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Modelling irrigated maize with a combination of coupled-model simulation and uncertainty analysis, in the northwest of China

Y. Li[1,2], W. Kinzelbach[3], J. Zhou[4], G. D. Cheng[4], and X. Li[4]

[1]College of Earth and Environmental Science, Lanzhou University, Lanzhou, 730000, China
[2]School of Information Science and Engineering, Lanzhou University, Lanzhou, 730000, China
[3]Institute of Environmental Engineering, ETH Zurich, Wolfgang-Pauli-Strasse 15, 8093 Zurich, Switzerland
[4]Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou, 730000, China

Correspondence to: Y. Li (liyan_2007@lzu.edu.cn), W. Kinzelbach (kinzelbach@ifu.baug.ethz.ch), J. Zhou (zhoujian@lzb.ac.cn), G. D. Cheng (gdcheng@lzb.ac.cn), X. Li (lixin@lzb.ac.cn)

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Abstract. The hydrologic model HYDRUS-1-D and the crop growth model WOFOST are coupled to efficiently manage water resources in agriculture and improve the prediction of crop production. The results of the coupled model are validated by experimental studies of irrigated-maize done in the middle reaches of northwest China's Heihe River, a semi-arid to arid region. Good agreement is achieved between the simulated evapotranspiration, soil moisture and crop production and their respective field measurements made under current maize irrigation and fertilization. Based on the calibrated model, the scenario analysis reveals that the most optimal amount of irrigation is 500–600 mm in this region. However, for regions without detailed observation, the results of the numerical simulation can be unreliable for irrigation decision making owing to the shortage of calibrated model boundary conditions and parameters. So, we develop a method of combining model ensemble simulations and uncertainty/sensitivity analysis to speculate the probability of crop production. In our studies, the uncertainty analysis is used to reveal the risk of facing a loss of crop production as irrigation decreases. The global sensitivity analysis is used to test the coupled model and further quantitatively analyse the impact of the uncertainty of coupled model parameters and environmental scenarios on crop production. This method can be used for estimation in regions with no or reduced data availability.

1 Introduction

In semi-arid and arid regions, there is an increasing competition between the limited water resources and the increasing demand for crop irrigation (Molden, 1997; Seckler et al., 1998). The efficient utilization of water in agriculture and tackling the issue of optimal water use are needed to balance water supply and demand (Tuong and Bhuiyan, 1999; Ines et al., 2002). In the last 20 yr, irrigation planning methods have switched from the allocation approach, e.g. based on socio-political considerations, to technological ones (Paudyal and Das Gupta, 1990; Raman et al., 1992). The development of mathematical models allows fundamental progress to guide irrigation quantitatively. The accurate estimation of soil moisture change, evaporation, and transpiration is important for determining availability of water resources (Scanlon et al., 2002) and the sustainable management of limited water resources, especially in arid and semi-arid regions (e.g. Gartuza-Payán et al., 1998). Variation in available soil moisture is one of the main causes of variation in crop yields (Rodriguez-Iturbe et al., 2001; Shepherd et al., 2002; Anwar et al., 2003; Patil and Sheelavantar, 2004). Meanwhile, actual evapotranspiration is the main variable for water loss in the soil-plant system and determines soil moisture status (Burman and Pochop, 1994; Monteith and Unsworth, 1990). Crops can only absorb the soil moisture that is present within the reach of their roots. Therefore, the root growth algorithm and plant water uptake modules are

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critical to estimate soil moisture and crop production in crop and ecological models. However, these processes are represented in hydrologic models, the coupling of hydrologic and crop growth models are useful for both hydrology and agronomy.

In the last few years numerous scientists have oriented their research towards enhancing the knowledge of the complex interactions between ecological systems and the hydrological cycle, contributing to the development of eco-hydrologic models and soil-plant-atmosphere models (Smettem, 2008; De Willigen, 1991; Engel and Priesack, 1993; Diekkrüger et al., 1995; Shaffer et al., 2001; Van Ittersum and Donatelli, 2003). Kendy et al. (2003) evaluated recharge specifically for irrigated cropland using a model in which soil water flow was governed by a tipping-bucket-type mechanism, and actual transpiration was computed based on the soil water condition using a method introduced by Campbell and Norman (1998). By coupling of hydrologic and crop growth models, Eitzinger et al. (2004) studied soil water movement during crop growth processes and concluded that the coupled modeling approach was better than a single model method. Many classical eco-hydrologic models, such as SWAP (Kroes et al., 2008), DSSAT (Jones et al., 2001, 2003), APSIM (Keating et al., 2003), STICS (Brisson et al., 2003) and Expert-N (Sperr et al., 1993; Priesack, 2006), have been mostly performed in the China by comparing the simulated crop production against observations and investigate the effects of soil moisture and nutrient distribution along the vertical soil profile on crop (e.g. Chen et al., 2010; Fang et al., 2010; Jiang et al., 2011; Yang et al., 2010). However, few studies have evaluated the performance of these models in arid region, northwest of China, or at in regions with no or reduced data availability.

Complex eco-hydrologic models can help to understand interactions between water and energy cycle in soil-plant-atmosphere systems. However, models have many degrees of freedom (with many parameters, state-variables and non linear relations) and can be made to produce virtually any desired behavior (Hornberger and Spear, 1981). Debates on the reliability of environmental models have emerged both in the academy and among practitioners (Veld, 2000; Lomborg, 2001; Van der Sluijs, 2002). The United States Environmental Protection Agency (EPA)'s science panel found that quantitative evidence must be characterized as having high uncertainties (David, 2008). The International Food Policy Research Institute (IFPRI) had raised about $460 000 for the modeling, which would have provided insights to help policymakers compare the outcomes of four broad policy scenarios, such as futures with more free trade or green technologies. But Greenpeace's Haerlin and others objected that the models were not "transparent" (Stokstad, 2008). Columbia University published the book titled "Useless Arithmetic: Why Environmental Scientists Can't Predict the Future" (Pilkey and Pilkey-Jarvis, 2007) presented "Quantitative mathematical models used by policymakers and government administrators to form environmental policies are seriously flawed". The main problem is that models are often asked to answer specific questions about the present or future behaviour of the system under uncertainty conditions (e.g. climate change, different environmental scenarios and presumptive boundary conditions of the dynamics). However, the model only can be confirmed or corroborated by demonstrating agreement between observations and predictions. So, we need a combination of model simulation and ensemble statistics to analyse and predict the scientific problem from a probabilistic viewpoint. In this view, uncertainty and sensitivity analysis (UA/SA) can help investigating the propagation of different sources of uncertainties to the output variables through ensemble sampling. UA/SA analysis is used to quantitatively identify the effect of model parameters and structure on the output estimation.

This paper aims to efficiently manage water resources in agriculture and improve the prediction of crop production in arid region. For this purpose, an eco-hydrological model is developed by coupling a HYDRUS model with a WOFOST model and calibration have been conducted in agricultural experimental field, located in arid region, northwest of China. Based on the coupled modeling, we use UA/SA methods to evaluate the coupled model, predict the risk of a crop production loss as irrigation decreases and quantitatively study impact of coupled model parameters and environmental factors change on maize production. This method can be used as reference for predicting the crop production in regions with no or reduced data availability.

2 Study region and experimental field description

The Heihe river basin, located in semi-arid and arid region, is the second largest inland river basin in China. The region has a typical temperate continental climate, with the mean annual precipitation and evaporation ranging from 60 to 280 mm and 1000 to 2000 mm, respectively. The main crops of this region are maize and wheat, and water use efficiency is low. The key to solve water scarcity and ecological problems of this region is effective management of agricultural water resource and of optimization irrigation. So, an agricultural experimental field (latitude 38°51′ N, longitude 100°25′ E, altitude 1519 m), which is shown in Fig. 1, is operated by CAS (Chinese Academy of Science) to study the impact of quantitative irrigation on maize growth. The station is managed according to agricultural practices in the Heihe river basin region, including crop rotations (maize and wheat) and flood irrigation.

2.1 Characterization of the soil properties

The experimental field was established on a clay loam soil (USDA classification system). To characterize the soil physical properties, five root zone soil samples were extracted

Table 1. Measured soil textural and bulk density data.

Depth (cm)	Textural fractions			Bulk density (g cm^{-3})
	2–0.05 mm	0.05–0.002 mm	<0.002 mm	
5 cm	33.86	45.44	20.70	1.43
15 cm	37.60	42.53	19.87	1.379
30 cm	49.69	33.87	16.44	1.483
55 cm	24.56	48.65	26.79	1.571
85 cm	16.61	53.68	29.71	1.644

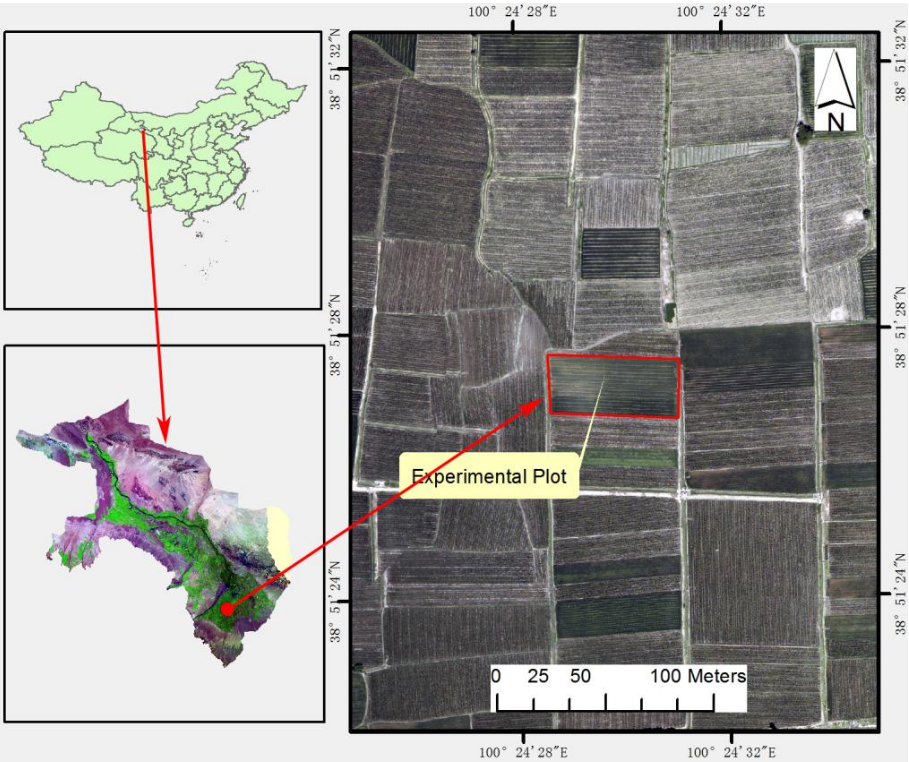

Fig. 1. The location of the experimental plot.

from the ground to a depth of 100 cm. The samples were analyzed in the laboratory to determine soil bulk density (Grossman and Reinsch, 2002), water retention properties (soil water contents at 0–1000 kPa matric potentials) (Equi-pf, New Zealand) and percentages of sand, silt, and clay (Gee and Or, 2002). Saturated conductivity was measured at 10 cm, 40 cm and 100 cm, respectively (Guelph 2800K1, USA). The analysis results are shown in Table 1 and Fig. 2. The nitrogen, potassium and phosphorus fertilizer are used 329 kg ha^{-1}, 220 kg ha^{-1}, 87 kg ha^{-1}, respectively during maize growth.

2.2 Field experiment

The field was instrumented to monitor soil water dynamics in the root zone and the groundwater table. The instrumentation consisted of time-domain reflectometers (TDR) (CS616, Cambell Scientific, USA) for soil moisture measurements and groundwater observation wells. The depth of soil moisture measurements was 10 cm, 20 m, 40 cm, 60 cm, 80 cm, 100 cm, respectively and the data were collected every hour.

The agricultural field was intensively monitored throughout the study period, which lasted from 20 April through 22 September 2009. The field was cultivated with maize and quantitatively irrigated. The field was irrigated 9 times throughout the period of crop growth. The water amount of irrigation is approximately 100 mm each time. The sowing date, emergence date and harvest date were 20 April, 6 May and 22 September respectively. Meanwhile, the data of Leaf area index (LAI) were measured once every 15 days by LAI-2200 instrument. Dry weight of storage organs, dry weight of total above-ground biomass and crop height were measured every 15 days by samples during crop growth.

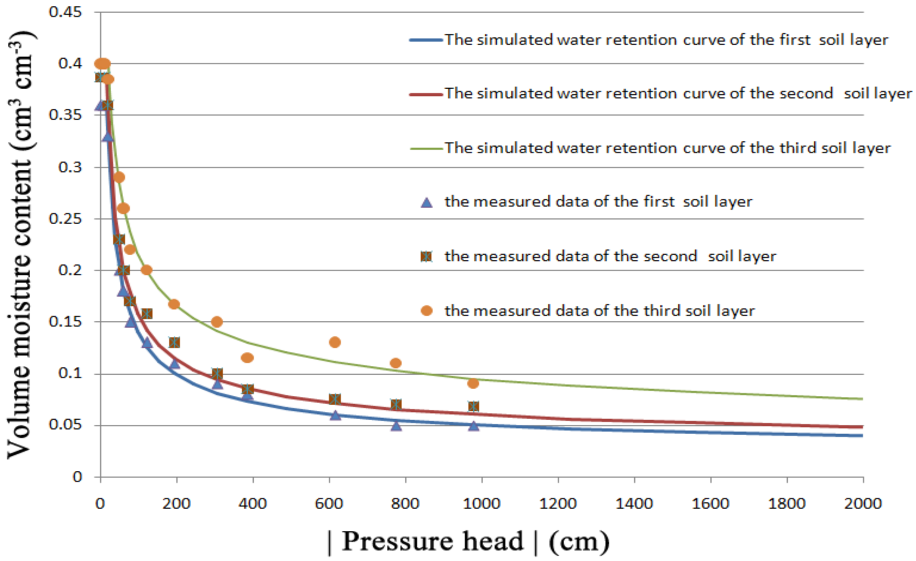

Fig. 2. Comparison between the fitted water retention curve and the measured data in the laboratory.

Half-hourly meteorological data were recorded by the meteorological station (Milos520, Vaisala Co, Finland), located in the experimental field. Available data were net radiation, solar radiation, maximum air temperature, minimum air temperature, precipitation, wind speed, atmospheric pressure, and relative humidity. We measured latent heat during crop growth using eddy covariance systems (EC) (Li7500 & CSAT3, Cambell Scientific, USA). The correction of EC data was produced with revised EdiRE software from the University of Edinburgh (Xu et al., 2008).

3 Materials and methods

3.1 Crop growth model

The numerical software, WOFOST (Van Keulen and Wolf, 1986; Boogaard et al., 1998), is a very useful code for determining the production potential, optimizing crop management and quantifying yield gaps of various crops (e.g. wheat, maize, potatoes) (Van Laar et al., 1997; Bouman et al., 2001; Wolf, 2002). The code can also be used to study the effects of environmental variability and climatic change on crop production (Kropff et al., 1996; Berge et al., 1997; Tsuji et al., 1998; Matthews and Stephens, 2002). However, in the water-limited situation, the soil water balance is calculated using a tipping bucket approach with three compartments, i.e. a root zone, a transmission zone, and a groundwater zone. The potential evapotranspiration is estimated with the Penman-Monteith equation (Monteith, 1965, 1981). The actual crop uptake from soil is calculated as the product of the potential evapotranspiration, a crop factor and a water stress factor. It is relatively simple and not accurate for the hydrologic cycle simulation during crop growth (Eitzinger et al., 2004; Priesack et al., 2006). A detailed model description can be found in Boogaard et al. (1998).

3.2 Hydrologic model

HYDRUS-1-D (Šimůnek et al., 2005) has an advantage in simulating water flow and root water uptake. The simulation is based on the following assumptions: (i) the soil is homogeneous and isotropic, (ii) the air phase does not affect liquid flow processes, and (iii) moisture movement due to thermal gradients is negligible. So, the governing equation for water flow is the 1-D Richards equation:

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial x}\left[K\,(\frac{\partial h}{\partial x+1})\right] - S \tag{1}$$

where h is soil water pressure head (L); θ represents volumetric water content (L^3 L^{-3}); t is time (T); x is the vertical space coordinate (L); K is the unsaturated hydraulic conductivity (L T^{-1}); and S represents a sink term (L^3 L^{-3} T^{-1}), defined as the volume of water removed from a unit volume of soil per unit time due to plant water uptake. The sink term is specified in terms of a potential water uptake rate and a stress factor (Feddes et al., 1978):

$$S = \frac{\alpha(h)\,R(z)}{\int_0^{lr} \alpha(h)\,R(z)\,\mathrm{d}z} T_\mathrm{P} \tag{2}$$

where S is the root water uptake rate (L^3 L^{-3} T^{-1}); $R(z)$ is the distribution function of the root; lr is the depth of root (L); T_P is potential transpiration (L); the dimensionless water stress response function $\alpha(h)$ $(0 \le \alpha(h) \le 1)$ prescribes the reduction in uptake that occurs due to drought stress. For

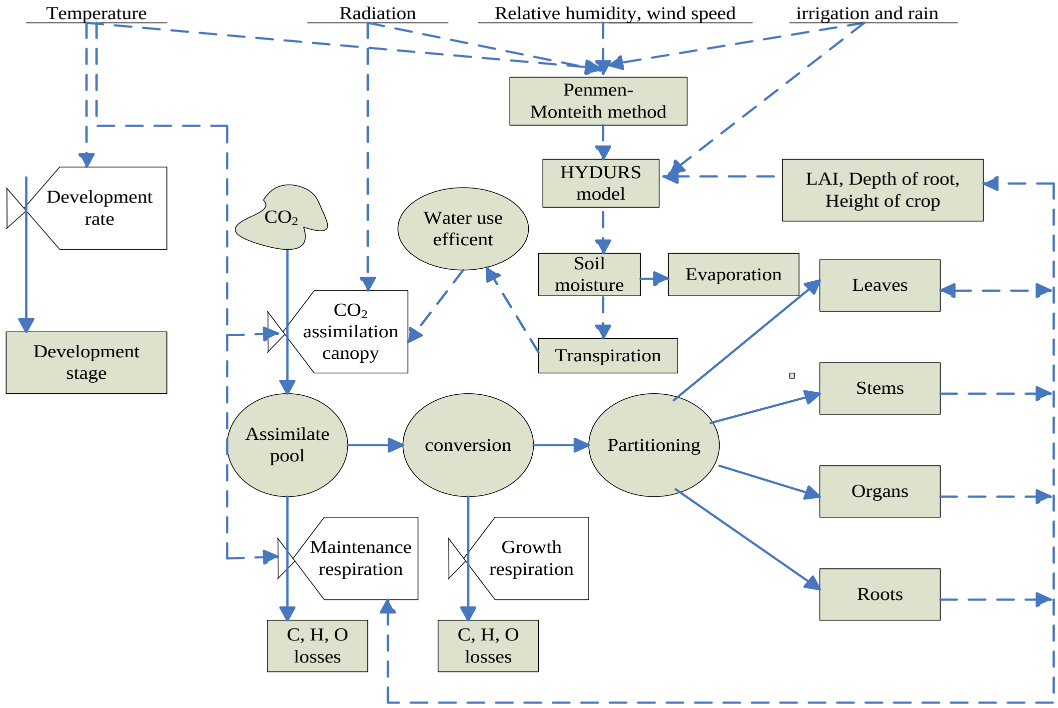

Fig. 3. Flow chart of the coupled HYDRUS and WOFOST models.

$\alpha(h)$, we use the functional form introduced by Feddes et al. (1978):

$$\alpha(h) = \left\{ \begin{array}{ll} (h-h_4)/(h_3-h_4) & h_4 < h \leq h_3 \\ 1 & h_3 < h \leq h_2 \\ (h-h_1)/(h_2-h_1) & h_2 < h \leq h_1 \\ 0 & h \leq h_4,\ h > h_1 \end{array} \right\} \quad (3)$$

where h_1, h_2, h_3, and h_4 are threshold parameters. The uptake is at the potential rate when the pressure head is between h_2 and h_3. It drops off linearly when $h > h_2$ or $h < h_3$. The uptake rate becomes zero when $h < h_4$ or $h > h_1$. Crop-specific values for these parameters are chosen from the database contained in HYDRUS-1D (Šimůnek et al., 2005).

An atmospheric boundary condition is implemented at the soil surface. The atmospheric boundary conditions required daily irrigation, precipitation rates, potential evaporation and transpiration rates as inputs. The detailed description about how to calculate potential evaporation and transpiration can be found in HYDRUS-1-D (Šimůnek et al., 2005). Meanwhile, a deep drainage condition is used at the bottom. The condition require the initial reference groundwater depth to be given (Šimůnek et al., 2005).

The soil hydraulic properties are modeled using the van Genuchten-Mualem constitutive relationships (Mualem, 1976; Van Genuchten, 1980):

$$\theta(h) = \left\{ \begin{array}{ll} \theta_r + \frac{\theta_s - \theta_r}{[1+(\alpha h_c)^n]^{1-1/n}} & h < 0 \\ \theta_s & h \geq 0 \end{array} \right\} \quad (4)$$

$$K(h) = K_s S_e^l \left\{ 1 - \left[1 - S_e^{n/(n-1)} \right]^{1-1/n} \right\}^2 \quad (5)$$

$$S_e = \frac{\theta(h) - \theta_r}{\theta_s - \theta_r} \quad (6)$$

where S_e is effective saturation and θ_s is saturated water content ($L^3\,L^{-3}$); θ_r is residual water content ($L^3\,L^{-3}$); K_s is saturated hydraulic conductivity ($L\,T^{-1}$); α is the air entry parameter; n is the pore size distribution parameter; and l is the pore connectivity parameter. The parameters α, n, and l are empirical coefficients that determine the shape of the hydraulic functions. To reduce the number of free parameters, we take $l = 1$, a common assumption which is based on Mualem's (1976) study result.

3.3 Coupling of the model

The coupling has been performed at a daily scale. Coupling process is shown in the Fig. 3:

1. The irrigation and precipitation, the daily net radiation, the daily maximum and minimum temperatures, the daily wind speed and the daily relative humidity are the input terms in the HYDRUS model.

2. The potential evaporation and transpiration are calculated by the Penman-Monteith combination method in the HYDRUS model.

3. The water uptake is calculated according to Feddes equation in the HYDRUS model.

4. The soil water balance, soil moisture and groundwater depth are calculated using the HYDRUS model.
5. The root water uptake and actual transpiration on a daily basis are assumed the same, because the most root water uptake is consumed by crop transpiration. Therefore, the ratio between calculated actual water uptake based on Feddes equation and potential transpiration based on Penman-Monteith method is regarded as an indicator for the degree of water stress.
6. The potential daily total gross CO_2 assimilation of the crop, which is calculated according to the WOFOST model, is multiplied by the water stress ratio to calculate the actual daily CO_2 assimilation. Then, carbohydrate allocation among different crop parts is calculated according to the WOFOST model.
7. The calculated vegetation parameters from the WOFOST[1] model, more specifically rooting depth, height of the crop and LAI, are then used as inputs for the HYDRUS model at the next step.

3.4 Sensitivity analysis

Sensitivity analysis determines the contribution of each input factor to the uncertainty of the outputs. Sensitivity analysis is evaluated using a two-step method: the screening method proposed by Morris (1991) and a variance-based technique proposed by Sobol (1993). The Morris method provides a qualitative assessment of the importance of each input factor, while the Sobol' method performs a quantitative analysis of sensitivity and uncertainty. This two-step methodology has been used in recent studies of input-output relationship and model evaluation (Fox et al., 2010; Jawitz et al., 2008; Muñoz-Carpena et al., 2010).

The one-factor-at-a-time Morris (Morris, 1991) method is particularly effective to screen a subset of relevant parameters among those contained in models with a large number of parameters or with time consuming simulations. The method calculates a set of incremental ratios (Δ output/Δ parameter) at various points of the parameters space and to obtain means (μ^*; calculated on absolute values) and standard deviations (σ) of these ratios. A large value of μ^* belongs to a parameter with an important overall influence (total effect), whilst a large value of σ indicates nonlinearities in model response or interactions with other parameters.

Sobol's method (Sobol, 1993) is a variance-based method. The method is modified by Saltelli (2002) by decomposing the output variance into terms of increasing dimensions (i.e. partial variances), representing the contribution of single parameters, and of groups of parameters to the overall uncertainty of the model output. This method allows the simultaneous exploration of the parameter space via a Monte Carlo method. Statistical estimators of partial variances are provided by quantifying the relevance of parameters and parameter groups through multi-dimensional integrals. The advantage of Sobol's method is that it allows the simultaneous computation of the first order and total order effect indices for a given parameter. A main sensitivity index (S_x) quantifies the first order effect of a parameter. A total sensitivity index ($S_{\mathrm{T}x}$) quantifies the overall effect of a parameter (i.e. including all the possible interactions).

[1]WOFOST model is revised to output Crop Height with equation: Crop height = 281.4/{1 + exp [−0.00310 × (TSUM-1281.3)]}

4 Results and discussion

4.1 Model validation

Running the coupled model requires atmospheric (minimum temperature, maximum temperature, irradiation, vapor pressure ,wind speed and precipitation) and irrigation conditions at a daily scale, the parameters of crop characteristics (including parameters referring to, among other things, phenology, assimilation and respiration characteristics, and partitioning of assimilates to plant organs) and the soil hydraulic parameters (θ_r, θ_s, α, n, K_s).

The meteorological data are acquired by the meteorological station. The amounts and times of irrigation are recorded. The parameters of crop characteristics choose the maize data (MAG 203) provided by the European Community (Boons-Prins et al., 1993). An atmospheric boundary condition is implemented at the soil surface. The potential evaporation and transpiration rates are calculated by the meteorological data and the parameters of the crop growth (LAI and height of the crop), which are shown in Fig. 4. The soil profile is divided into three layers in vertical direction according to the soil physical properties. The fist layer is from the ground to a depth of 30 cm. The second layer and the third layer are from a depth of 30 cm to a depth of 60 cm and from a depth of 60 cm to a depth of 100 cm, respectively. The measured relation between pressure head and water content and percentages of sand, silt, and clay for three layers are inputted into Rosetta software (Schaap and Bouten, 1996; Schaap et al., 1998) to calculate van Genuchten (1980) model's water retention parameters. The fitted curve and parameters are shown in Fig. 2 and Table 2.

The simulation time is during the cultivation of maize from sowing (20 April 2009) to harvest (22 September 2009), comprising day of year (DOY) 110–265. The computation time step is one day.

The comparison between simulated soil moisture and observed soil moisture is shown in Fig. 5. The NSE values of the soil moisture for the three soil layers are 0.750, 0.699 and 0.842, respectively. The dry matter accumulation and partition between the various plant organs, the final yield and harvest index are simulated by the coupled model, as shown in Table 3. The observed TAGP (total above-ground dry production), WSO (dry weight of storage organs) and

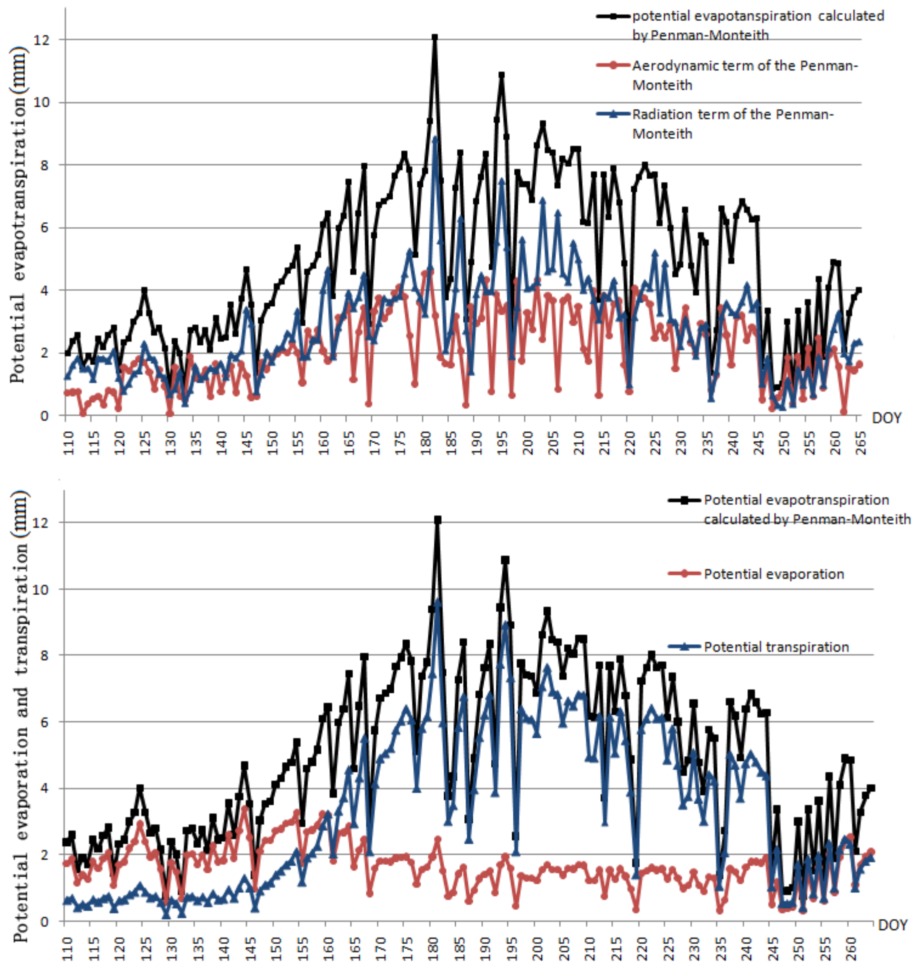

Fig. 4. The estimated potential evapotranspiration, potential evaporation and potential transpiration.

Table 2. The estimated van Genuchten-Mualem parameters of soil hydraulic properties of three layers by ROSETTA.

	θ_r ($cm^3\,cm^{-3}$)	θ_s ($cm^3\,cm^{-3}$)	α	n
The first layer (10 cm)	0.05	0.41	0.08	0.13
The second layer (40 cm)	0.05	0.41	0.087	0.115
The third layer (100 cm)	0.05	0.41	0.11	0.10

the LAI (Leaf area index) are compared with the simulation results, which are shown in Figs. 6 and 7. The NSE value of TAGP, WSO and LAI are 0.965, 0.978 and 0.924, respectively. The results show the simulated dry matter accumulation and partition between the various crop organs match the observations well. The related parameter values are reasonable for local maize characteristics and soil properties in the study field. The comparison between simulated and observed actual evapotranspiration are shown in Fig. 8. The RMSE and NSE values for actual evapotranspiration are 0.721 mm and 0.783, respectively. The results show the simulated evapotranspiration also well match the observed evapotranspiration by eddy covariance systems (EC). The simulated evapotranspiration is divided into actual transpiration and actual evaporation. The cumulative simulated actual transpiration is 364 mm. The cumulative simulated actual evaporation is 203 mm. The result reveals that the crop's effective transpiration is approximately 1.79 times the soil evaporation during maize growth under realistic irrigation conditions.

The calibrated model is then used to evaluate the water balance and to search for a potential, water-saving scheme. The number of irrigations remains nine, but the ratio between actual root uptake and potential transpiration is not less than 0.8. The simulated results indicate the maize quantitatively irrigated in 60 mm water at each would be enough in this region. The simulated water balance under the guided irrigation scheme is compared with the actual irrigation scheme results (Table 4). These results indicate that the guided irrigation scheme can save 350 mm of irrigation water. Water-saving is mainly due to decreases in deep percolation (284.2 mm) that accounts for 81.2 % of total

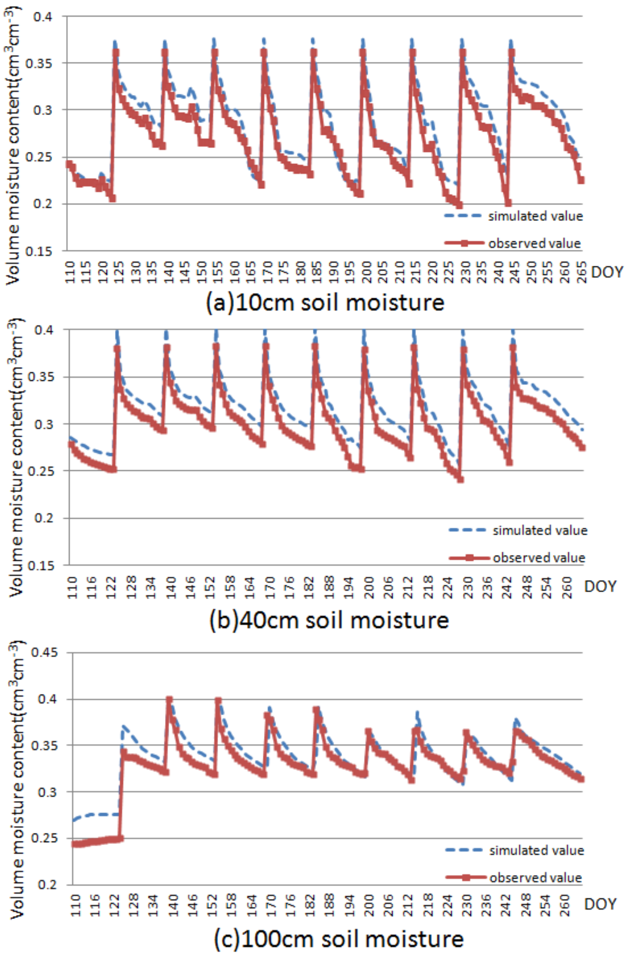

Fig. 5. Comparison between observed soil moisture and simulated soil moisture.

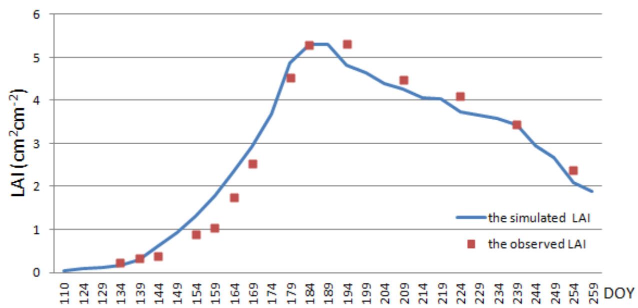

Fig. 6. Comparison between simulated and observed LAI.

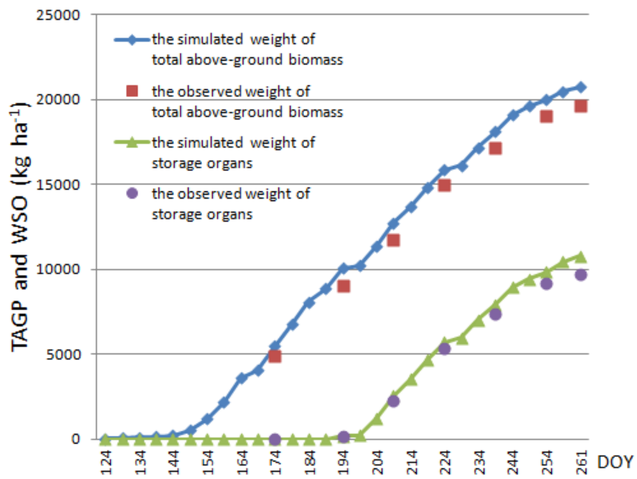

Fig. 7. Comparison between simulated and observed weight of total above-ground biomass and weight of storage organs.

water-saving. The ineffective evaporation decrease 52 mm that accounts for 14.86 % of total water-saving. Transpiration under the guided irrigation scheme is close to that under actual irrigation scheme. Therefore crop production can be guaranteed, while water is conserved.

4.2 Sensitivity analysis

Prior to performing sensitivity analysis, the ranges of the 34 input factors are defined (Table 5) based on values from literature review, experience, research objectives and default, minimum and maximum values of WOFOST and HYDRUS databases. Uniform distributions are assigned to input factors when only the base value is known, the range is considered finite, and no explicit knowledge of the distribution is available (McKay, 1995). This conservative assumption allows an equal probability of occurrence of the input factors along the probability range (Muñoz-Carpena et al., 2010). We divide the parameters into 13 groups according to physical properties and functions. The groups of parameters and the value ranges of all parameters are shown in Table 5.

One model output for weight of storage organs (WSO) at physiological maturity is considered in this analysis because it is a synthetic representation of the numerical model's results. The variation of WSO in response to variations of the crop and environment parameters are investigated using Morris and Sobol's sensitivity study methods, based on SimLab Dynamic Link Library (http://simlab.jrc.ec.europa.eu/), integrated in the coupled HYDRUS and WOFOST models.

For Morris method, the means and standard deviations of the sensitivity parameters (μ^*, σ) for each factor are obtained from 320 samples using the total range of trajectories (10) and levels (4) (Saltelli et al., 2004). For Sobol' method, Monte Carlo sample size is set to 5000 for each factor.

The guided irrigation scheme (Each time 60 mm of water is applied to maize, in total 9 times) is explored in this study. Figure 9 displays graphically the average strength (μ^*) and spread (σ) of model response (change of yield) to the variation of parameters according to their various functions of crop growth (phenology, assimilation, respiration, conversion, etc.) and environment factors (sowing

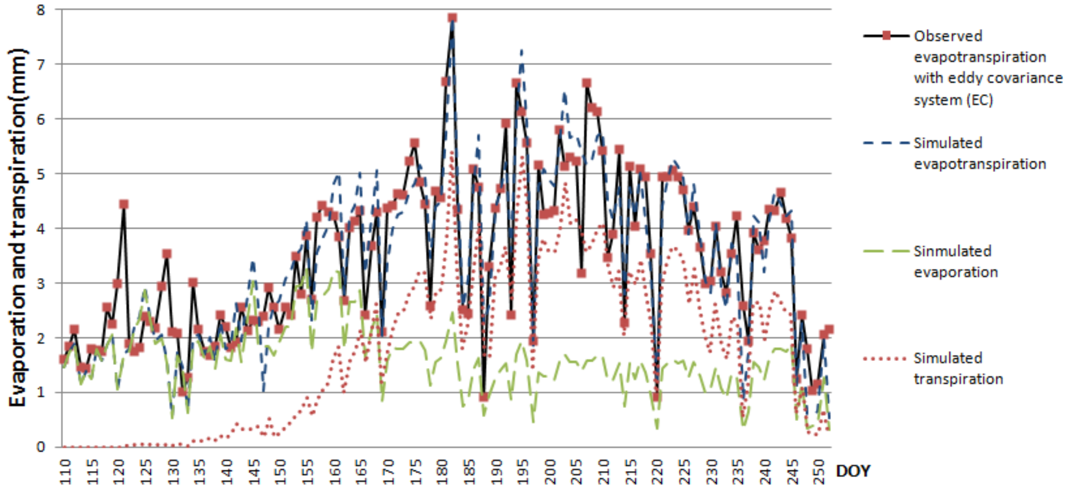

Fig. 8. Comparison between simulated and observed actual evapotranspiration.

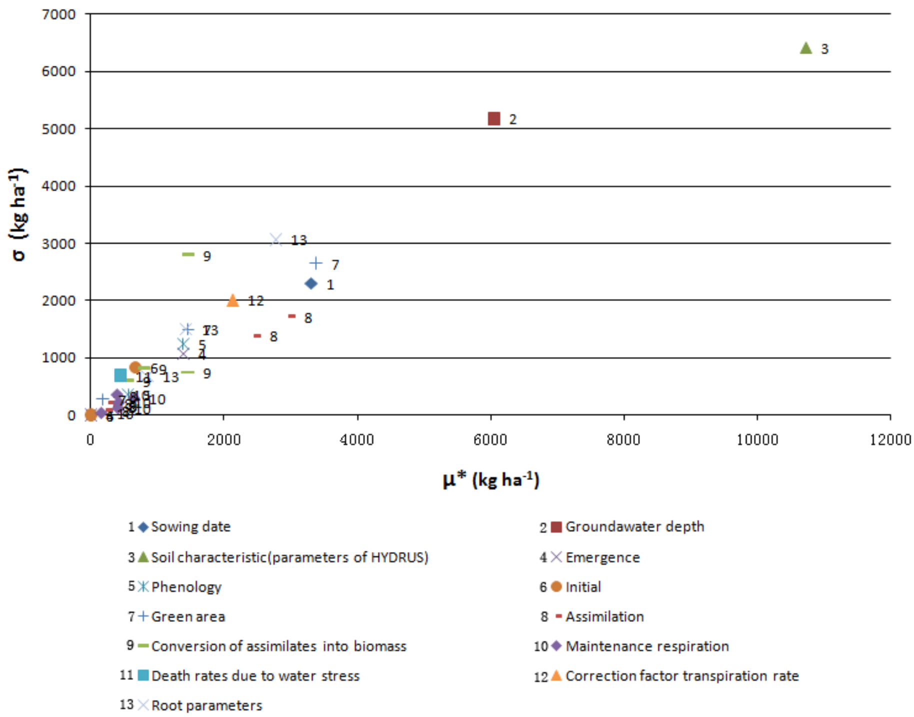

Fig. 9. Graph displaying the Morris sensitivity measures μ^* and σ for 13 groups of parameters.

date, groundwater depth, soil characteristics, etc.). The parameters are ranked in descending order of the μ^* values, which are shown Table 6. The screening carried out with the Morris method allows identifying 13 out of 33 parameters (40 %) as not relevant. Each parameter causes a yield change less than 500 kg ha^{-1}, which approximately accounting for 5 % of the total output 10 777 kg ha^{-1}. The 12 out of 33 parameters (36 %) are identified with an effect between 500 and 2000 kg ha^{-1}. The 8 out of 33 parameters (24 %) have an effect greater than 2000 kg ha^{-1} (including HYDRUS parameters, ZIT, SLATB1, IDSOW, EFFTB, RDMCR, KDIFIB, CFET). Further, σ indicates that interaction, correlation and non-linearity are relevant for coupled model.

We also analyze the distribution of simulated yields with Monte Carlo methods to gain information about the reaction of maize production to the variations of the parameters under various irrigation schemes. The Monte Carlo sample size is set to 5000. Four scenarios are proposed. In the four scenarios the single application of irrigation-water is respectively

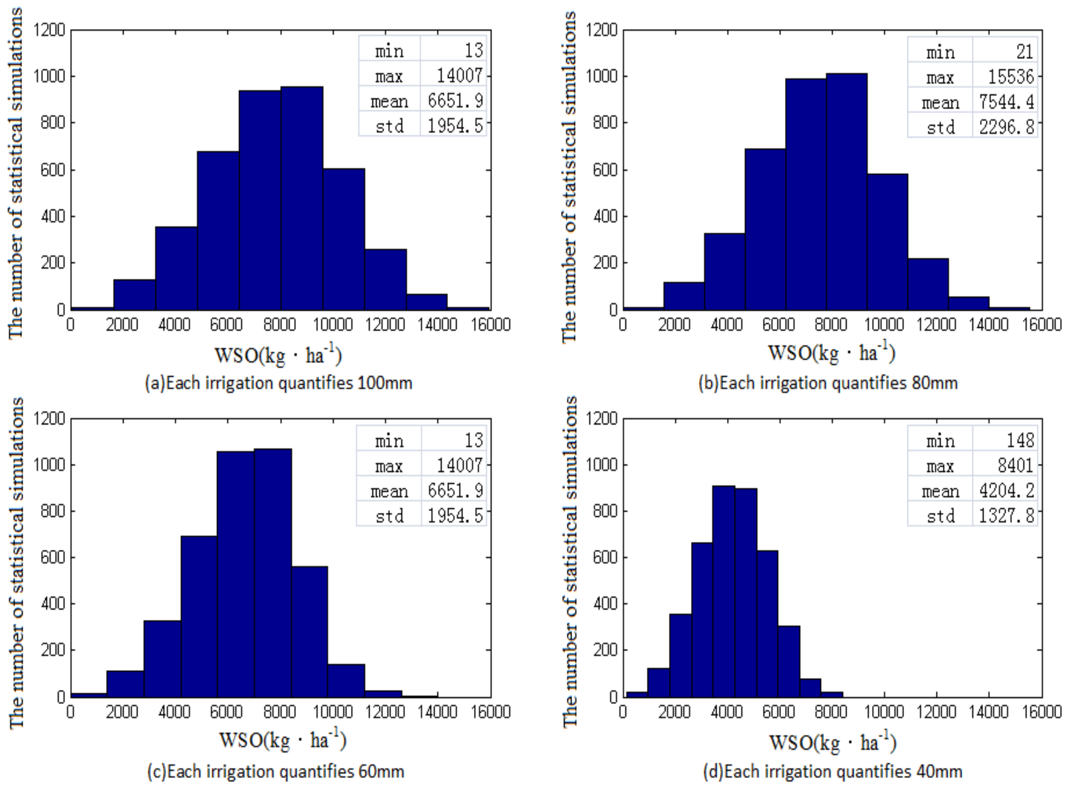

Fig. 10. Histograms of the output distributions in four different irrigation scenarios.

assumed to be 40 mm, 60 mm, 80 mm and 100 mm for a total of 9 irrigation times. The uncertainty analysis is performed. The results are shown in Fig. 10, which reveal the risk of crop production loss with decrease of irrigation. The average crop production increases from 4204.2 kg ha^{-1} in the case where each irrigation-water is 40 mm to 7781.2 kg ha^{-1} in the case where each irrigation-water is 100 mm. When each irrigation- water is more than 60 mm, the distribution of simulated yields is mainly between 5500 kg ha^{-1} and 11000 kg ha^{-1}, which account for 85 % realizations. This method can predict probability of crop production in uncertain range of crop parameters and environment parameters.

The Sobol' method is used to improve our understanding of the effect of parameter groups on crop production under various irrigation schemes. The results are shown in Table 7. In the above mentioned irrigation-water scenarios, summations of first-order indices of parameters are always close to 1, which suggests that the coupled model has not over-parameterization. Total-order indices of parameters are not significantly different in the coupled model, which may be attributed to the coupled model as being balance. Summation of total-order indices leads to values between 2.65 ¬ 3.8, suggesting that the simulated yield is always affected by more parameters acting in conjunction with each other. Table 7 reveals that the crop outputs are mainly influenced by physiological parameters (including CO_2 assimilation, green area, correction factor transpiration rate, the conversion of assimilates into the various organs compounds) and environment parameters (including sowing date, groundwater depth, soil hydraulic characteristic). Table 7 further shows that the effect of groundwater, soil hydraulic characteristic and correction factor transpiration rate on output increases as irrigation-water decreases. The effect of most physiological parameters on output decreases as irrigation-water decreases, owing to the fact that a shortage of transpiration supplied water uptake from the soil causes stomata closure and reduces assimilation and respiration of crops. These results demonstrate the water limitation is the major factor to maize yield in arid region.

5 Summary and conclusions

The objective of this study is to develop a fully coupled hydrology–crop growth model which can optimize irrigation-water under different climatic and environmental conditions. A crop growth model (WOFOST) has been coupled to a hydrologic model (HYDRUS) for this purpose. The coupled model considers not only the physiological processes of the crop, but also the water balance during the crop growth process.

The coupled model is calibrated using field data collected at an experimental field in the middle reaches of northwest China's Heihe River, located in a semi-arid to arid region.

Table 3. The output variables of maize growth obtained by the coupled model.

DOY	TAGP	TWLV	TWST	TWSO	TWRT	LAI	HI	GASS
Day of year	Total above ground production	Total dry weight of the leaves	Total dry weight of the stems	Total dry weight of storage organs	Total dry weight of the roots	Leaf area index	Harvest index	Gross assimilation rate
–	$kg\,ha^{-1}$	$kg\,ha^{-1}$	$kg\,ha^{-1}$	$kg\,ha^{-1}$	$kg\,ha^{-1}$	$m^2\,m^2$	–	$kg\,ha^{-1}\,d^{-1}$
124	30	19	11	0	20	0.05	0	2.4
129	62	39	24	0	40	0.08	0	30.6
134	102	63	39	0	64	0.11	0	19.8
139	134	83	51	0	82	0.16	0	29.9
144	230	143	87	0	132	0.28	0	103.1
149	503	312	191	0	264	0.61	0	227.8
154	1197	741	456	0	566	0.93	0	284.4
159	2165	1291	875	0	931	1.31	0	608
164	3587	2016	1570	0	1397	1.78	0	577.9
169	4055	2231	1824	0	1531	2.33	0	101.6
174	5476	2737	2739	0	1831	2.92	0	649.7
179	6759	3108	3651	0	2042	3.67	0	635.2
184	8080	3378	4702	0	2179	4.87	0	205.9
189	8877	3497	5380	0	2223	5.31	0	651.7
194	10 081	3662	6256	164	2233	5.29	0.02	265.4
199	10 218	3677	6325	217	2233	4.81	0.02	220.5
204	11 385	3709	6457	1219	2233	4.64	0.11	661
209	12 724	3709	6457	2558	2233	4.38	0.20	605.1
214	13 674	3709	6457	3508	2233	4.27	0.26	93.5
219	14 852	3709	6457	4686	2233	4.06	0.32	436.2
224	15 874	3709	6457	5708	2233	4.04	0.36	314.2
229	16 139	3709	6457	5973	2233	3.74	0.37	175
234	17 169	3709	6457	7003	2233	3.65	0.41	512.5
239	18 103	3709	6457	7937	2233	3.57	0.44	483.5
244	19 112	3709	6457	8946	2233	3.43	0.47	167.1
249	19 612	3709	6457	9446	2233	2.95	0.48	80.3
254	20 013	3709	6457	9847	2233	2.68	0.49	124.1
259	20 498	3709	6457	10 332	2233	2.1	0.50	219.3
261	20 743	3709	6457	10 577	2233	1.89	0.51	206.4

Table 4. The simulated water balance under actual and guided irrigation schemes.

	Irrigation + precipitation	Transpiration	Evaporation	Deep percolation	Change of soil moisture storage
	mm				
Realistic irrigation scheme	983.6	364	203	344.6	72
Guided irrigation scheme	633.6	355	151	60.4	67.2
Difference	−350	−9	−52	−284.2	−4.8

The results show the good agreement is achieved between coupled model simulations and field measurements under water limited-conditions. The results also show that the coupled model can have a higher precision than the WOFOST model alone owing to HYDRUS model's advantage in simulating soil moisture and root water uptake as a physical process. Based on the coupled model, the scenario analysis results indicate that the most optimal irrigation amount for maize growth is 500–600 mm in this region. These applications illustrate the coupled model can be used for analysis of saving-water approach and also for the study on interaction between crop growth and the hydrological cycle.

Table 5. The groups of parameters and the value ranges of parameters for UA/SA.

group	parameter	meaning	unit	values range
Sowing date	IDSOW	sowing date	(d)	U (103–117)
Groundwater depth	ZIT	Initial depth of groundwater table	(cm)	U (50–500)
Soil hydraulic parameters (HYDRUS)	Parameters of HYDRUS model	soil hydraulic parameters	(cm cm^{-1}) (cm cm^{-1}) – – (cm day^{-1})	θ_r U (0.01–0.1) θ_s U (0.25–0.4) a U (0.02–0.14) n U (0.2–0.6) K_s U (10–800)
Emergence	TBASEM TEFFMX	Lower threshold temperature for emergence Maximum effective temperature for emergence	(°C) (°C)	U (2–5) U (20–30)
Phenology	TSUM1 TSUM2	Thermal time from emergence to anthesis Thermal time from anthesis to maturity	(°C d^{-1}) (°C d^{-1})	U (700–900) U (800–1200)
Initial	RGRLAI LAIEM	Maximum relative increase in LAI Leaf area index at emergence	(ha ha^{-1} d^{-1}) (ha ha^{-1})	U (0.01–0.04) U (0.1–0.2)
Green area	SPAN SLATB SLATB1	Life span of leaves growing at 35 °C Specific leaf area as a function of development stage Specific leaf area as a function of development stage	(d) (ha kg^{-1}) (ha kg^{-1})	U (30–36) U (0.002–0.003) U (0.001–0.002)
Assimilation	AMAXTB	Maximum leaf CO_2 assimilation rate at development stage of the crop growth	(kg ha^{-1} h^{-1})	U (50–70)
	AMAXTB1	Maximum leaf CO_2 assimilation rate at the first development stage of the crop maturity	(kg ha^{-1} h^{-1})	U (50–70)
	AMAXTB2	Maximum leaf CO_2 assimilation rate at the second development stage of the crop maturity	(kg ha^{-1} h^{-1})	U (50–70)
	AMAXTB3	Maximum leaf CO_2 assimilation rate at the third development stage of the crop maturity	(kg ha^{-1} h^{-1})	U (30–50)
	AMAXTB4	Maximum leaf CO_2 assimilation rate at the fourth development stage of the crop maturity	(kg ha^{-1} h^{-1})	U (0–25)
	EFFTB	Initial light-use efficiency of CO_2 assimilation of single leaves as function of daily temperature	((kg ha^{-1} h^{-1})/(Jm^{-2} s^{-1}); °C)	U (0.4–0.5)
	KDIFTB	Extinction coefficient for diffuse visible light as function of development stage		U (0.5–0.7)
Conversion of assimilates into biomass	CVO CVS CVL CVR	Conversion efficiency of assimilates into storage organ Conversion efficiency of assimilates into stem Conversion efficiency of assimilates into leaf Conversion efficiency of assimilates into root	 (kg kg^{-1}) (kg kg^{-1}) (kg kg^{-1})	U (0.6–0.8) U (0.59–0.76) U (0.61–0.75) U (0.62–0.76)
Maintenance respiration	RMS RML Q10	Relative maintenance respiration rate stems Relative maintenance respiration rate leaves Relative change in respiration rate per 10 °C temperature change	(kg (CH_2O) kg^{-1} d^{-1}) (kg (CH_2O) kg^{-1} d^{-1})	U (0.013–0.02) U (0.027–0.033) U (1.6–2)
	RMO RMR	Relative maintenance respiration rate storage organs Relative maintenance respiration rate roots	(kg (CH_2O) kg^{-1} d^{-1}) (kg (CH_2O) kg^{-1} d^{-1})	U (0.005–0.015) U (0.01–0.016)
Death rates due to water stress	PERDL	Maximum relative death rate of leaves due to water stress	(kg kg^{-1} d^{-1})	U (0.02–0.06)
Correction factor transpiration rate	CFET	correction factor transpiration rate		U (0.7–1.2)
Root parameters	RRI RDI RDMCR	Maximum daily increase in rooting depth Initial rooting depth maximum rooting depth	(cm d^{-1}) (cm) (cm)	U (2–3) U (7–14) U (90.5–120)

Table 6. The Morris sensitivity measures μ^* and σ for 13 groups of parameters.

parameter	μ^*	σ	parameter	μ^*	σ
Soil characteristics (parameters of HYDRUS)	10 731	6411.7	Q10	639	297.5
ZIT	6053	5172.5	TSUM2	562	359.6
SLATB1	3375	2650.9	CVS	562	598.6
IDSOW	3306	2304.1	PERDL	441	688.8
EFFTB	2970	1723.4	RMO	419	221.1
RDMCR	2775	3062	RMS	410	119.1
KDIFTB	2455	1389.9	RML	394	363.2
CFET	2127	2008.6	AMAXTB	351	326.1
CVL	1464	2801.4	AMAXTB1	343	159.7
SLATB	1458	1498.6	AMAXTB2	338	136.8
CVO	1452	745.1	AMAXTB3	268	212.4
RDI	1427	1505	AMAXTB4	232	82.9
TSUM1	1387	1245	SPAN	180	278.6
TBASEM	1385	1068.1	RMR	162	36.4
RRI	845	683.3	TEFFMX	0	0
CVR	802	815.4	LAIEM	0	0
RGRLAI	667	837.4			

Table 7. First effect and total effect indices of 13 groups of parameters.

	Irrigation 100 mm		Irrigation 80 mm		Irrigation 60 mm		Irrigation 40 mm	
Group of parameters	first	total	first	total	first	total	first	total
sowing date	0.1057	0.2686	0.0982	0.2228	0.1002	0.1887	0.0731	0.1376
groundwater depth	0.0817	0.2601	0.1257	0.3466	0.2588	0.4384	0.3469	0.651
Soil hydraulic parameters (HYDRUS)	0.1355	0.2805	0.1446	0.2997	0.1846	0.3627	0.2561	0.4034
emergence	0.0385	0.1383	0.0345	0.1843	0.0385	0.1956	0.0307	0.1246
phenology	0.0335	0.103	0.0276	0.1171	0.0195	0.1224	0.0056	0.1136
initial	0.0432	0.3609	0.0398	0.3541	0.0273	0.1161	0.027	0.0809
green area	0.0965	0.3596	0.0566	0.263	0.0247	0.1691	0.0054	0.0913
assimilation	0.1474	0.5965	0.1446	0.6634	0.0958	0.3577	0.0416	0.1421
conversion of assimilates into biomass	0.093	0.36	0.1023	0.3113	0.0642	0.2049	0.0144	0.1556
maintenance respiration	0.0441	0.2523	0.0407	0.306	0.0277	0.266	0.0193	0.1618
death rates due to water stress	0.0112	0.1429	0.0042	0.2882	0.0048	0.1632	0.0083	0.0924
correction factor transpiration rate	0.0907	0.2563	0.0764	0.2858	0.088	0.3538	0.096	0.404
root parameters	0.0569	0.2057	0.0382	0.1615	0.0293	0.1885	0.0164	0.0981
Total	0.9779	3.5847	0.9334	3.8038	0.9634	3.1271	0.9408	2.6564

Uncertainty and sensitivity analysis methods are used to evaluate the coupled model, to predict maize production, and to study effect of crop parameters and environmental factors on maize production. The study results indicate that the uncertainty analysis using Monte Carlo method can reveal the risk of a possible loss of crop production with irrigation decrease and provide the probability of crop production in the uncertainty range of crop parameters and environment parameters. The sensitivity analysis reveals the effect of coupled model parameters and environment scenarios on maize production. This developed method can be used for crop production estimation in a region with limited available data. Synthetically, the method of integrating a coupled hydrologic and crop growth model with uncertainty analysis and sensitivity analysis can be used for guiding agricultural irrigation, saving water resources, predicting agricultural production and researching effects of the climatic and environmental change on agricultural production.

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