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Simulation of the soil water balance of wheat using daily weather forecast messages to estimate the reference evapotranspiration

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Abstract

Aiming at developing real time water balance modelling for irrigation scheduling, this study assesses the accuracy of using the reference evapotranspiration (ET_o) estimated from daily weather forecast messages ($ET_{o,WF}$) as model input. A previous study applied to eight locations in China (Cai et al., 2007) has shown the feasibility for estimating $ET_{o,WF}$ with the FAO Penmam-Monteith equation using daily forecasts of maximum and minimum temperature, cloudiness and wind speed. In this study, the global radiation is estimated from the difference between the forecasted maximum and minimum temperatures, the actual vapour pressure is estimated from the forecasted minimum temperature and the wind speed is obtained from converting the common wind scales into wind speed. The present application refers to a location in the North China Plain, Daxing, for the wheat crop seasons of 2005–2006 and 2006–2007. Results comparing $ET_{o,WF}$ with ET_o computed with observed data ($ET_{o,\mathrm{obs}}$) have shown favourable goodness of fitting indicators and a RMSE of 0.77 mm d^{-1}. ET_o was underestimated in the first year and overestimated in the second. The water balance model ISAREG was calibrated and validated for both years using $ET_{o,\mathrm{obs}}$ by comparing the predicted and observed soil water content relative to various irrigation treatments. The calibrated crop parameters were used in the simulations of the same treatments using $ET_{o,WF}$ as model input. Errors in predicting the soil water balance are small, 0.010 and 0.012 m^3 m^{-3} respectively for the first and second year. Other indicators also confirm the goodness of model predictions. It could be concluded that using ET_o computed from daily weather forecast messages provides for accurate model predictions, thus making it viable to use an irrigation scheduling model in real time with daily weather forecast messages.

1 Introduction

Recent developments in irrigation management consist in real-time irrigation decision-making. This requires that appropriate weather data are available to perform soil water balance computations for accurately predict the timing and volumes of irrigation. Real-time irrigation scheduling has proved appropriate when using weather data forecasts provided by commercial services to estimate the reference evapotranspiration (ET_o). Applications are reported for several crops such as potato (Gowing and Ejieji, 2001), lettuce (Wilks and Wolfe, 1998) and maize (Cabelguenne et al., 1997). In alternative to weather data forecasts, generated weather data produced by a climatic data generator may also be used (Donatelli et al., 2003; Stöckle et al., 2003, 2004).

Another approach to real-time irrigation scheduling consists of deriving actual crop coefficients (K_c) from remote sensing and using ground and satellite weather data to estimate the actual crop evapotranspiration (ET_c) for determining irrigation requirements. Various applications and modelling approaches are reported with applications for estimation of actual ET_c at regional or irrigation system scales (Ray and Dadhwal, 2001; Consoli et al., 2006; Tasumi and Allen, 2007). Relative to the field scale, Hunsaker et al. (2005) developed a model for determining wheat basal crop coefficients from observations of the normalized difference vegetation index (NDVI) and to estimate wheat evapotranspiration using the FAO-56 procedures. Chavez et al. (2008) computed daily ET_c from instantaneous latent heat flux estimates derived from digital airborne multispectral remote sensing imagery. Reviews are presented by Courault et al. (2005) and Gowda et al. (2008). Applications aiming at using crop coefficients estimated from remote sensing for supporting irrigation scheduling have been reported recently (Calera Belmonte et al., 2005; Garatuza-Payan and Watts, 2005; Santos et al., 2008). The mentioned applications refer to relatively large fields; when small fields (0.1–0.5 ha) are considered, as it is the case in China, the use of remote sensing data is not appropriate due to pixel size limitations.

To develop real-time irrigation management for North China, a different approach was developed combining weather data forecast messages produced by the China

Meteorological Administration with an irrigation scheduling simulation model. This approach allows to determine in real-time both the crop evapotranspiration (ET_c) and the available soil water, thus to determine when and how much to irrigate.

The FAO Penman-Monteith reference evapotranspiration (PM-ET_o) equation (Allen et al., 1998) is worldwide adopted as the standard method to compute ET_o from meteorological data. Numerous papers that either compare several equations or adopt the concepts behind its formulation confirm the goodness of the PM-ET_o equation. Its computation requires weather data on maximum and minimum temperature (T_{max} and T_{min}), solar radiation (R_s), relative humidity (RH) and wind speed at 2 m height (u_2). Alternative calculation procedures proposed by Allen et al. (1998) to be adopted when not all these data are available were tested and validated in China (Liu and Pereira, 2001; Pereira et al., 2003a) and elsewhere (Popova et al., 2006b; Jabloun and Sahli, 2008).

Considering that good results were obtained for North China using those alternative procedures, a new analytic methodology for computing the PM-ET_o equation using weather forecast messages (WF) has been developed (Cai et al., 2007). It was tested for several locations in China at different latitudes and longitudes representing various climates. ET_o estimated with WF data can thus be used as input to a simulation model for real-time irrigation scheduling. Testing this approach using the model ISAREG, which has been previously calibrated and validated in North China (Liu et al., 1998, 2006), constitutes the main objective of this research.

The purpose of this paper is to examine the accuracy of using the WF estimates of ET_o ($ET_{o,WF}$) when compared with those obtained when the PM-ET_o equation is used with observed weather data ($ET_{o,\text{obs}}$). The paper includes the calibration and validation of the model using observations of the soil water content as well as the comparison of results of the same model when $ET_{o,WF}$ are used as model inputs. The application refers to various irrigation treatments of a wheat crop at Daxing, in the North China Plain.

2 Material and methods

2.1 Reference ET estimations

For the purpose of this study, two sets of weather data were used to estimate ET_o: one using hourly observations from a nearby weather station, which computed daily values and are referred hereafter as $ET_{o,\text{obs}}$; the other consisting of weather forecast messages from the public media, which estimated daily values are referred as $ET_{o,WF}$.

The daily ET_o (mm d^{-1}) was computed with the PM-ET_o equation (Allen et al., 1998):

$$ET_o = \frac{0.408\Delta\left(R_n - G\right) + \gamma\frac{900}{T+273}u_2\left(e_s - e_a\right)}{\Delta + \gamma\left(1 + 0.34u_2\right)} \tag{1}$$

where R_n is the net radiation at the crop surface (MJ m^{-2} d^{-1}), G is soil heat flux density (MJ m^{-2} d^{-1}), T is the air temperature at 2 m height (°C), u_2 is the wind speed at 2 m height (m s^{-1}), e_s is the vapour pressure of the air at saturation (kPa), e_a is the actual vapour pressure (kPa), Δ is the slope of the vapour pressure curve (kPa °C^{-1}), and γ is the psychrometric constant (kPa °C^{-1}). G may be ignored for daily time step computations.

The ET_o estimation procedure using WF data (Cai et al., 2007) consists of estimating the parameters of Eq. 1 from the weather forecast messages relative to daily maximum and minimum air temperatures, wind grade and weather conditions (such as sunny, cloudy, rainy). The forecasted values of $T_{\max}$ and $T_{\min}$ (°C) are used similarly to the observed ones in ET_o computations. The daily actual vapour pressure (e_a) is estimated from the forecasted daily $T_{\min}$ adopting the following equation (Allen et al, 1998):

$$e_a = e^0\left(T_{\min}\right) = 0.611\exp\left[\frac{17.27T_{\min}}{T_{\min} + 237.3}\right] \tag{2}$$

where e_a is the actual vapour pressure (kPa) and $e^0(T_{min})$ is the saturation vapour pressure at T_{min} (kPa).

In the former study (Cai et al., 2007), the global radiation R_s (MJ m^{-2} d^{-1}) was estimated from the forecasted "weather condition" referring to five cloudiness conditions: clear sky, clear to cloudy, cloudy, overcast and rainy. The actual duration of sunshine hours n was then estimated from the day time duration N as n=aN, where the parameter a assumed the values 0.9, 0.7, 0.5, 0.3 and 0.1 respectively for the five cloudiness conditions referred above. Then R_s was computed with the Angström equation. However, considering the good results obtained for the estimation of R_s from the difference $T_{max}-T_{min}$ (Liu and Pereira, 2001; Popova et al., 2006a, 2006b; Jabloun and Sahli, 2008), the above mentioned procedure was replaced in this study by the Hargreaves' radiation equation modified by Allen et al. (1998):

$$R_s = k_{Rs}\,(T_{max} - T_{min})^{0.5}\,R_a \tag{3}$$

where k_{Rs} is the adjustment coefficient (°C$^{-0.5}$), and R_a is the radiation on top of the atmosphere (MJ m^{-2} d^{-1}). k_{Rs} is empirical and differs for "interior" or "coastal" regions. For "interior" locations, where land mass dominates and air masses are not strongly influenced by a large water body, $k_{Rs}\approx0.17$; for "coastal" locations, situated on or adjacent to the coast of a large water body and where air masses are influenced by that water body, $k_{Rs}\approx0.19$.

The daily wind speed (u_z) at height z (m) is obtained from the weather forecast messages of wind grade relative to the standards of meteorological observation (CMA, 2003) using a conversion table reported by Cai et al. (2007). The wind speed at 2 m height (u_2) is then obtained from u_z through the following equation:

$$u_2 = u_z \frac{4.87}{\ln(67.8z-5.42)} \tag{4}$$

where u_2 is the wind speed at 2 m height (m s^{-1}), u_z is the measured wind speed at height z ($\mathrm{m\,s^{-1}}$), and z is the height of wind measurements above the ground surface (m).

2.2 Field experiments and data collection

Field experiments with winter wheat (*Triticum aestivum* L.) were carried out at the Irrigation Experiment Station of the China Institute of Water Resources and Hydropower Research (IWHR) at Daxing, south of Beijing (39°37′ N latitude, 116°26′E longitude and 40.1 m a.s.l. elevation). The climate in the experimental site is semiarid to sub-humid, with cold and dry winter and hot and humid summer, when monsoon rains occur. The average values of main climatic variables are presented in Fig. 1 relative to the winter wheat growing season.

The soil is sandy loam, with average field capacity (θ_{FC}) and wilting point (θ_{WP}) of 0.334 and 0.128 $\mathrm{m^3\,m^{-3}}$ in the crop root zone (1 m depth). The main soil hydraulic properties are presented in Table 1. Observations have shown that the groundwater table is generally deeper than 18 m; therefore, capillary rise was not considered in the soil water balance calculations.

The experiments were developed during two winter wheat growing seasons, 2005–2006 and 2006–2007. The daily ET_o and precipitation for both seasons are shown in Fig. 2. The wheat crop season developed from 10 October to 18 June for both years. The total precipitation was 99.6 mm for 2005–2006 and 112.6 mm for 2006–2007. In this season there were less rainfall events than for the 2005–2006 period. Differences in rainfall distribution explain differences in irrigation treatments in those years.

The experiments were performed using a randomized block design with three or more replications for a total of 15 plots. Every plot was 5.5 m×5.5 m in a N-S row direction. There were four irrigation treatments for 2005–2006 and five for 2006–2007 as described in Table 2. All irrigation treatments were performed under surface irrigation and conventional tillage. Irrigations were applied taking as upper limit the soil water at field capacity. Water applications were controlled by an automated low pressure valve.

The soil water content was measured every 4 days in each plot with two replicates using a TRIME probe system from 0.2 to 1.2 m depth with observations every 0.2 m. For the surface layer, soil samples were taken to be dry in the oven. Crop heights were observed every ten days. Field measurements were performed only after the soil defrosts, when the crop starts growing by the end of winter.

An automatic weather station was installed in the experimental station. This provided for measurements of air temperature, relative humidity, global and net radiation, wind speed at 2 m height, soil temperature at various depths, and precipitation. Data were collected every 30 min and integrated to the hour. These hourly values were used to compute the $ET_{o,\mathrm{obs}}$ adopting the procedures described by Allen et al. (1998, 2006). The $ET_{o,WF}$ was computed daily from the weather forecast messages available from the Beijing Daily Newspaper acceded through the web. This allowed adopting automatic digital processing of those messages to compute $ET_{o,WF}$.

2.3 Simulation of the soil water balance

The ISAREG model was used to simulate the soil water balance for all treatments using both $ET_{o,\mathrm{obs}}$ and $ET_{o,WF}$ as inputs, which allowed to assess the accuracy of $ET_{o,WF}$ as input for modelling.

ISAREG is an irrigation scheduling simulation model that performs the soil water balance at the field scale. The model is described with detail by Teixeira and Pereira (1992), Liu et al. (1998) and Pereira et al. (2003b). The latter describes the Windows version of the model that was used for the simulations. Inputs are precipitation, reference evapotranspiration (ET_o), total and readily available soil water, soil water content at planting or first day of simulations, and crop factors relative to crop growth stages: crop coefficients, root depths and soil water depletion fractions for no stress. These crop factors refer to four crop development periods: initial (which comprises a period when the soil is frozen), crop development, mid season and end season. The actual crop ET is computed using the single crop coefficient approach (Allen et al., 1998) as a function of the available soil water when it is below the non-stress

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threshold. ISAREG has two auxiliary programs, EVAP56 to compute ET_o, and KCISA to estimate the crop factors. EVAP56 performs the calculation of ET_o with any of the alternative methods proposed in the FAO-56 guidelines (Allen et al., 1998) depending on the availability of weather data. ISAREG has been validated in numerous applications (e.g. Liu et al., 1998, 2006; Popova et al., 2006a; Cholpankulov et al., 2008).

The soil water balance was performed with a daily time step as:

$$SW_i = SW_{i-1} + P_{e,i} + I_i + G_{c,i} - ET_{a,i} - D_{r,i} \quad (5)$$

where SW_i is the soil water content in the crop root zone at the end of day i (mm); SW_{i-1} is the soil water content at the end of the previous day, i-1 (mm); $P_{e,i}$ is the precipitation on day i (mm); I_i is the net irrigation depth on day i that infiltrates the soil (mm); $G_{c,i}$ is the capillary rise from the groundwater table on day i (mm); $ET_{a,i}$ is the actual crop evapotranspiration on day i (mm), $D_{r,i}$ is the deep percolation out of the root zone on day i (mm). $G_{c,i}$ was neglected because the groundwater table was generally below 18 m depth; $D_{r,i}$ was computed using the parametric approach described by Liu et al. (2006).

2.4 Indicators to assess the accuracy of ET_o estimates and model simulations

ET_o estimates with observed and forecasted weather data, respectively $ET_{o,\mathrm{obs}}$ and $ET_{o,WF}$, were compared and the accuracy of WF predictions were evaluated through the linear regression forced to the origin and adopting other statistical indicators: the root mean square error, the relative error, the Willmott index of agreement and the modelling efficiency. The same indicators were used to evaluate the accuracy of model predictions of the soil water content compared with the soil water observations relative to the treatments referred above. This evaluation was performed for both the model calibration and validation and for model testing when $ET_{o,WF}$ was used.

The mentioned statistical indicators (Loague and Green, 1991; Legates and MacCabe, 1999; Cholpankulov et al., 2008) are defined as follows:

- Coefficient of regression, b (when the regression is forced to the origin):

$$b = \frac{\sum_{i=1}^{m} O_i \times P_i}{\sum_{i=1}^{m} O_i^2} \tag{6}$$

- Coefficient of determination, R^2:

$$R^2 = \left\{ \frac{\sum_{i=1}^{m} \left(O_i - \overline{O}\right)\left(Pi - \overline{P}\right)}{\left[\sum_{i=1}^{m} \left(O_i - \overline{O}\right)^2\right]^{0.5} \left[\sum_{i=1}^{m} \left(P_i - \overline{P}\right)^2\right]^{0.5}} \right\}^2 \tag{7}$$

- Root Mean Square Error, RMSE:

$$\mathrm{RMSE} = \left[\frac{\sum_{i=1}^{m} (P_i - O_i)^2}{m} \right]^{0.5} \tag{8}$$

- Relative Error, RE:

$$RE = \frac{\mathrm{RMSE}}{\overline{O}} \tag{9}$$

- Modelling efficiency, EF:

$$EF = 1.0 - \frac{\sum_{i=1}^{m} (O_i - P_i)^2}{\sum_{i=1}^{m} \left(O_i - \overline{O}\right)^2} \tag{10}$$

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– The Willmott index of agreement, d:

$$d = 1 - \frac{\sum_{i=1}^{m} (O_i - P_i)^2}{\sum_{i=1}^{m} \left(\left| P_i - \overline{O} \right| + \left| O_i - \overline{O} \right| \right)^2} \tag{11}$$

where the m is the number of observations, O_i and P_i are respectively the ith observed and predicted data; $\overline{O}$ is the average value forO_i with $i = 1, 2, \ldots$, m, $\overline{P}$ is the average of the data arrays of P_i. The values of EF and d vary from 0 to 1'0 according to the quality of model fitting and are desirably close to 1.0. The estimation error indicators RE and RMSE are hoped to be as small as possible. When R^2 is close to 1.0 indicates that the variance of the estimation errors is small. The coefficient b may be larger or smaller than 1.0 when there is respectively overestimation or underestimation of the target variable.

3 Results and discussion

3.1 Comparing ET_o estimates obtained from observed and forecast messages weather data

As analysed by Cai et al. (2007), the weather forecasted data do not exactly match those observed and leads to over- or underestimation of the climatic parameters of the Penman-Monteith reference evapotranspiration and respective results. Figure 3 compares the daily values of ET_o computed with observed weather data ($ET_{o,\mathrm{obs}}$) and with WF data ($ET_{o,WF}$). For the wheat crop season 2005–2006 $ET_{o,WF}$ is underestimated relative to $ET_{o,\mathrm{obs}}$ while for 2006–2007 $ET_{o,WF}$ is overestimated. Considering the regression forced to the origin when comparing both sets of daily ET_o values, the regression coefficients are respectively 0.88 and 1.16. The corresponding R^2 values are high, respectively 0.83 and 0.85.

Results for both years are summarized in Table 3. The RMSE values are 0.76 and 0.77 mm d^{-1} respectively for the 2005–2006 and 2006–2007 crop seasons. These values are near to the upper range of those referred by Cai et al. (2007) for eight locations in China. The relative errors are 0.27 and 0.39, which are larger than those computed for those eight locations. These RE values decrease to 0.18 and 0.25 when only the data relative to the period after crop reviving are considered because the ET_o values are then larger than those for the autumn and winter period, thus impacts of inaccuracy in weather forecasting result less important than during the spring-summer period. The values for the index d are high (0.94 and 0.95) but smaller than those in the mentioned original study (Cai et al., 2007). The modelling efficiency EF are also high, 0.75 and 0.77 respectively for 2005–2006 and 2006–2007.

These results indicate that estimating ET_o from weather forecast messages is feasible but the accuracy of estimation is smaller than expected from the former study. This may be explained by the fact that in the present study the forecasted values refer to a non synoptic weather station while the former study (Cai et al., 2007) was performed for synoptic stations explored by the China Meteorological Administration (CMA). These results indicate that daily forecast messages may be used for ET_o computations for agrometeorological weather stations non-explored by the CMA but the expected forecasting accuracy is smaller than for synoptic stations. This fact justifies the need to assess the impacts of using $ET_{o,WF}$ estimates instead of $ET_{o,\text{obs}}$ when performing the soil water balance for irrigation scheduling, whose results are analysed below.

3.2 Model calibration and validation

The calibration and validation of the model ISAREG was performed using $ET_{o,\text{obs}}$ data. Irrigation treatments data for 2005–2006 was used for the calibration and those of 2006–2007 were used for validation. The calibration led to select appropriate values for the crop coefficients K_c and the depletion fractions p, which are given in Table 4. The calibration was performed iteratively until the simulated soil water content matches the observed one. Initial values for the crop parameters were those tabled by Allen et al. (1998) after being corrected for climate. The simulations concern the period after soil defrost or crop reviving, i.e. the crop development, mid season and end season stages.

Results comparing the soil water content observed and simulated for the calibration are shown in Fig. 4 for two treatments (W2 and W3) and in Fig. 5a relative to all treatments. The statistical indicators for the goodness of model fitting are presented in Table 5. For the four treatments, the coefficient of regression range 0.98 to 1.02, thus very close to the target 1.0 value. The determination coefficients are quite high, ranging 0.85 to 0.96. The estimation errors are small, with RMSE varying in a very short range (0.006 to 0.008 $m^3 m^{-3}$) and with *RE* ranging from 0.024 to 0.035. The values for *d* and *EF* show that model fitting is good, with d ranging 0.94 to 0.99 and *EF* varying from 0.69 to 0.97. These results show that the simulated soil water content matches well with the observed values, i.e., the model accurately simulates the soil water balance of the wheat crop when the calibrated parameters are used.

The results for the validation with field data from the treatments of 2006–2007 are similar to those obtained for the calibration (Figs. 4 and 5b, and Table 5). The *b* values are just slightly higher than those for the calibration and R^2 range from 0.62 to 0.93. The estimations errors are also slightly higher than for the calibration, with RMSE=0.010 $m^3 m^{-3}$ and *RE*=0.034 when all treatments are considered. The *d* and *EF* indices are consequently slightly smaller than those for the calibration, with *d* ranging 0.90 to 0.98 and *EF* ranging 0.66 to 0.92. Considering both the calibration and validation results, it can be concluded that the model performed very well to predict the soil water content of the wheat crop during the development, mid-season and end-season crop stages.

3.3 Accuracy of model predictions when ET_o is estimated from weather forecast messages

The treatments W1 to W4 in 2006 and T1 to T5 in 2007 were simulated with the model using the calibrated crop parameters given in Table 4 and adopting as model input the

WF estimated $ET_{o,WF}$ instead of $ET_{o,\mathrm{obs}}$. The initial soil water content values used for these simulations are the same as for the calibration and validation. Results for the goodness of model predictions of the soil water content are given in Table 6. Selected simulation results relative to the treatments W2 and W4 in 2006, and T3 and T4 in 2007 are shown in Fig. 6. Results of the regression forced to the origin for both crop seasons are presented in Fig. 7.

The coefficients of regression are close to 1.0 (Table 6), ranging 1.0 to 1.04 for 2006 and from 0.96 to 1.0 in 2007, i.e., there is a slight overestimation of the soil water content in 2006 and underestimation in 2007. These trends are different of those observed when $ET_{o,\mathrm{obs}}$ was used (Table 5) because $ET_{o,WF}$ was respectively under- and overestimated in the same years. Nevertheless, differences in b values are very small when the $ET_{o,\mathrm{obs}}$ or $ET_{o,WF}$ data sets are used. The determination coefficients are also similar but those relative to using $ET_{o,WF}$ are slightly smaller than those obtained for the calibration and validation of the model. They range 0.78 to 0.97 for the first year and 0.74 to 0.93 for the second.

When computations are performed with $ET_{o,WF}$ the estimation errors RMSE and RE are small but slightly larger than those using $ET_{o,\mathrm{obs}}$. Considering all treatments, RMSE is 0.010 and 0.012 $\mathrm{m^3\,m^{-3}}$ for respectively 2006 and 2007 while RE is 0.041 and 0.043 for the same years. These good results are confirmed by the d and EF indices, whose values range respectively from 0.89 to 0.98 and from 0.55 to 0.93 when considering both years. Results in Fig. 7 confirm the goodness of fitting for all treatments simulated.

These results indicate that when the soil water balance is performed with a proper modelling approach it is possible to use as model input the reference evapotranspiration estimates $ET_{o,WF}$ with appropriate accuracy. It is then possible to run a model in real time with daily inputs of $ET_{o,WF}$ and actual observations of precipitation.

4 Conclusions

This study confirmed that the reference evapotranspiration can be accurately estimated from daily weather forecast messages using the FAO Penman Monteith equation. With this approach the global radiation is estimated from the difference between the forecasted maximum and minimum temperatures, the actual vapour pressure is estimated from the forecasted minimum temperature and the wind speed is obtained from converting the common wind scales used by the China Meteorological Administration into wind speed. The estimated ET_o shows a RMSE of 0.77 mm d^{-1} and acceptable indicators for the goodness of fitting when compared with the ET_o computed with observed weather data. However, this application to an agrometeorological station produced worse results than those obtained when the estimations were done for synoptic weather stations explored by the China Meteorological Administration. These results indicate that daily forecast messages may be used for ET_o computations for non-synoptic agrometeorological stations non-explored but the expected forecasting accuracy is smaller than for synoptic stations.

To assess the impacts of using $ET_{o,WF}$ estimates instead of $ET_{o,\mathrm{obs}}$ when modelling the soil water balance for irrigation scheduling, the model ISAREG was first calibrated and validated for several winter wheat treatments and using $ET_{o,\mathrm{obs}}$ as input data for the crop seasons of 2005–2006 and 2006–2007. Simulations were performed for the period after soil defrost and crop reviving after the winter, thus during the development, mid-season and end-season crop stages. The respective results show that the simulated soil water content matches well with the observed values, i.e., the model accurately simulates the soil water balance of the wheat crop when the calibrated parameters are used.

The results of the simulations relative to both crop seasons and the same irrigation treatments using $ET_{o,WF}$ have also shown that the simulated soil water content matches well with the observed values. In the present study, the RMSE values ranged from 0.007 to 0.016 m^3 m^{-3}, which indicates a good modelling accuracy. Other model fitting indicators confirm this accuracy. It can be concluded that when the soil water balance is performed with a proper modelling approach and using a calibrated model it is appropriate to use as model input the reference evapotranspiration estimated from daily weather forecast messages. Since the objective of the study is to use daily weather forecast messages to perform the water balance simulations for real time irrigation scheduling, results described above allow to consider that this approach is feasible, i.e. running a calibrated/validated model in real time with daily inputs of $ET_{o,WF}$ and actual observations of precipitation. Further research is required to extrapolate ET_o estimates from the local to the regional scale, so widening the applicability of real time irrigation scheduling.

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Table 1. Main soil hydraulic properties in Daxing experimental station.

Layer	Depth (cm)	Particle density ($g\,cm^{-3}$)	Saturated water content ($cm^3\,cm^{-3}$)	Field capacity ($cm^3\,cm^{-3}$)	Wilting point ($cm^3\,cm^{-3}$)
1	0–10	1.30	0.46	0.32	0.09
2	10–20	1.46	0.46	0.34	0.13
3	20–40	1.48	0.47	0.35	0.10
4	40–60	1.43	0.45	0.33	0.11
5	60–100	1.39	0.44	0.31	0.16

Table 2. Irrigation treatments for the wheat crop in both seasons.

Crop season	Treatment	Initial stage	Development stage	Mid-season stage	Late stage
2005–2006	W1	90 mm (20/11)			
	W2	90 mm (20/11)	90 mm (05/04)	80 mm (12/5)	
	W3	90 mm (20/11)	65 mm (05/04)	80 mm (05/04)	
	W4	90 mm (20/11)	115 mm (05/04)	115 mm (12/05)	
2006–2007	T1	90 mm (18/11)	30 mm (06/04)[1]	60 mm (21/04) 63 mm (07/05)	67 mm (04/06)
	T2	90 mm (18/11)	30 mm (06/04)[1]	97 mm (30/04) 84 mm (14/05)	
	T3	90 mm (18/11)	30 mm (06/04)[1]	102 mm (07/05)	
	T4	90 mm (18/11)	30 mm (06/04)[1]	65 mm (26/04)	86 mm (04/06)
	T5	90 mm (18/11)	30 mm (06/04)[1]	96 mm (07/05)	70 mm (04/06)

[1] Fertilizers were applied with this irrigation event.

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Table 3. Statistical indicators comparing ET_o computations using fully observed data sets ($ET_{o,\mathrm{obs}}$) and weather forecasted data ($ET_{o,WF}$) for two wheat crop seasons.

	b	R^2	RMSE	RE	EF	d
2005–2006	0.88	0.83	0.764	0.272	0.75	0.94
2006–2007	1.16	0.85	0.771	0.389	0.77	0.95

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Table 4. Wheat crop coefficients K_c and depletion fractions for no stress p obtained from model calibration in the crop season of 2005–2006.

Crop growth stages	Dates[1]	K_c	p
Crop development	(01/03-20/04)	0.40–1.00	0.50
Mid-season	(21/04-31/05)	1.00	0.50
End season	(01/06-18/06)	1.00–0.30	0.60

Table 5. Statistical indicators for model goodness of fitting when comparing the soil water content observed and predicted by the model for the treatments used for calibration and validation.

	b	R^2	RMSE ($m^3 m^{-3}$)	*RE*	*EF*	*d*
Calibration (2005–2006)						
W1	0.98	0.85	0.007	0.035	0.69	0.94
W2	0.98	0.92	0.008	0.035	0.89	0.97
W3	0.99	0.89	0.006	0.027	0.88	0.97
W4	1.02	0.96	0.006	0.024	0.97	0.99
All treatments	0.99	0.97	0.007	0.030	0.96	0.99
Validation (2006–2007)						
T1	1.02	0.75	0.009	0.030	0.77	0.93
T2	1.02	0.62	0.003	0.010	0.66	0.90
T3	1.00	0.88	0.008	0.028	0.92	0.98
T4	1.02	0.93	0.010	0.037	0.92	0.98
T5	1.01	0.87	0.010	0.034	0.89	0.97
All treatments	1.01	0.92	0.010	0.034	0.88	0.97

Table 6. Statistical indicators for model goodness of fitting when comparing the soil water content observed and predicted by the model when ET_o was estimated from weather forecast messages ($ET_{o,WF}$).

	b	R^2	RMSE ($m^3\,m^{-3}$)	*RE*	*EF*	*d*
2005–2006						
W1	1.01	0.78	0.007	0.037	0.64	0.93
W2	1.02	0.92	0.010	0.039	0.87	0.97
W3	1.04	0.83	0.012	0.052	0.55	0.89
W4	1.00	0.97	0.009	0.035	0.93	0.98
All treatments	1.03	0.95	0.010	0.041	0.92	0.98
2006–2007						
T1	0.98	0.74	0.012	0.041	0.57	0.90
T2	1.00	0.78	0.009	0.031	0.78	0.94
T3	0.96	0.84	0.016	0.057	0.69	0.93
T4	0.99	0.93	0.010	0.037	0.92	0.98
T5	0.98	0.80	0.013	0.046	0.80	0.94
All treatments	0.99	0.82	0.012	0.043	0.81	0.95

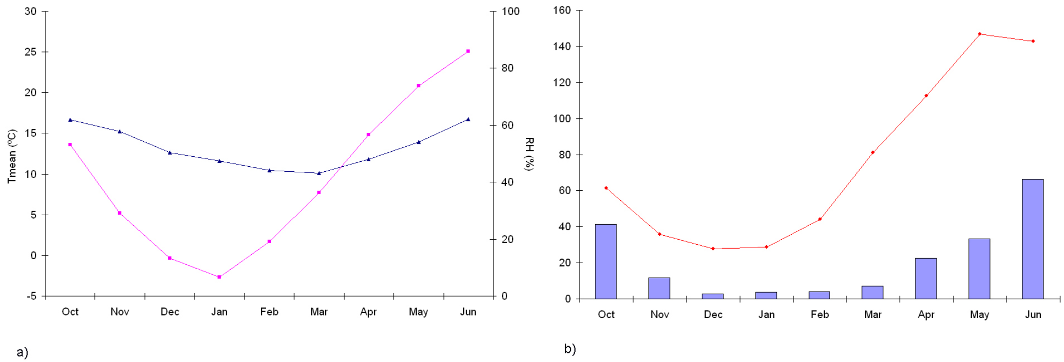

Fig. 1. Average weather characteristics of the winter wheat crop season at Daxing, 1995–2005: **(a)** monthly temperature (—■—) and relative humidity (—▲—); **(b)** monthly precipitation (▢) and reference evapotranspiration, ET_o (—●—).

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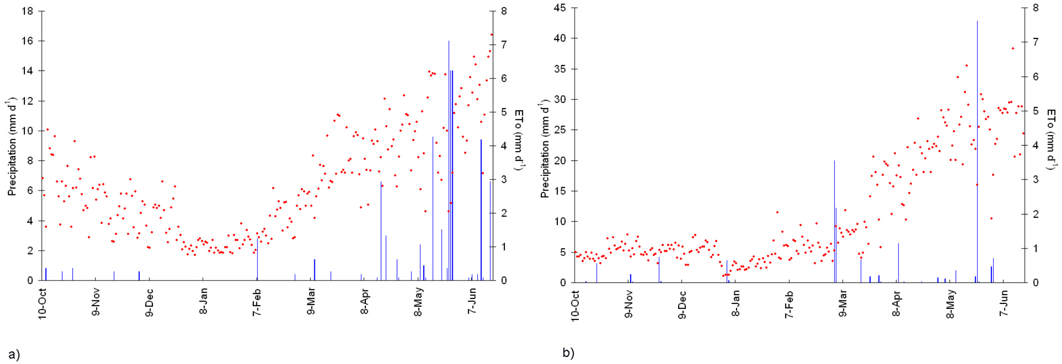

Fig. 2. Daily ET_o (•) and precipitation (|) during the wheat experiments: **(a)** 2005–2006; and **(b)** 2006–2007.

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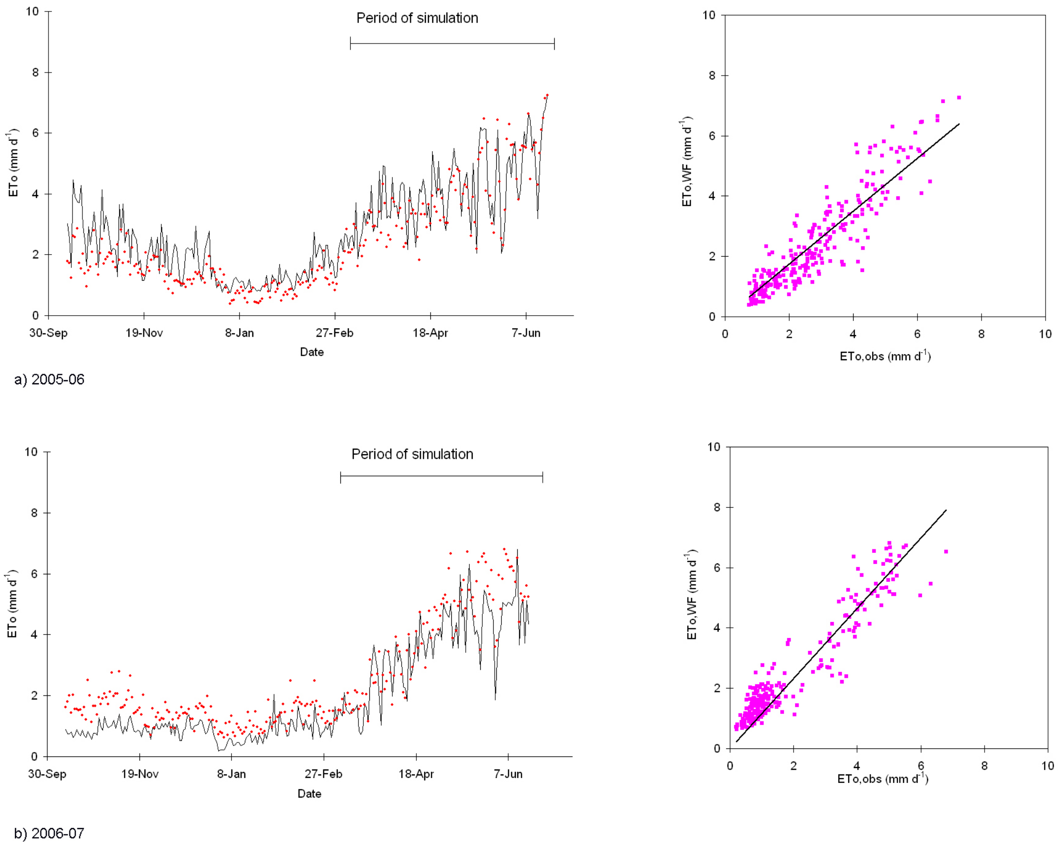

Fig. 3. Comparison of the ET_o values computed from observed and weather forecast messages data for the wheat crop season **(a)** for 2005–2006 and **(b)** for 2006–2007. On the left, the daily course of $ET_{o,\mathrm{obs}}$, (—) and $ET_{o,WF}$ (•) from planting (October) to harvesting (June); on the right, the respective regression forced to the origin.

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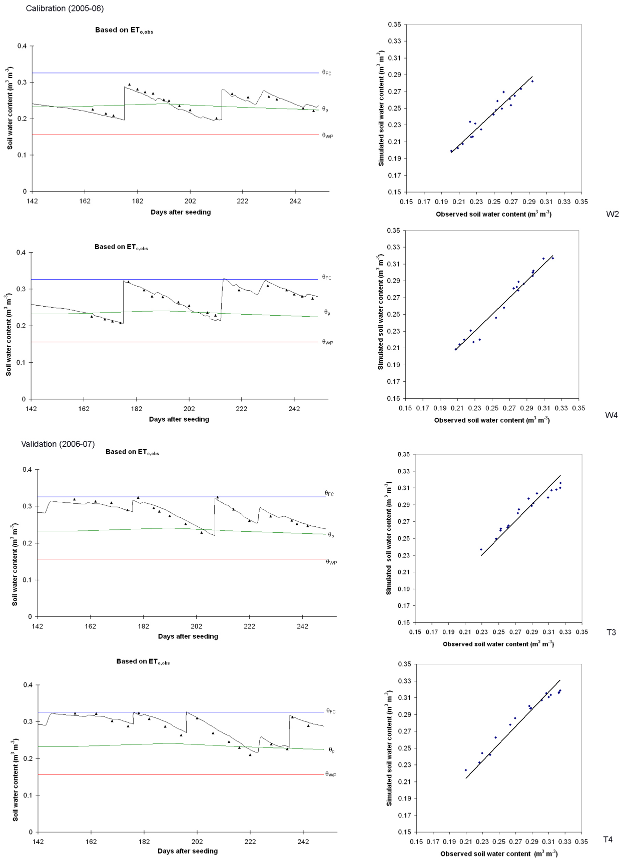

Fig. 4. Comparing the soil water content observed and predicted by the model for two calibration treatments (W2 and W4) and two validation treatments (T3 and T4). On the left, the daily course of the soil water; on the right, the respective regressions forced to the origin. The lines of θ_{FC}, θ_p and θ_{WP} refer to the soil water content at field capacity, at the depletion fraction for no stress and at the wilting point, respectively.

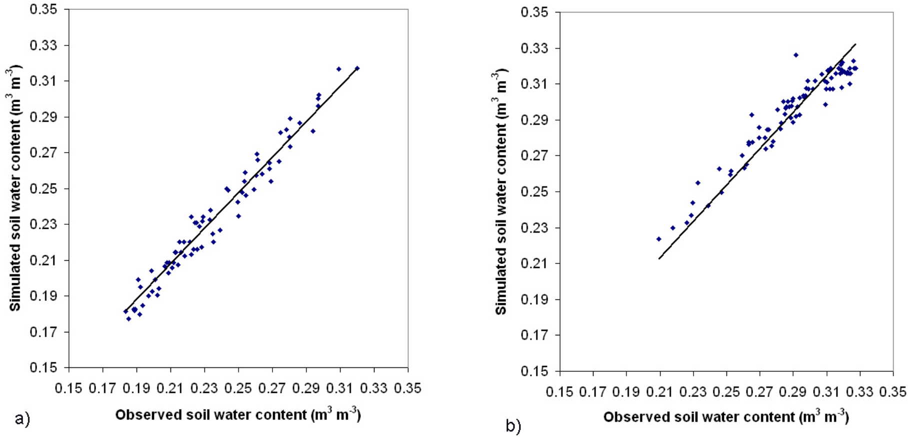

Fig. 5. Linear regression forced to the origin comparing the observed and model predicted soil water content relative to all treatments used for calibration **(a)** and validation **(b)**.

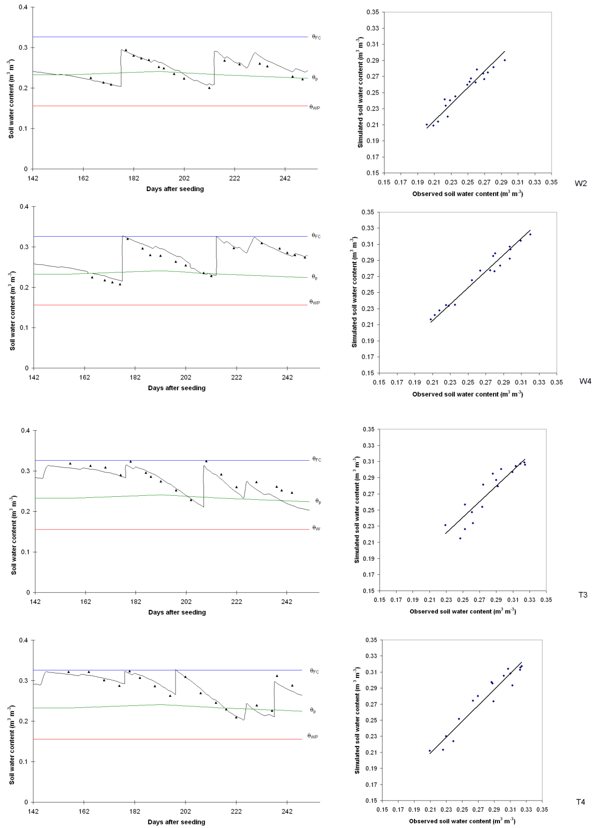

Fig. 6. Comparing the soil water content observed and predicted by the model when ET_o was estimated from weather forecast messages ($ET_{o,WF}$) for two treatments in 2005–2006 (W2 and W4) and two other treatments in 2006–2007 (T3 and T4). On the left, the daily course of the soil water; on the right, the respective regressions forced to the origin. The lines of θ_{FC}, θ_p and θ_{WP} refer to the soil water content at field capacity, at the depletion fraction for no stress and at the wilting point, respectively.

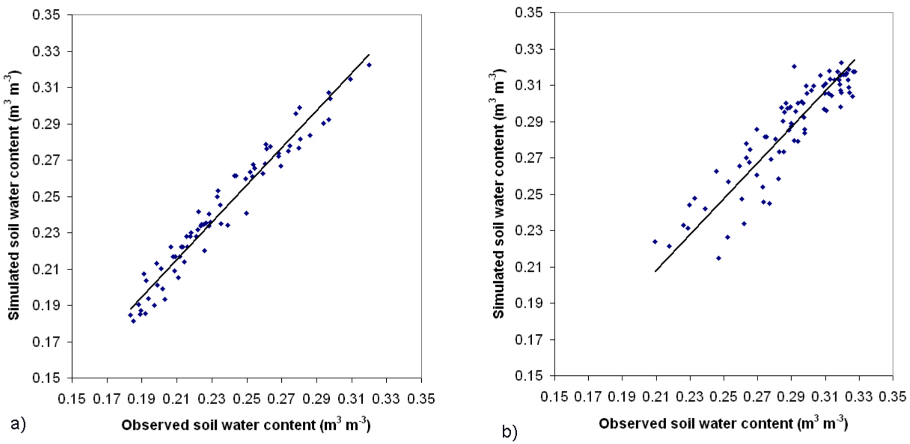

Fig. 7. Linear regression forced to the origin comparing the observed and model predicted soil water content when ET_o was computed from weather forecast messages ($ET_{o,WF}$) for all treatments of 2005–2006 **(a)** and 2006–2007 **(b)**.