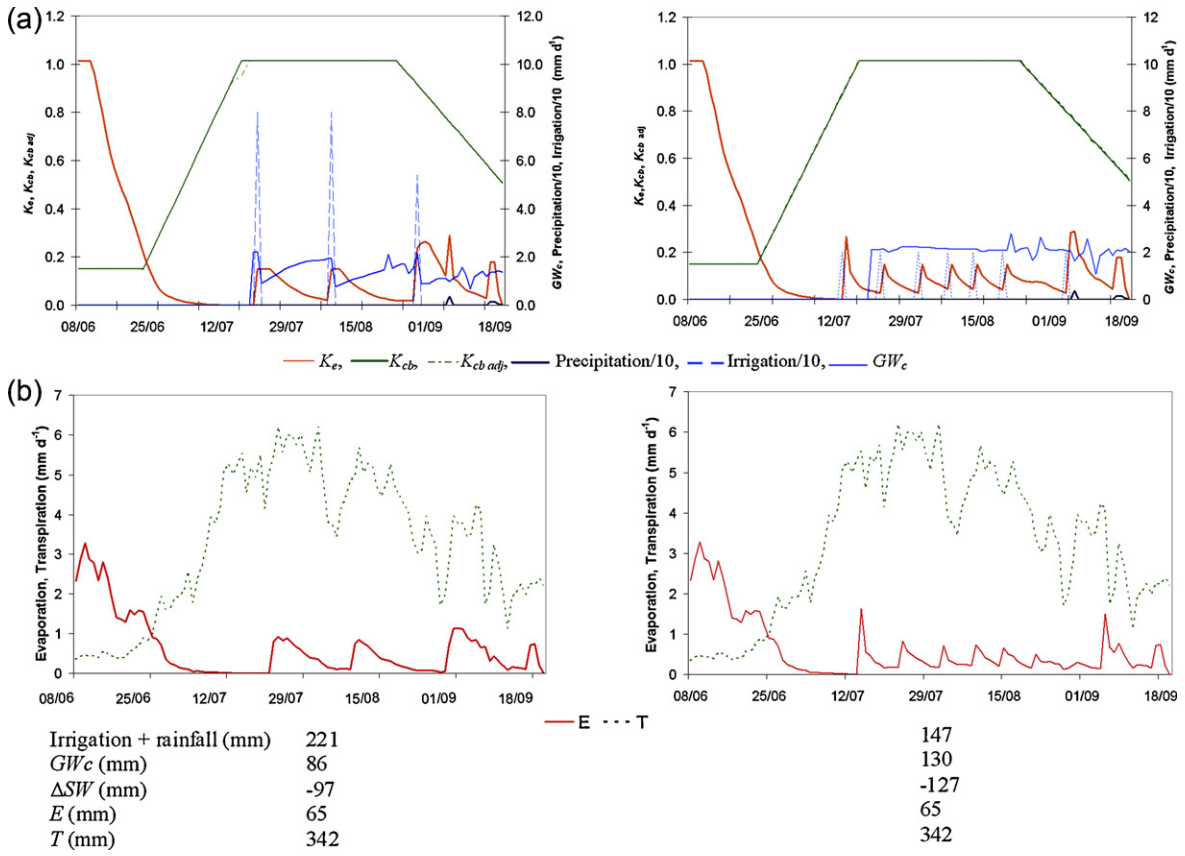

Fig. 5. Variation of K_e, K_{cb}, $K_{cb\ adj}$, GWc, $I/10$, $P/10$ (a) and E and T (b) for fully irrigated maize under basin irrigation (left) and center-pivot sprinkler irrigation (right) (for easier reading of the figure, irrigation and precipitation are divided by 10).

due to the fact that irrigations were applied when f_c was large, i.e., when plant cover was high. GW_c increased from 86 to 130 mm because more soil water was depleted as indicated by a higher decrease in ΔSW over the growing season (Fig. 5). Thus, the same crop transpiration (T around 342 mm) was supplied by a smaller sum of $I+P$ which decreased from 221 to 147 mm due to increased GW_c, i.e., with net irrigation decreasing by 74 mm when changing from basin to sprinkler irrigation (Fig. 5). Estimated E/ET_c = 16% was maintained.

4. Case study on wheat

4.1. Site characteristics

ICARDA's headquarters and research farm are located at Tel Hadya, 30 km south of Aleppo, within a major dryland farming area of northern Syria. Wheat is the primary research crop at ICARDA, and on going field trials include responses to supplemental irrigation (e.g., Oweis et al., 1998; Zhang et al., 1998; Zhang and Oweis, 1999; Oweis and Hachum, 2001; Sato et al., 2006). Climatic characteristics of Tel Hadya (36.01° N latitude; 36.56° E longitude; altitude 284 m) during 1992–1993 are given in Fig. 6, including the reference evapotranspiration computed with the FAO-PM method (Allen et al., 1998). Tel Hadya also has a Mediterranean climate with little rainfall during summer.

The primary soil type is a red brown calcareous loamy soil. Principal soil characteristics are presented in Table 8. The soil depth ranges from 1.0 to 1.8 m and the measured maximum rooting depth during the experimental year (1992–1993) was 1.5 m (Zhang and Oweis, 1999). Considering these soil characteristics and the effective maximum rooting depth, a maximum TAW value of 282 mm

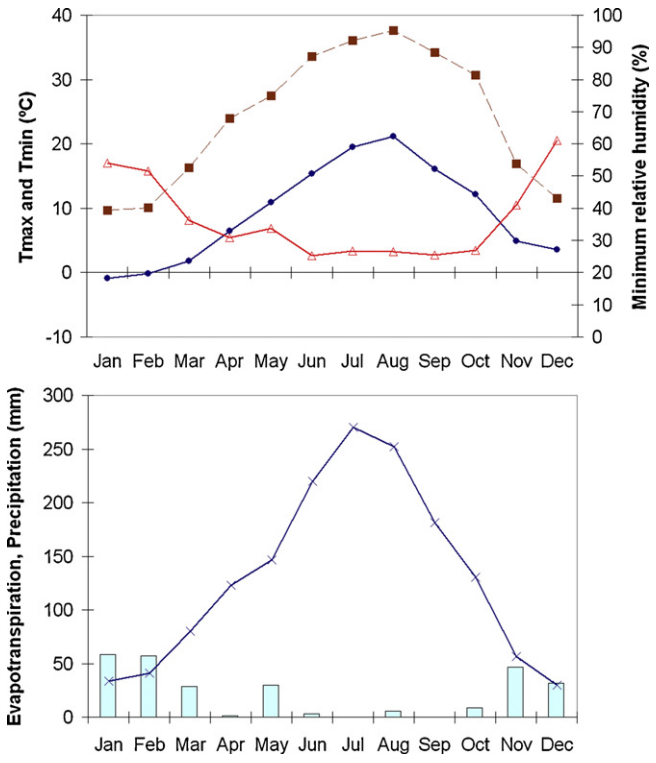

Fig. 6. Climatic data of the ICARDA meteorological station (1992–1993): (a) average monthly maximum (- ■ -) and minimum (—●—) temperature, and minimum (—△—) relative humidity; and b) monthly precipitation (□) and reference evapotranspiration (ET_o) (—✕—).

Table 8
Textural and basic soil hydraulic properties of the experimental site at Tel Hadya, Aleppo, Syria (Oweis et al., 2003).

Soil layer (m)	Sand (%)	Silt (%)	Clay (%)	θ_{FC} ($m^3\ m^{-3}$)	θ_{WP} ($m^3\ m^{-3}$)
0.0–0.45	16.0	24.0	60.0	0.40	0.24
0.45–1.80	17.0	25.0	58.0	0.40	0.22

Table 9
Crop stage dates for the winter wheat crop, Aleppo, Syria (Oweis et al., 2003).

Crop growth stages	Dates
Planting/initiation	11 December
Start rapid growth	17 February
Start mid-season	10 April
Start senescence/maturity	15 May
End-season/harvest	27 May (rainfed) 6 June (supplemental irrigation)

was utilized during modeling. An initial rooting depth of 0.25 m was assigned until the start of rapid growth, increasing to 1.5 m at the start of midseason. Observations of soil water content were made weekly. The gravimetric method was used for the upper soil layer and the neutron scattering method was used for soil depths below 0.15 m at every 0.15 m until 1.80 m (Zhang and Oweis, 1999).

The wheat crop development stages are defined in Table 9. Plant density at mid season was near 150 plants m^{-2}. Impacts of plant density on the partition of *ET* into crop *T* and soil *E* were analyzed by Eberbach and Pala (2005). Supplemental irrigation was applied using basin irrigation and the scheduled dates for the experiment are listed in Table 10. Crop practices were the same for both plots except for irrigation. Treatments analyzed herein are described by Oweis et al. (2003).

4.2. Results

4.2.1. Calibration, validation and model fitting

The K_{cb} and p values proposed by FAO-56 were used during initial model simulation, as well as *REW*, *TEW* and Z_e values recommended by Allen et al. (2005b) for loamy soils, which are given in Table 11. The initial depletion of the evaporable layer was set as 85% of *TEW*. The depletion of the entire root depth was initialized at 75% of *TAW* on the date of planting. Estimated values for f_c during the initial period varied from 0.0 to 0.30, and increased to 0.80

Table 10
Irrigation dates and depths (mm) for the test trial of irrigated wheat, 1992–1993 crop season (Oweis et al., 2003).

Date	Net irrigation depth (mm)
12 April	82
26 April	75
12 May	45

Table 11
Standard (initial) and calibrated basal crop coefficients, p depletion fractions, and soil evaporation parameters for the wheat experiments, Tel Hadya, Aleppo.

	Standard[a]	Calibrated
$K_{cb\ ini}$	0.15	0.15
$K_{cb\ mid}$	1.10	1.05
$K_{cb\ end}$	0.15	0.25
p_{ini}	0.55	0.50
p_{dev}	0.55	0.50
p_{mid}	0.55	0.50
p_{end}	0.55	0.50
REW (mm)	10	8
TEW (mm)	28	22
Z_e (m)	0.15	0.10

[a] From Allen et al. (1998, 2005b).

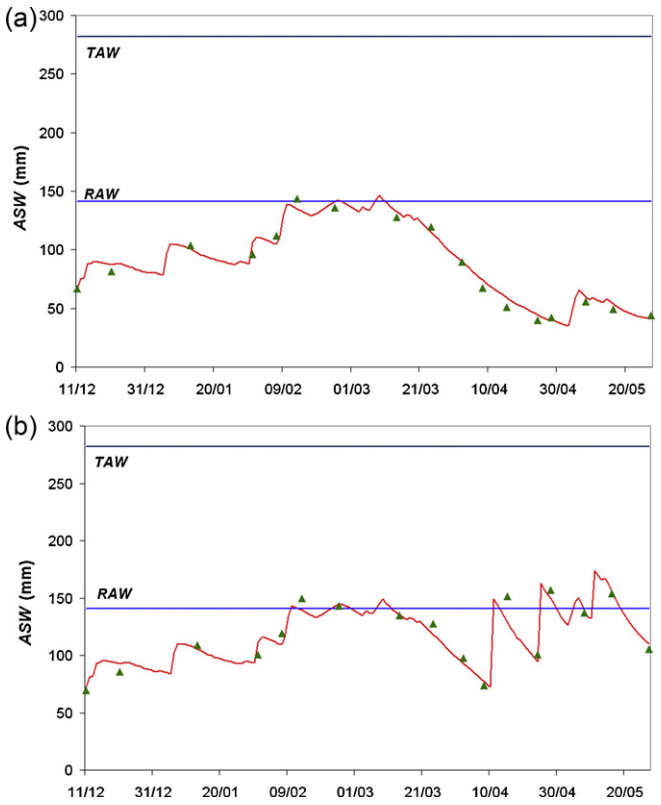

Fig. 7. Comparison between observed (▲) and simulated (▬) available soil water (ASW) for wheat near Aleppo, Syria: (a) rainfed (after calibration), and (b) supplemental irrigation (validation). TAW and RAW are respectively the total and readily available soil water.

during the crop development period for both rainfed and irrigation treatments. The value $f_c = 0.8$ was maintained during midseason and decreased to 0.2 at harvesting in case of supplemental irrigation; differently, for the rainfed crop, due to severe water stress, f_c decreased to 0.5 at the end of midseason and thereafter to 0.2 at harvesting.

Fig. 7 presents results comparing simulated with observed available soil water following calibration. As with case 1, calibration was conducted by varying $K_{cb\ mid}$, $K_{cb\ end}$ and p to decrease or increase total fluxes of ET from the root zone so that simulated *ASW* came closest to observed values during midseason and late season periods. *REW* and *TEW* were adjusted to cause simulated change in *ASW* to match observed *ASW* over the periods following wetting events. The calibrated crop and evaporation parameters are presented in Table 11.

The calibrated values for K_{cb} and p (Table 11) are close to the standard values proposed by Allen et al. (1998, 2007). Values of $K_{cb\ mid}$ are slightly lower than the values presented by Hunsaker et al. (2007), López-Urrea et al. (2009), Liu and Luo (2010) and Zhao et al. (2010). The reduction of 0.05 at midseason relative to the starting value from FAO-56 may reflect a slight reduction in $K_{cb\ mid}$ caused by impacts of water stress, plant variety or reduced vigor, or may be an artifact of soil water measurement error or compensation for other model uncertainties including estimates for p and ET_o. The proximity of calibrated and standard K_{cb} values does support the validity of using general, transferable values for K_{cb} for routine modeling.

During the validation run (Fig. 7b), where supplemental irrigation was applied, simulated *ASW* came close to observed values during the late season. Both water treatments were estimated to incur mild stress during the development period (March) so that $K_s < 1.0$. The rainfed experiment transitioned into severe water

Table 12
Indicators of goodness of fit relative to the model tests for the wheat crop, when using crop and soil evaporation calibrated parameters.[a]

Goodness of fit indicators	*b*	R^2	*RMSE* (mm)	*RMSE*/*TAW* (%)	*ARE* (%)	*AAE* (mm)	*EF*	d_{IA}
Calibration (rainfed)	1.01	0.98	5.5	2.0	6.3	4.8	0.97	0.99
Validation (supplemental irrigation)	0.97	0.92	8.2	2.9	5.4	6.3	0.91	0.97
All experiments	0.99	0.96	7.0	2.5	5.9	5.6	0.96	0.99

[a] Parameter values presented in Table 11.

stress during midseason (April–June) when *ASW* became less than 1/3 of *RAW* so that K_s also went below 1/3 (Fig. 7a). The relatively simple, linear reduction function of FAO-56 for K_s performed well for the wheat crop.

Goodness of fit indicators are presented in Table 12. Results show that the coefficients of regression were close to 1.0 and the coefficients of determination ranged from 0.92 to 0.98. The estimation error *RMSE* for *ASW* were 5.5 and 8.2 mm respectively for the rainfed and irrigated treatment; for the same treatments, *AAE* results were 4.8 and 6.3 mm, respectively. These values represent less than 3% of *TAW*, which is considered to be quite satisfactory. *EF* and d_{IA} indicators were high. Fig. 8 presents the comparison between observed and simulated *ASW* (mm) when using all data from both experiments. The data adhere relatively well to the 1:1 line with similar variance over the range of *ASW*. Some underestimation in *ASW* occurred at high *ASW*. Results indicate that the model was able to reproduce the observed available soil water over a wide range of observed values, with only minor calibration.

To assess the simulation errors when observed soil water data are not available for model calibration/validation, the SIMDualKc model was applied to both experiments using only standard data (*REW*, *TEW*, Z_e, K_{cb} and *p*) from Allen et al. (1998, 2007) but adopting observed dates for crop stages. The respective indicators for goodness of fitting are shown in Table 13. As observed for the maize applications, using standard data produced less accuracy as compared to using calibrated parameters, but results were still quite acceptable with *RMSE* averaging 12.5 mm, *ARE* around 9%, and relatively high *EF* and d_{IA} values, averaging 0.90 and 0.97, respectively. These results suggest that the model could have been used with standard parameters provided dates for crop growth stages were specified as those observed in the field.

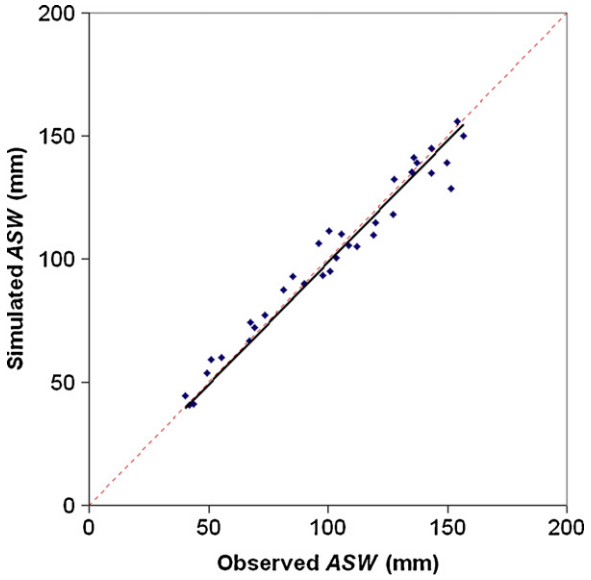

Fig. 8. Comparison between observed and simulated available soil water (*ASW*) using all experimental data for a wheat crop near Aleppo, Syria, after model calibration.

4.2.2. Evaporation and transpiration components

The model results for *E* (mm) and *T* (mm) for both treatments averaged over each of the four crop growth stages and total growing season are presented in Table 14. Results show that *E* was the dominant component of ET_a during the initial crop growth stage, representing 85% of ET_a. This was due to a high moisture content in the evaporable layer during this period, which occurred during the rainy season. Total precipitation was 133 mm during the initial period, and numerous precipitation events occurred. In addition, crop cover was low, creating a large fraction of wetted soil that was exposed to radiation, thus favoring evaporation. During the vegetative growth period, *E* decreased to 25% of ET_a while f_c increased. The precipitation during this period was 42 mm. During both crop stages, there were no differences between treatments because there was no irrigation at that time. During the mid-season period, the irrigation treatment produced large increases in both *T* and *ET*. *E* was also larger for the irrigated treatment due to soil wetting by irrigation. Differences between treatments were also high during the late season. Growing season evaporation was of the same magnitude for both treatments because it mostly originated from rainfall. However, the percentages of soil evaporation in total growing season *ET* were different, 25% for the supplemental irrigated treatment, and 38% for the rainfed treatment. These differences illustrate the importance of supplemental irrigation of wheat and its impact on partitioning total water consumption into *E* and *T* and associated marketable yields (Oweis and Hachum, 2001). Results on the ratios of E/ET_c are similar to those reported by Zhang et al. (1998) for the same area: 29–43% with higher values for rainfed wheat. These values are higher than other results reported in literature: Hunsaker et al. (2005) reported much lower values for a low rainfall area near Phoenix, AZ, USA, of 6–8%; Er-Raki et al. (2007) reported 10–17% for a dry climate in Morocco; López-Urrea et al. (2009) indicated 24% for Spain; Yu et al. (2009) have shown a range of 20–28% for China, with the higher values occurring when insufficient irrigation was practiced; Zhao et al. (2010) reported 16–22% for well irrigated wheat in North China; and Sadras and Rodriguez (2010) reported a range of 22–34% in Australia, depending on the variety.

4.2.3. Assessing an alternative irrigation management issue

An alternative modeling scenario was considered using the same climatic, soil and crop data as for validation and the previously calibrated parameters (K_{cb}, *p*, *TEW*, *REW* and Z_e) but with the objective of assessing the influence of the irrigation system type and management and maintaining a soil mulch on soil evaporation dynamics. The alternative scenario used sprinkler irrigation having application depths of $D = 40$ mm (Zhang et al., 1998) and with direct seeding, thus preserving a surface mulch (crop residue). The impact of the mulch was modeled assuming a mulch density of 0.6, a covered fraction of 1.0 and a soil evaporation reduction of 30%. The 30% reduction in evaporation under the residues mulch was an arbitrary setting following the recommendation in FAO-56 and was selected primarily to assess the sensitivity of total *E* and *ET* under those conditions. The irrigation schedule was set similar to that observed for supplemental irrigation: (a) the first irrigation was scheduled on the same date (12/04); (b) after this date and until grain filling by 20/05, irrigation was set to fulfill full wheat water requirements;

Table 13
Indicators of goodness of fit relative to the model tests for the wheat crop, when using crop and soil evaporation standard parameters.[a]

Goodness of fitting indicators	*b*	R^2	*RMSE* (mm)	*RMSE/TAW* (%)	*ARE* (%)	*AAE* (mm)	*EF*	d_{IA}
Rainfed	0.94	0.97	7.8	2.8	8.3	6.5	0.95	0.99
Supplemental irrigation	0.91	0.89	14.0	5.0	9.9	12.1	0.74	0.92
All experiments	0.92	0.95	11.3	4.0	9.1	9.3	0.90	0.97

[a] Parameter values presented in Table 11.

Table 14
Evaporation (*E*) and transpiration (*T*) during each crop development stage for the wheat crop (1992–1993) at Tel Hadya, Aleppo, Syria.

	Initial crop stage		Vegetative growth		Mid season		End season		Entire growing season		
	E (mm)	*T* (mm)	*E* (mm)	*T* (mm)	*E* (mm)	*T* (mm)	*E* (mm)	*T* (mm)	*E* (mm)	*T* (mm)	*E/ET* (%)
Rainfed	60	11	24	70	5	55	2	15	91	150	38
Supplemental irrigation	60	11	24	71	12	143	3	75	99	300	25

and (c) no irrigation was considered after 20/05. Fig. 9 shows the time-wise variation of coefficients K_{cb}, $K_{cb\ adj}$, and K_e, as well as a summary of components of the water balance, *E, T, P, I,* and ΔSW. Results show: (a) a large decrease in soil *E* due to mulching, mainly during the early stages of the crop if a 30% reduction in evaporation were realized; (b) a smaller associated value for K_e during the initial and crop development stages; (c) a smaller reduction of $K_{cb\ adj}$ relative to K_{cb} in late March prior to irrigation due to higher availability of soil water made available via a smaller *E*; (d) associated higher *T*, mainly during the last part of the crop development stage and mid season. This simulation suggests that even when adopting the same irrigation thresholds, the maintenance of mulch on the surface may lead to the transfer of a valuable amount of water from soil *E* into crop *T*. *ET* was still about the same, which shows the positive impacts of mulching. This application illustrates the utility of employing the dual crop coefficient approach when investigating impacts on soil evaporation. More sophisticated models and experimentation on surface residue effects, including surface energy balance measurements, can be used to calibrate or validate the dual K_c approach of SIMDualKc.

5. Case study on cotton

5.1. Site characteristics

The SIMDualKc model was applied to furrow irrigated cotton using field and meteorological data collected near Fergana, in the Fergana Valley, Uzbekistan. The Fergana Valley is bordered by the

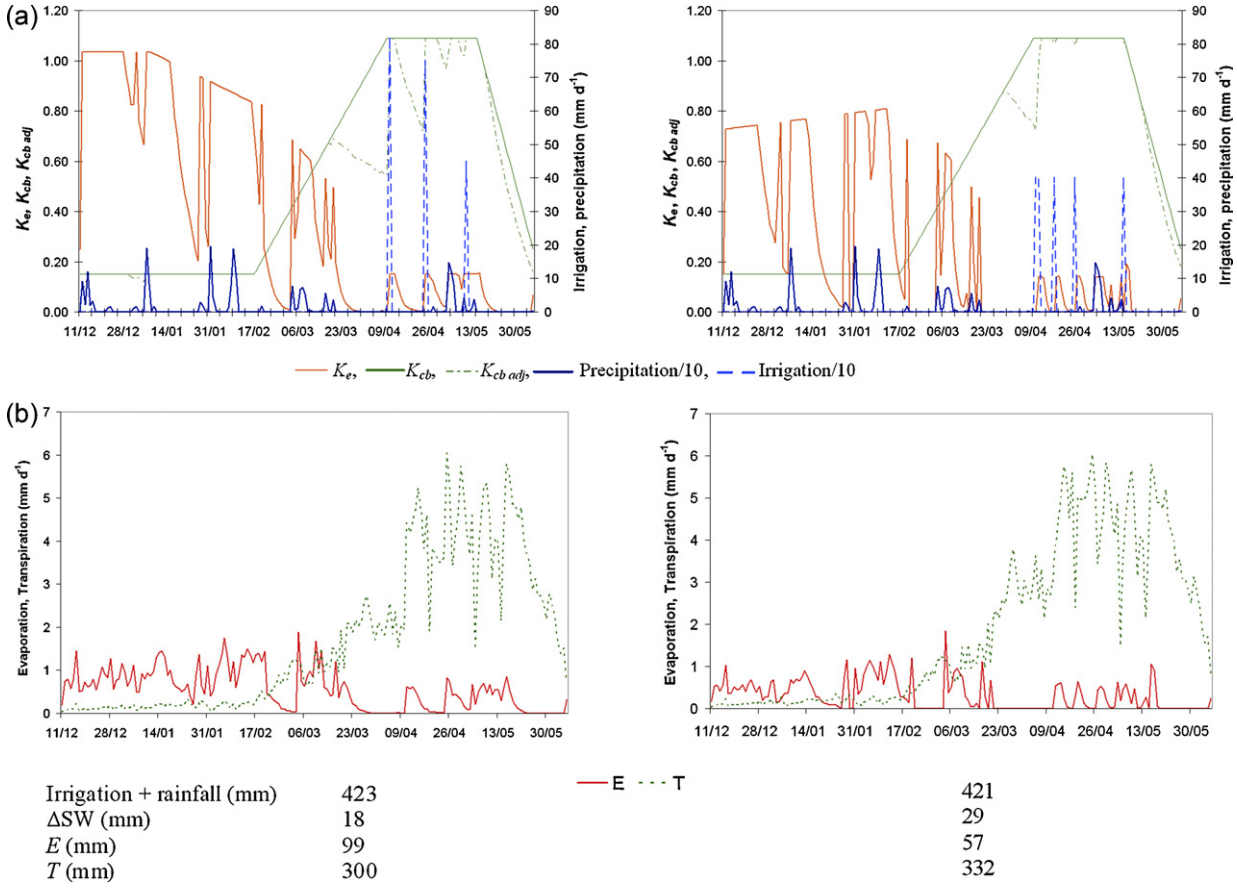

Fig. 9. Comparing the current surface irrigation (left) with an alternative sprinkler irrigation with surface mulching (right): seasonal variation of K_e, K_{cb}, $K_{cb\ adj}$, irrigation and precipitation (a), and of *E* and *T* (b).

Table 15
Textural and soil hydraulic properties for two experimental sites near Fergana, Uzbekistan (Cholpankulov et al., 2008).

	Soil layer (m)	Sand (%)	Silt (%)	Clay (%)	θ_{FC} ($m^3\ m^{-3}$)	θ_{WP} ($m^3\ m^{-3}$)
Site A, 2001	0.00–0.35	34.0	46.0	20.0	0.30	0.13
	0.35–0.50	45.0	48.0	7.0	0.30	0.12
	0.50–0.62	43.0	41.0	16.0	0.31	0.12
	0.62–0.76	41.0	44.0	15.0	0.30	0.11
	0.76–0.91	51.0	42.0	7.0	0.30	0.13
	0.91–1.10	44.0	49.0	7.0	0.30	0.11
Site B, 2003	0.00–0.15	34.0	46.0	20.0	0.34	0.17
	0.15–0.35	38.0	47.0	15.0	0.35	0.17
	0.35–.050	45.0	48.0	7.0	0.35	0.17
	0.50–0.62	43.0	41.0	16.0	0.34	0.18
	0.62–0.76	41.0	44.0	15.0	0.36	0.18
	0.76–0.91	51.0	42.0	7.0	0.35	0.17
	0.91–1.00	44.0	49.0	7.0	0.34	0.16

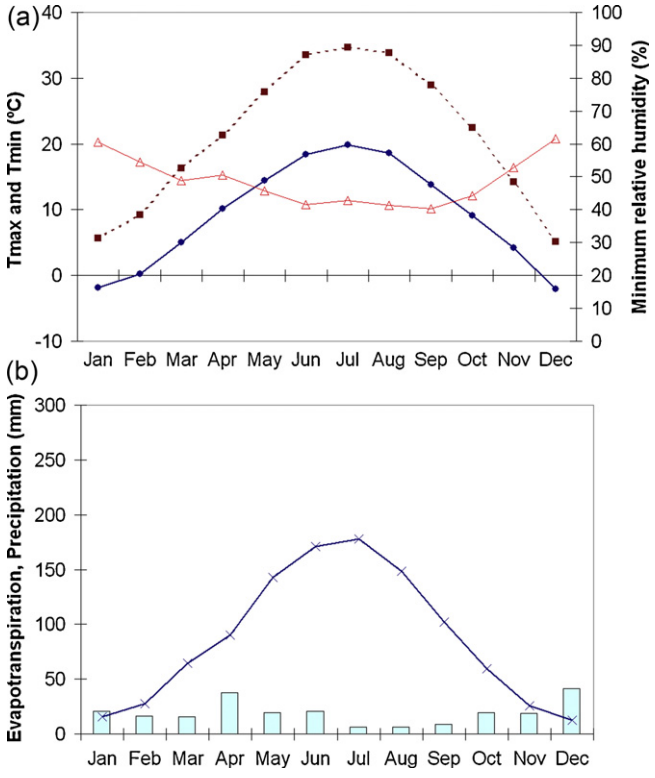

Fig. 10. Climatic data of the Fergana meteorological station (2001–2003): (a) average monthly maximum ( ) and minimum ( ) air temperature, and minimum ( ) relative humidity; and (b) monthly precipitation ( ) and monthly reference evapotranspiration (ET_o) ( ).

Fergana ridge to the East, the Alai and Turkestan ridges to the South and the Kurama and Chatkal ridges to the Northwest and the North. The valley is drained by the SyrDarya River, which is fed by numerous mountain streams. All experiments occurred south of the SyrDarya River. Data relative to all cotton treatments were reported by Cholpankulov et al. (2008).

The Fergana meteorological station located near the experimental site has coordinates 40.77° N, 71.09° E and altitude 439 m. The respective monthly average maximum and minimum temperatures, minimum relative humidity, precipitation and reference evapotranspiration computed with the FAO-PM method are shown in Fig. 10.

The primary soils in the experimental sites are loamy and clay-loam soils. Principal soil characteristics for the two plots of Fergana are presented in Table 15. These experimental plots are identified

Table 16
Cotton crop growth stages for the Fergana experiments (Cholpankulov et al., 2008).

Crop growth stages	2001	2003
Planting/Initiation	13 April	06 April
Start rapid growth	18 May	21 May
Start mid-season	18 July	20 July
Start senescence/Maturity	01September	01 September
End-season/Harvest	10 October	14 October

by the year experiments were performed, 2001 and 2003. The effective root depths were 1.10 and 1.00 m for 2001 and 2003, respectively, based on field observations and depleted soil water (Cholpankulov et al., 2008). Therefore, *TAW* was estimated as 198 and 176 mm for 2001 and 2003, respectively.

The dates for crop growth stages for the two experiments are defined in Table 16. The planting density was 8 plants/m^2. The irrigation schedules and depths adopted are summarized in Table 17. Further information on these experiments and measurement details are provided by Cholpankulov et al. (2008).

At Fergana the water table was high and was observed frequently (Fig. 11). During 2001, the water table depth decreased from 2.5 m at the beginning of the crop season to 1.1 m at mid season, increasing again to a depth of 2.5 m at harvest; during 2003, the water table depth varied between 1.8 m and 2.5 m (Fig. 11). The variation and presence of the water table reflects the impact of deep percolation associated with excess water applications.

Observation of soil water content was performed weekly or more frequently between irrigation events, as well as before and after irrigations. Measurements were made at 27.5, 42.5, 67.5, 82.5 and 97.5 cm, with the gravimetric method used for the upper soil layer, and the neutron scattering method used for the remaining soil depths.

Table 17
Irrigation dates and depths (mm) for the furrow irrigated cotton experiments at Fergana, Uzbekistan (Cholpankulov et al., 2008).

Year	Date	Net irrigation depth (mm)
2001	02-06-2001	127
	25-06-2001	174
	11-07-2001	123
	25-07-2001	111
	07-08-2001	86
2003	15-06-2003	125
	09-07-2003	103
	24-07-2003	123
	10-08-2003	114
	26-08-2003	91
	12-09-2003	93

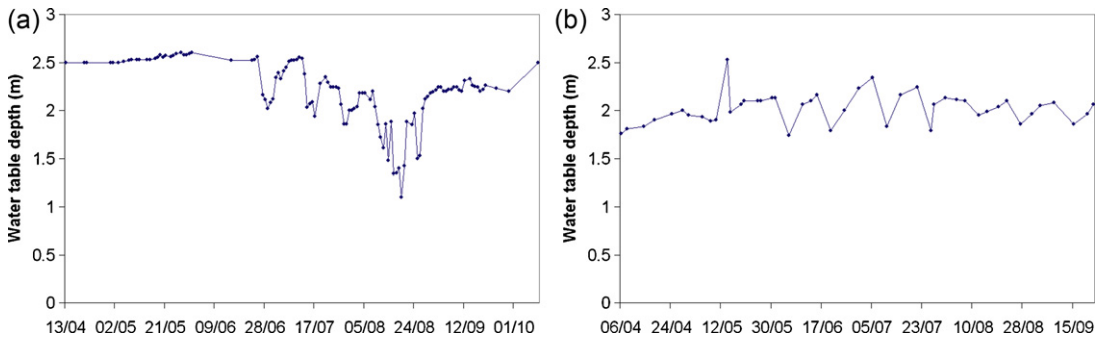

Fig. 11. Water table depth at Fergana throughout the cotton crop seasons of (a) 2001 and (b) 2003 (dots refer to observations).

5.2. Results

5.2.1. Calibration, validation and model fitting

The base values proposed by FAO-56 for K_{cb}, *p*, *REW*, *TEW* and Z_e were used during initial model simulations (Table 18). The initialization parameters for the capillary rise and percolation equations are also presented in Table 18. For the year 2001, the initial depletion in the evaporation upper soil layer was assumed to be 70% of *TEW* because the soil surface was nearly dry at planting, and 55% of *TEW* in 2003. The initial soil water depletion in lower layers of the root zone was estimated from field measurements as 4 and 7% of *TAW* for 2001 and 2003, respectively. Effective rooting depth was assumed to be 0.2 m at planting and linearly increasing to 0.4 m at the start of rapid growth, then increasing to 1.1 and 1.0 m at mid-season, respectively for the 2001 and 2003 experiments. Values for f_c were: 0 to 0.1 over the initial period, 0.1 to 0.85 over the development period, 0.85 during the mid-season, and 0.3 at harvest. f_w was equaled to 0.8 for furrow irrigation.

Simulated and observed available soil water values are compared in Fig. 12. The simulations show a large range of variation in *ASW* over time and the impact of different irrigation scheduling strategies between the two years, with a later start for irrigation in 2003. Irrigation additions were estimated to be typically in excess of retainable water as represented by field capacity and the *TAW* line in the figures. SIMDualKc simulated initially high values for *ASW* exceeding *TAW*, with drainage to *TAW* (i.e., field capacity) within one or two days following irrigation. The calibrated parameters for Fergana are presented in Table 18, where the values for $K_{cb\ mid}$ and $K_{cb\ end}$ were unchanged from those proposed by FAO-56, and $K_{cb\ ini}$ was slightly increased. The values for $K_{cb\ ini}$ and $K_{cb\ mid}$ are smaller than those presented by Hunsaker et al. (2003) but the $K_{cb\ end}$ is similar; however, the cotton varieties were different. When comparing with K_{cb} values for cotton presented by Howell et al. (2004), the $K_{cb\ ini}$ and $K_{cb\ mid}$ values are similar but estimates for $K_{cb\ end}$ are higher, probably reflecting impacts of excess irrigation as analyzed by Pereira et al. (2009). The calibrated *p* values are equal to those proposed by FAO-56. Results for $K_{cb} + K_e$ are similar to those presented by Cholpankulov et al. (2008) for the same experiments.

Table 18
Standard (initial) and calibrated basal crop coefficients, *p* depletion fractions, soil evaporation parameters, groundwater contribution and deep percolation parameters for the cotton experiments at two sites in Fergana.

	Standard[a]		Calibrated	
$K_{cb\ ini}$	0.15		0.20	
$K_{cb\ mid}$	1.15		1.15	
$K_{cb\ end}$	0.50		0.50	
p_{ini}	0.65		0.65	
p_{dev}	0.65		0.65	
p_{mid}	0.65		0.65	
p_{end}	0.65		0.65	
			Site A, 2001	Site B, 2003
REW (mm)	10		11	11
TEW (mm)	28		37	30
Z_e (m)	0.10		0.15	0.12
	Site A, 2001	Site B, 2003		
a_1	300	348	300	348
b_1	−0.32	−0.32	−0.32	−0.32
a_2	230	286	200	286
b_2	−0.16	−0.16	−0.5	−0.16
a_3	−1.4	−1.4	−1.4	−1.4
b_3	6.8	6.8	6.8	6.8
a_4	1.11	1.11	1.00	1.11
b_4	−0.98	−0.98	−0.98	−0.98
a	360	410	310	390
b	−0.017	−0.017	−0.05	−0.05

[a] From Allen et al. (1998, 2005b) and Liu et al. (2006).

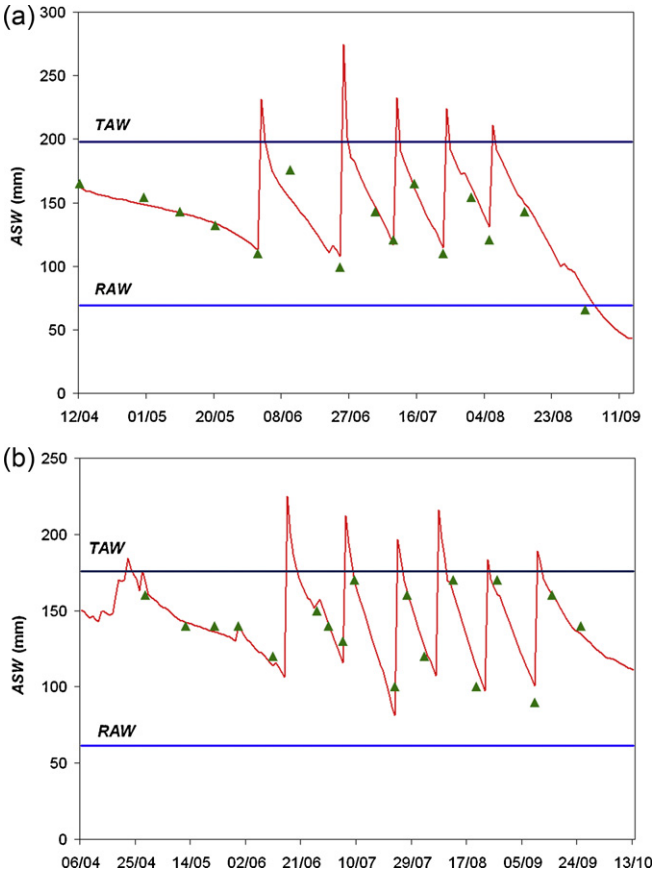

Fig. 12. Comparison between observed (▲) and simulated (▬) available soil water (*ASW*) for the cotton crop in Fergana for (a) 2001 (calibration), (b) 2003 (validation). TAW and RAW are respectively the total and readily available soil water.

Table 19
Indicators of goodness of fit relative to the model tests for cotton in Fergana when using calibrated values for *REW*, *TEW*, Z_e, K_{cb} and *p*.[a]

Goodness of fit indicators	*b*	R^2	*RMSE* (mm)	*RMSE*/*TAW* (%)	*ARE* (%)	*AAE* (mm)	*EF*	d_{IA}
Calibration (2001)	1.00	0.93	8.6	4.4	5.6	6.7	0.91	0.97
Validation (2003)	0.99	0.89	8.3	4.7	5.4	6.6	0.88	0.97
All experiments	1.00	0.90	8.6	4.6	5.7	6.8	0.89	0.97

[a] Parameter values presented in Table 18.

Table 20
Indicators of goodness of fit relative to the model tests for cotton in Fergana when using standard values (Allen et al., 1998, 2007) for *REW*, *TEW*, Z_e, K_{cb} and *p*.[a]

Goodness of fit indicators	*b*	R^2	*RMSE* (mm)	*RMSE*/*TAW* (%)	*ARE* (%)	*AAE* (mm)	*EF*	d_{IA}
2001	1.02	0.94	9.0	4.5	6.4	7.2	0.90	0.97
2003	1.00	0.89	8.1	4.6	5.4	6.6	0.89	0.97
All experiments	1.01	0.90	8.6	4.6	5.8	6.9	0.89	0.97

[a] Parameter values presented in Table 18.

Errors and other goodness of fit indicators yielded similar values for both studies (Tables 19 and 20). The goodness of fit indicators show good agreement between simulated and observed soil water content data for calibration (2001) and validation (2003) years. Only small differences occurred to *ASW* following calibration because changes were only made to *TEW* and *REW*. The regression coefficients *b* were all close to 1.0 and the coefficients of determination were high, ranging from 0.89 to 0.93. The regression for all Fergana results combined is presented in Fig. 13; it shows the regression slope to be close to the 1:1 line. The errors of estimation were small: *RMSE* was less than 9 mm and *AAE* was 7 mm, which are less than 5% of TAW. *ARE* were small, approximately 6%. The index of efficiency (*EF*) ranged from 0.88 to 0.91 and the indices of agreement (d_{IA}) were 0.97.

To investigate how well the model simulates the soil water without calibration of parameters, the model was applied to the same experiments using only standard data (*REW*, *TEW*, Z_e, K_{cb} and *p*) from Allen et al. (1998, 2007) but adopting the same, observed dates for crop stages taken from field notes. The equations for computing GW_c and *DP* were parameterized as for the calibration and validation applications. Results are shown in Table 20, with errors being only slightly higher than for the simulations using calibrated parameters. The *RMSE* remained at 8.6 mm and *ARE* increased from 5.7 to 5.8%. All *EF* and d_{IA} values are high, thus indicating that the model performed well in simulating soil water content when both standard and calibrated parameters were used. Therefore, as for maize and wheat, results for cotton show that the model may be used with standard values if dates for crop growth stages correspond to local field observations, as is recommended by FAO-56, and when groundwater contribution and deep percolation are adequately parameterized when a shallow ground-water table is present.

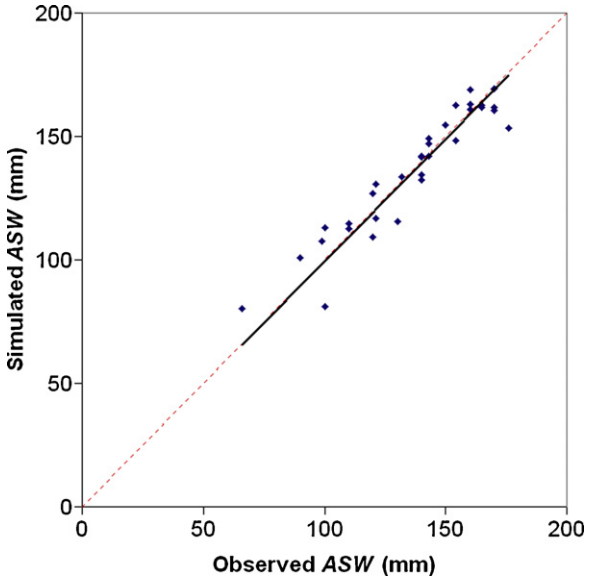

Fig. 13. Comparison between observed and simulated available soil water (*ASW*) using all experimental data for the cotton crop in Fergana, Uzbekistan, after model calibration, with the solid line representing the regression and the dashed line a 1:1 relationship.

5.2.2. Evaporation and transpiration components

The results for *E* (mm) and *T* (mm) for each experiment and crop growth stage are presented in Table 21. Soil evaporation *E* was the main component of ET_a during the initial crop growth stage for 2003, representing 68% of ET_a for that period. For 2001 *E* was only 49% of ET_a because the soil surface was relatively dry. Comparing results for the initial period at Fergana (Table 21), crop transpiration was 19 mm in 2001 and 29 mm in 2003 while soil evaporation was 18 and 63 mm, respectively in 2001 and 2003. During the crop development stage, *E* decreased substantially in relation to *T*, but for the experiment of 2001 the application of irrigation water increased soil evaporation in absolute terms when compared with the initial stage. During mid season, because soil shading effects were dominant, estimated *E* values were negligible when compared to *T* for both years. For the late season, *E* remained low, especially during 2001. Ratios of E/ET_c of 10 and 17%, are in agreement but smaller than those previously reported for Uzbekistan for different locations: Forkutsa et al. (2009) reported E/ET_c in the range of 32–40%, and Qureshi et al. (2011) reported an average of 22%. Results by Farahani et al. (2009) ranged from 16 to 34%, with the highest value for a water stressed crop.

The computed capillary rise estimated for Fergana was 42 mm for 2001 and negligible (8 mm) for 2003 because of high available soil water maintained throughout the crop growing season (Fig. 12); Deep percolation was high, 184 and 170 mm for the same years, thus reflecting poor control of irrigation water as analyzed by Pereira et al. (2009).

5.2.3. Assessing an alternative irrigation method

An alternative scenario was developed for management purposes to assess the impact of using drip irrigation on the water balance components. Climatic, soil and crop data for 2001 were used as well as the previously calibrated parameters K_{cb}, *p*, *TEW*, *REW* and Z_e. Simulations assumed a drip irrigation system having small application depths of $D = 7$ mm, i.e., daily frequencies during the peak period as suggested by DeTar (2008); for management purposes the date of the last irrigation was set at 20 days before

Table 21
Evaporation (E) and transpiration (T) over each development stage for the cotton crop, Fergana.

	Initial crop stage		Vegetative growth		Mid season		End season		Entire growing season		
	E (mm)	*T* (mm)	*E* (mm)	*T* (mm)	*E* (mm)	*T* (mm)	*E* (mm)	*T* (mm)	*E* (mm)	*T* (mm)	*E/ET* (%)
Cotton (2001)	18	19	40	235	7	258	1	75	66	586	10
Cotton (2003)	63	29	41	223	7	249	14	112	124	613	17

harvest because cotton lint quality is affected when its moisture content at harvest is higher than 8% (Barker, 1996). The f_w term, representing the fraction of soil surface wetted by irrigation was set to 0.4. Due to the small irrigation depths and very frequent water application specified for the drip system, deep growth of roots may not be promoted (Klepper, 1991). Z_r was assumed to grow at the same rate as for surface irrigation until the 4th micro-irrigation was applied, when root depth was around 0.8 m; therefore, Z_r was set to 0.8 m. The simulated irrigation schedule was targeted for no stress and for management of deep percolation. Fig. 14 presents the variation of coefficients K_{cb}, $K_{cb\ adj}$, and K_e over time as well as a summary for components of the water balance, *E, T, P, I, GW*$_c$ and ΔSW.

The model application to the alternative drip irrigation scenario estimated total water use (rainfall and irrigation) to be slightly lower than for furrow irrigation but with water balance components substantially changed. The simulated results show: () an increase of soil *E*, from 66 to 120 mm, due to high irrigation frequency during the development stage and in the late season, when the crop does not completely cover the soil, even though f_w was estimated to be small; (b) a small increase in capillary rise from 42 to 53 mm; (c) maximum values for K_e during the crop development stage were smaller than for furrow irrigation due to smaller f_w, but the average K_e was considerably higher; (d) a negligible reduction of potential K_{cb} (i.e., $K_{cb\ adj} \approx K_{cb}$), hence a higher *T* due to more soil water availability during late season; (e) a full control of deep percolation because applied depths were small (this assumes an effective and accurate water measurement and management program is in place); (f) a decrease in soil water use, with ΔSW decreasing by 48 mm, likely related to smaller root development. Overall, transpiration slightly increased because the simulated irrigation scheduling provided more adequate irrigation, although irrigation was stopped 20 days before harvest. The results show that drip irrigation by itself does not seem more beneficial than

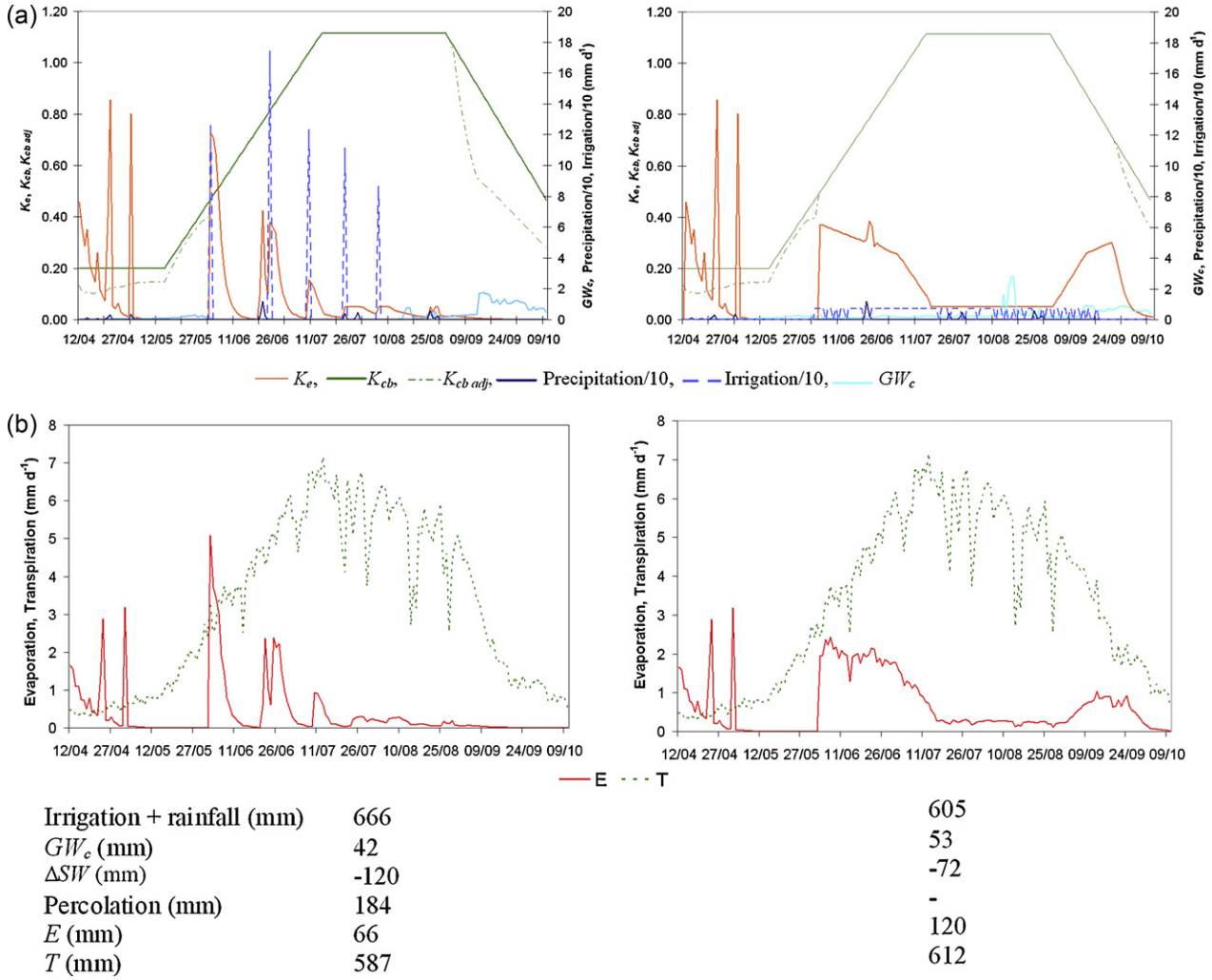

Fig. 14. Comparison of seasonal variation of K_e, K_{cb}, $K_{cb\ adj}$, irrigation/10 and precipitation/10 (a), and of *E* and *T* (b) for the current surface irrigation (left) with an alternative micro-irrigation (right) (for easier reading of the Figure, irrigation and precipitation are divided by 10).

furrow irrigation since it leads to higher water losses by evaporation, changing from 66 to 120 mm, and may not allow for leaching, which is often required in the region. Evaporation would have been even higher if a larger value for f_w had been employed, which would be the case for many forms of surface drip irrigation. If an irrigation schedule for adequate furrow irrigation is adopted, deep percolation may be controlled and *E* losses are minimized when compared with drip irrigation. The value of adopting a dual crop coefficient approach in simulating ET is again evidenced from this modeling study.

6. Conclusions

The SIMDualKc model was tested using data from experiments that were independently performed. Tests consisted of comparing model results with field measurements of *ASW* before and after calibration of basic model components of K_{cb}, threshold for stress, rooting depth, fraction of soil cover, and potential evaporation depths (*REW* and *TEW*) for maize, wheat and cotton cropped under different climates and irrigation management conditions. Soils generally had high silt and clay contents. Experimental treatments included rainfed, full and deficit irrigation, and a variety of irrigation methods. Thus, the field data represented a relatively broad spectrum of field and cultural conditions.

Comparison of simulated and observed soil water showed, for all cases, regression slopes close to the target value of 1.0, even when using standard (FAO-56) values for K_{cb}, p and soil evaporable water parameters (*TEW*, *REW* and Z_e), and indicated that the model does not show any tendency to over- or underestimate the *ASW* or the soil water content during the different crop growth stages. The coefficients of determination ranged from 0.89 to 0.99. The errors of estimates were small in terms of both *RMSE* and *AAE*. The average relative errors ranged from around 3 to 6%. The model efficiency and the index of agreement, *EF* and d_{IA}, ranged from 0.88 to 1.00 and 0.97 to 1.00, respectively. In conclusion, all indicators support the ability of the model to accurately estimate the soil water content for the crops and irrigation systems considered. These results suggest that one can analyze the partitioning of actual crop evapotranspiration into soil evaporation and crop transpiration under different water management and irrigation system types and rainfall frequencies. The respective results tend to support the assumptions underlying the dual crop coefficient approach.

In general, adjustments to standard model parameters required during calibration were small. However, computations confirmed the importance of using appropriate observations of the fractions of soil covered by vegetation, of soil wetted by irrigation and of soil wetted and exposed to solar radiation. A challenge in this study, using past observed data, was that these variables were not purposefully observed at the time of experiments. However simulations could still be performed because it was possible to reconstruct these types of observed data. It is likely that if those variable fractions had been purposefully observed simulations would have been more accurate.

The model accuracy is considered to be good, considering the conditions of this study, where observation data collected in the past with objectives that were different from this particular model testing were utilized. Results indicate that the model effectively implemented the dual crop coefficient approach for assessing crop irrigation water uses and scheduling and that the dual K_c approach was adequate to simulate the observed *ASW* data. This study also shows that using standard K_{cb}, p and soil evaporable water parameters from FAO-56 provides soil water and *ET* estimates having acceptably small errors, provided that dates for crop growth stages corresponding to field conditions are observed or approximated and that fractions of ground cover, soil wetted and soil exposed and wetted are selected that effectively characterize the crop canopy throughout the season.

All three case studies were also used to develop and assess scenarios for changes in irrigation methods and management. Results demonstrated the ability of the model to deal with those different conditions and to assess changes in the water balance components due to adopting different irrigation depths and schedules. However, conclusions for these simulations should be interpreted with caution despite that results are in agreement with common knowledge on these topics.

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