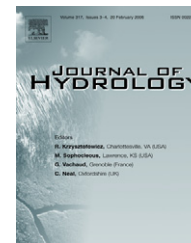




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# Assessment of crop growth and soil water modules in SWAT2000 using extensive field experiment data in an irrigation district of the Yellow River Basin

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## KEYWORDS

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**Summary** SWAT, a physically-based, hydrological model simulates crop growth, soil water and groundwater movement, and transport of sediment and nutrients at both the process and watershed scales. While the different versions of SWAT have been widely used throughout the world for agricultural and water resources applications, little has been done to test the performance, variability, and transferability of the parameters in the crop growth, soil water, and groundwater modules in an integrated way with multiple sets of field experimental data at the process scale. Using an multiple years of field experimental data of winter wheat (*Triticum aestivum* L.) in the irrigation district of the Yellow River Basin, this paper assesses the performance of the plant–soil–groundwater modules and the variability and transferability of SWAT2000. Comparison of the simulated results by SWAT to the observations showed that SWAT performed quite unsatisfactorily in LAI predictions during the senescence stage, in yield predictions, and in soil-water estimation under dry soil-profile conditions. The unsatisfactory performance in LAI prediction might be attributed to over-simplified senescence modeling; in yield prediction to the improper computation of the harvest index; and in soil water under dry conditions to the exclusion of groundwater evaporation from the soil water balance in SWAT. In this paper, improvements in crop growth, soil water, and groundwater modules in SWAT were implemented. The saturated soil profile was coupled to the oscillating groundwater table. A variable evaporation coefficient taking into account soil water deficit index, groundwater depth, and crop root depth was used to replace the fixed coefficient in computing groundwater evaporation. The soil water balance included the groundwater evaporation. The

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modifications improved simulations of crop evapotranspiration and biomass as well as soil water dynamics under dry soil-profile conditions. The evaluation shows that the crop growth and soil water components of SWAT could be further refined to better simulate the hydrology of agricultural watersheds.

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## Introduction

Hydrologic models are useful tools for understanding and analyzing watershed processes and their interactions, testing research hypotheses, and assessing management scenarios (He, 2003). During the past three decades, a number of agricultural watershed models such as AGNPS (Agricultural Non-point Source Pollution Model, Young et al., 1989), EPIC (Erosion Productivity Impact Calculator, Williams et al., 1989), and SWAT (Soil and Water Assessment Tool, Arnold et al., 1993) have been developed to support soil erosion assessment, water resource analysis, and water quality management in agricultural watersheds (He et al., 1993). SWAT, as a physically-based, spatially distributed hydrological model, has been widely used to simulate the ecological, hydrological, and environmental processes under a range of climate and management conditions throughout the world since 1993 (as indicated by nearly 150 publications documented by Gassman et al., 2007). For example, SWAT was used for assessing the impact of irrigation diversion on river flow in the Midwest of the US (e.g., Ritschard et al., 1999; Hatch et al., 1999; Sophocleous and Perkins, 2000; Bosch et al., 2004; Santhi et al., 2005; Behera and Panda, 2006), for simulating climate change scenarios and their related impacts (Edmonds and Rosenberg, 2005; Izaurrealde et al., 2005), and for modeling sediment or nutrient yield (Haggard et al., 2005; Lenhart et al., 2005). The wide applications of SWAT are probably attributed to the comprehensive considerations of hydrologic, biological, and environmental processes, incorporation of management scenarios, availability of parameter databases, and its robustness, flexibility, and user friendliness. Heuvelmans et al. (2004) presented a discussion in model parameter transferability for simulating the impact of land use on catchment hydrology. While SWAT is widely applied to broad range of conditions, however, few studies have reported on the variability and transferability of the model parameters, and on evaluation of its crop growth, soil water, and groundwater modules using extensive field experimental data at the process scale. How do SWAT parameters change over different climates and regions? How should the uncertainties of SWAT simulations be assessed? Can SWAT as a watershed model be used to accurately simulate crop growth and assess the impacts of agricultural management practices at the field scale as well? Since SWAT has been widely used in different countries of the world, testing the variability and transferability of its parameters would be of interest to many users. Thus, this paper uses multiple years of field experimental data of winter wheat (*Triticum aestivum* L.) to test the variability and transferability of SWAT to the irrigation districts in the lower reaches of the Yellow River in China. It first gives a brief description of crop growth, soil water, and groundwater modules in SWAT, and then discusses the

limitations of those modules in simulating soil water dynamics and crop growth and yield at the field scale by comparing them against experimental data. Subsequently, the paper makes modifications to the crop growth and groundwater modules in SWAT. Finally, the paper discusses the performance of the modified SWAT in the Yellow River Basin for hydrological simulation and yield prediction.

SWAT is a comprehensive, physically-based, hydrological model that incorporates hydrological, chemical, and ecological processes and management practices in watershed simulation and analysis. It simulates the plant growth by simplifying the generic crop growth module from the EPIC model (Neitsch, 2005). The crop growth module first calculates the plant growth under optimal conditions, and then computes the actual growth under stresses by water, temperature, nitrogen, and phosphorous. The generic module does not differentiate crop types and varieties and their specific response to various water and nutrient stresses. While the EPIC model has been evaluated and applied under a wide range of circumstances (e.g., Steduto et al., 1995; Lacko-bartosova and Kosovan, 1998; Guerra et al., 2004; Huang et al., 2006; Wang et al., 2006), the variability of the plant parameters that were built into the crop database and incorporated in SWAT and their inter-seasonal transferability remain to be studied.

SWAT uses a cascading approach to simulate the dynamics of soil water content. It computes infiltration using either the Curve Number (CN) method at daily intervals or the Green-Ampt method when hourly precipitation data are available. A routing module is used to simulate flow of soil water through each soil layer in the root zone. Downward movement or percolation occurs when field capacity of a soil layer is exceeded and the underlying layer is not saturated. SWAT simulates the movement of saturated flow between soil layers and assumes the uniform distribution of soil moisture within a given layer. Unsaturated flow between soil layers is indirectly estimated by the distributions of plant water uptake and soil water evaporation through two parameters: the soil evaporation compensation coefficient, ESCO and the plant uptake compensation factor, EPCO, respectively (Neitsch et al., 2002; Vazquez-Amabile and Engel, 2005). While these two parameters relate directly to crop water stress, determination of their values is not documented in SWAT.

Groundwater evaporation is the upward movement of water from the saturated zone to the unsaturated soil zone driven by the hydraulic gradient toward lower potential soil. It is dependent upon the depth of the groundwater, the soil properties and water content, the plant root, and the atmospheric driving force (Yang et al., 2000; Steinwand et al., 2006; Cooper et al., 2006). Higher evapotranspiration (ET) rates often occur in sites with shallow water tables, and lower ET rates in sites with deep water tables (Robinson,

1958; Nichols, 1994; Duell, 1990). A number of empirical functions have used water table depth to estimate ET rates from groundwater (Emery, 1970; Nichols, 1994; Nichols, 2000). These functions are attractive because they make physical sense, and require measurement of only one variable: water table depth, which can be estimated either using maps of water table depth, or from groundwater models such as MODFLOW (McDonald and Harbaugh, 1988; McDonald and Harbaugh, 1996).

SWAT estimates evaporation from shallow groundwater simply as a ratio of potential evaporation and assumes that it goes to the atmosphere directly (Neitsch et al., 2002). The groundwater evaporation is not included in the soil water balance or any other processes in the SWAT model, even though inclusion of it into soil water balance can be found in a modified version of the SWAT model, e.g., SWAT-MOD99 (Sophocleous and Perkins, 2000). The shallow aquifer is treated as a tank located somewhere below the soil profile. The soil profile and shallow aquifer are physically disconnected. In reality, the unsaturated soil profile is influenced by the fluctuation of the water table. The groundwater may move upward to the unsaturated soil profile and hence affect a series of soil water processes. It can replenish soil water, improve crop root uptake, or cause over-watering to crop growth. Thus coupling the soil water and groundwater is especially important in regions where groundwater is shallow.

Calibrations of SWAT model have been mostly performed by comparing the simulated surface runoff, and/or sediment yield and nutrient concentration in runoff against observations at the watershed outlets (e.g., Cabelguenne et al., 1990; Debaeke et al., 1996; Cabelguenne and Debaeke, 1998; Cabelguenne et al., 1999; Santos et al., 2000; Chanasyk et al., 2003; Bosch et al., 2004; Behera and Panda, 2006; Du et al., 2006). However, few studies have evaluated the performance of SWAT at the process scale (e.g., Anand et al., 2007). For example, a number of studies have reported the results of crop yield predictions of the EPIC model (Steduto et al., 1995; Lacko-bartosova and Kosovan, 1998; Cabelguenne et al., 1999; Cavero et al., 2000, 2001). Little has been reported on the growth module, especially yield prediction in SWAT, however, Behera and Panda (2006) can be cited as an example for evaluating the impact of tillage and fertilizer levels to crop yields in an agricultural watershed using the SWAT model. In agricultural watersheds, the relationships of crop growth and yield, soil and groundwater processes, and crop response to agricultural practices including crop yield prediction are even more important than the rainfall–runoff processes. Assessment of such relationships and processes in SWAT, therefore, is essential, particularly at the field scale.

The objectives of this paper are to (1) evaluate the generic crop growth module in SWAT and the inter-seasonal variability of the crop parameters in the module, (2) assess the performance of the soil water module in simulating the water stress to crop growth, (3) improve the representation of the physically connected soil water and groundwater simulation schemes, and (4) formulate and test a physically-based groundwater module for simulating groundwater evaporation and its effect to crop root uptake by using extensive experiment data at the field scale.

## Experiment design and revision of SWAT

### Field experiment

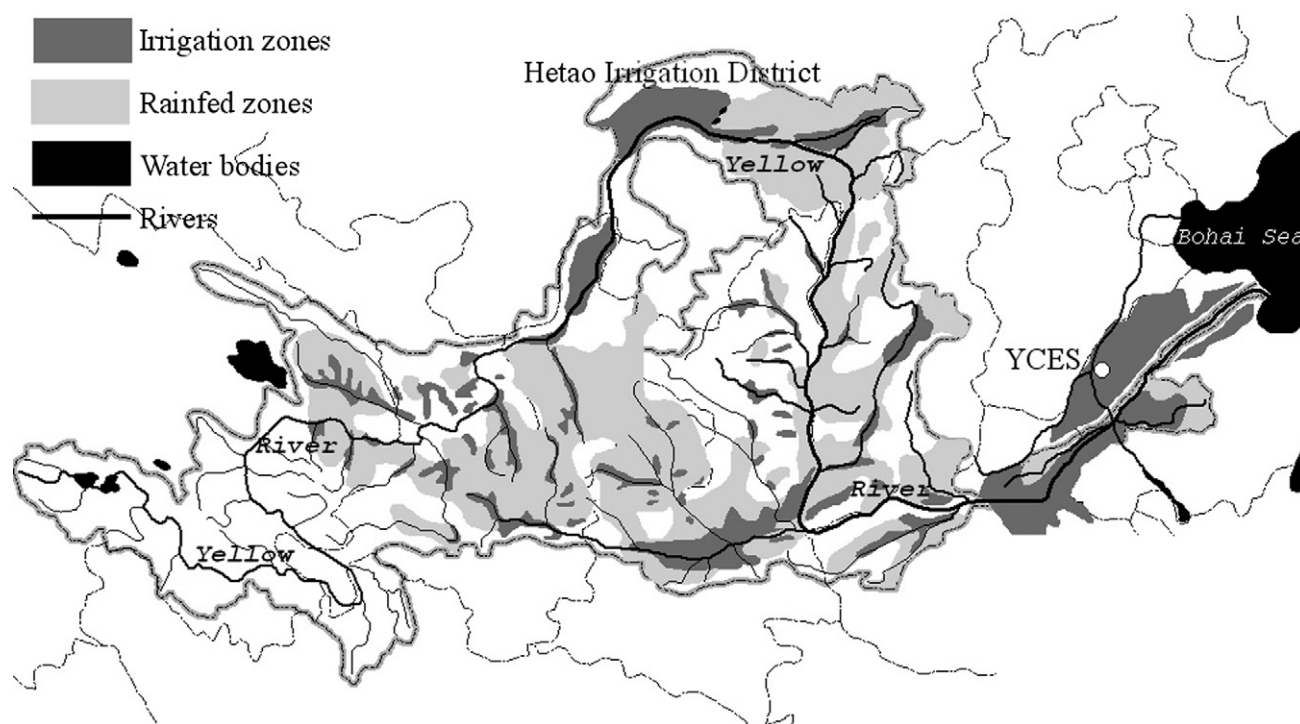
A field experiment was conducted at the Yucheng Comprehensive Experimental Station (YCES) of the Chinese Academy of Sciences at Yucheng City, Shandong Province, China, for the period of 2002–2005 to implement the objectives of this study. YCES is located in the Panzhuang Irrigation District in the fluvial plain of the Yellow River, Hai River, and Huai River, known as Huang (Yellow) – Huai – Hai Plain (Fig. 1). The predominant crops are winter wheat and summer maize in the irrigation districts in the lower reaches of the Yellow River Basin. The mean annual precipitation of 600 mm cannot meet the crop water requirements, especially during the winter wheat growth season for which the average seasonal precipitation is only about 150 mm, far less than the water requirement of wheat. Thus canal irrigation is widely used to supplement the crop water requirements. Due to irrigation recharge, water table is usually shallow, fluctuating between 0.5 and 3.0 m. In some cases, heavy summer storms may cause groundwater to flow to the surface. Hence, both soil water and groundwater are an integral part of crop production in the lower reaches of the Yellow River Basin.

There are approximately 6.67 million hectares (mha) of irrigated cropland in the Yellow River Basin. Annually, agricultural irrigation withdrawals are more than 70% of the flow from the Yellow River and its tributaries (Yellow River Commission, 2004). In recent years, water shortages have caused large losses and damages to both the economy and environment of the Yellow River Basin. Therefore, understanding the water transformation mechanism and processes at the field scale is essential to support effective use of limited water resources and improve agricultural production in the Yellow River Basin.

The experiment consisted of 32 equal-sized plots of  $5 \times 10 \text{ m}^2$ . The 32 plots were divided into four rows named A, B, C, and D, with eight sequentially numbered plots in each row (Table 1). Concrete barriers of 0.1 m thick, 1 m deep (below ground), and 0.1 m high (above the ground) were constructed to block lateral flow among the plots. Each plot was irrigated individually through a pipe system. The irrigation amount was measured with hydrometers for each application. In the middle of each plot, an access tube for the neutron probe moisture meter was installed down to a depth of 1.4 m to monitor the soil water profile at every 0.1 m layer at 5-day intervals and before each irrigation event. The depth to water table was measured once every two days manually.

A survey of the soil profiles was conducted for the four diagonally located plots: D1, C3, B5, and A7 at the experiment site. Soil samples were taken using an auger for every 0.1 m below the ground. Analysis of the soil texture including bulk density and grain composition was performed in the soil laboratory at the Yucheng Comprehensive Experimental Station.

The crops selected for the experiment were winter wheat (local variety name: series 13) and summer maize. The wheat experiment had eight treatments, each with four replications. The eight treatments were combinations of



**Figure 1** Distribution of irrigation and rainfed agricultural zones in Yellow River Basin and location of the Yucheng Comprehensive Experimental Station (YCES).

**Table 1** Plots arrangement and irrigation treatment design for the winter wheat experiment

	1	2	3	4	5	6	7	8	Plant density
A	Treatment I: No irrigation				Treatment II: 40%FC				Normal level
B	Treatment III: 60%FC				Treatment IV: 80%FC				
C	Treatment V: No irrigation				Treatment VI: 40%FC				75% of the normal level
D	Treatment VII: 60%FC				Treatment VIII: 80%FC				

Note: FC, field capacity.

two planting densities: normal level and one with 25% reduction, and four water supply levels: no irrigation, 40% of field capacity (FC), 60% FC, and 80%FC. Once the soil water storage in the top 50 cm soil layer was depleted to 40%, 60%, or 80% of field capacity, irrigation was applied to fill the 50 cm soil layer to field capacity. Crop growth observations included population, phenology, leaf area index (LAI), and biomass. The LAI and biomass measurements were done at 5-day intervals. At harvest, wheat yield of 1 m<sup>2</sup> samples and the entire plots were both recorded. Fertilizer application rates are 180 kg/ha of N and 150 kg/ha of P, which are generally implemented in the local fertilizer management.

## Model description

The work of this paper is based on SWAT2000. The code modification was done to this version before the latest version, SWAT2005 was released. While focusing on SWAT2000, the topics discussed in the following parts are still relevant to SWAT2005 (Neitsch, 2005; Neitsch et al., 2005).

## Crop growth

The plant growth component of SWAT model is a simplified version of the EPIC plant growth module. It computes potential plant growth, i.e. plant growth under optimal conditions (adequate water and nutrient supply and a favorable climate). Differences in growth between plant species are defined by the parameters contained in the plant growth database. Plant growth is simulated by computing leaf area development, light interception and its conversion to biomass (for details of the crop growth module, see Neitsch et al., 2002). The LAI curve after senescence was modified in SWAT2005 and documented as follows (Neitsch et al., 2005)

$$LAI = \frac{LAI_{sen}}{(1 - fr_{phu, sen})^2} \cdot (1 - fr_{phu})^2, \quad fr_{phu} \geq fr_{phu, sen} \quad (1)$$

where LAI is the leaf area index for a given day, LAI<sub>sen</sub> is the LAI at fr<sub>phu, sen</sub>, LAI<sub>mx</sub> is the maximum leaf area index, fr<sub>phu</sub> is the fraction of potential heat units accumulated for the plant on a given day during the growing season, and fr<sub>phu, sen</sub> is the fraction of growing season (PHU) at which senescence becomes the dominant growth process.

A variable shape coefficient is assigned to Eq. (1) instead of the constant exponential 2:

$$LAI = \frac{LAI_{sen}}{(1 - fr_{phu, sen})^\alpha} \cdot (1 - fr_{phu})^\alpha, \quad fr_{phu} \geq fr_{phu, sen} \quad (2)$$

where  $\alpha$  is introduced as another shape coefficient of the optimal LAI curve.

### Modified formulas for soil water and groundwater evaporation

The SWAT2000 model simulates soil water movement in a cascading approach. The soil profile is divided into layers with different soil properties. The processes and their modeling approaches are described in detail in the SWAT2000 theoretical document (Neitsch et al., 2002). However, a few problems exist in the current version of SWAT2000, and these problems remain in the latest version of SWAT2005.

1. The unsaturated soil profile is simulated separately from the underlying saturated aquifers. The predefined soil layers remain unchanged during the simulation. The storage of the shallow aquifer is simulated only as a tank, and the groundwater table is calculated but not used in the model. Physically, the lower boundary of the unsaturated soil profile is changing with the fluctuating water table and groundwater storage.
2. Groundwater evaporation is simply assumed as a fixed fraction of potential evapotranspiration (Neitsch et al., 2002):

$$W_{revap, mx} = \beta_{rev} E_0 \quad (3)$$

where  $W_{revap, mx}$  is the maximum amount of water moving into the soil zone in response to water deficiencies (mm H<sub>2</sub>O),  $\beta_{rev}$  is the groundwater evaporation coefficient, and  $E_0$  is potential evapotranspiration for the day (mm H<sub>2</sub>O). The actual amount of groundwater evaporation that will occur on a given day depends upon the predefined threshold value of evaporation occurrence and the aquifer water storage. The value of  $\beta_{rev}$  ranges between 0.02 and 0.20. Meanwhile, SWAT2000 assumes that groundwater enters the atmosphere directly instead of enriching the unsaturated soil profile above the water table (Neitsch et al., 2002). This is not physically reasonable in most cases.

Groundwater evaporation is influenced by several factors, such as the atmospheric forcing (potential evapotranspiration), the soil water status of the unsaturated soil profile, the root depth of crop and its distribution, and the depth to water table from the surface. To formulate a groundwater evaporation budget that takes into account evaporative demand, crop, soil water, and water table depth, the water table is calculated by using the relationship between aquifer storage to the specific yield and groundwater height (Vazquez-Amabile and Engel, 2005). The physical connection of the unsaturated soil profile and water table is subsequently established, and eventually, a formula for groundwater evaporation is proposed.

The shallow aquifer storage is given as follows:

$$\frac{dW_{shallow}}{dt} = Q_{rchg} - Q_{pump} - Q_{gw} - Q_{deep} \pm Q_{boundary} \quad (4)$$

where  $W_{shallow}$  is the storage of the shallow aquifer (mm),  $Q$  is the flow rate (mm/d), the subscripts rchg, pump, gw, deep, and boundary represent recharge to shallow aquifer, pumping rate from the shallow aquifer, groundwater base-flow, percolation from shallow to deep aquifer, and lateral flow into or out of the shallow aquifer at the shallow aquifer boundary, respectively.

Based on the methods of DRAINMOD, Vazquez-Amabile and Engel (2005) proposed a procedure to compute perched water table depth using SWAT outputs. However, the bottom of the soil profile remains unchanged in their work. In this paper, similar concepts to those by Vazquez-Amabile and Engel (2005) were used, and further, the oscillating water table and the bottom of the soil profile were coupled. The water table was derived through the storage volume–groundwater height curve as follows:

$$W_{shallow} = \int_0^h S_y(h) dh \quad (5)$$

where  $S_y(h)$  is the specific yield coefficient of the shallow aquifer and varies with aquifer properties,  $h$  is the groundwater height. Eq. (4) is then rewritten as

$$\frac{d[\int_0^h S_y(h) dh]}{dt} = Q_{rchg} - Q_{pump} - Q_{gw} - Q_{deep} \pm Q_{boundary} \quad (6)$$

At each time step, the groundwater height  $h$  is calculated from Eq. (6). In this paper, the model was used at the field scale and water table measured throughout the growing season was used as input.

The upward movement of shallow groundwater to the unsaturated zone depends on many factors, including the depth to water table, soil hydraulic properties like water holding capacity and hydraulic conductivity, evaporative demand, root development, and salinity and toxicity levels in both soil water and the groundwater (Grimes and Henderson, 1984; Ayars and Schoneman, 1984; Soppe and Ayars, 2003). While it is too complex to incorporate all those factors into groundwater evaporation calculations, this paper proposes a formula that is simple but still takes into account the main factors to estimate groundwater evaporation:

$$W_{revap, mx} = (SWDI - 0.3)^a \left(1 - \frac{DTW}{EXDP}\right)^b E_0 \quad (7)$$

$$\beta = (SWDI - 0.3)^a \left(1 - \frac{DTW}{EXDP}\right)^b \quad (8)$$

where DTW is the depth to water table (mm), EXDP is the extinction depth of groundwater evaporation (mm) (McDonald and Harbaugh, 1988; McDonald and Harbaugh, 1996).  $a$  and  $b$  are constants. SWDI is soil water deficit index which is defined as

$$SWDI = 1 - \sum_{l=1}^N \frac{SW_l - SW_{wp, l}}{SW_{fc, l} - SW_{wp, l}} \frac{THK_l}{THK} \quad (9)$$

where  $SW_l$ ,  $SW_{fc, l}$ ,  $SW_{wp, l}$  are the soil water content, soil water content at field capacity, and soil water content at wilting point, respectively. The letter  $l$  is the number of the soil layer.  $THK_l$  is the thickness of the layer  $l$ , and  $THK$  is the total thickness of the soil layers ( $N$ ).  $N$  is related to the thickness of the main root zone. SWDI ranges from 0.0 to 1.0. It is empirically assumed that when SWDI is less than

0.3, soil is wet enough that no groundwater will move upward to replenish the unsaturated profile. From Eqs. (7)–(9), it can be seen that the drier the unsaturated soil profile is, the more groundwater will move upward.

Eq. (7) can be rewritten as

$$W_{\text{revap,mx}} = \beta E_0 \quad (10)$$

Eq. (10) has the same form as Eq. (3). However, the coefficient  $\beta$  here is dependent of the buried depth on groundwater, soil moisture, and plant root depth rather than a constant.

## Model input

### Weather data

Weather data were acquired from the weather station located at YCES. The data included daily maximum and minimum temperature (°C), wind speed (m/s) at 10 m height, relative humidity, precipitation (mm), and sunshine hours (h). Daily wind speed was converted from the 10 m measurement height to the 1.7 m height that is used in SWAT model using a formula in the SWAT2000 theoretical document (Neitsch et al., 2002). The daily solar radiation was calculated using the daily sunshine hours by the Penman–Monteith formula (Allen et al., 1998). The parameters  $a$  and  $b$  in the radiation estimation approach of the Penman–Monteith formula were locally calibrated against measured net radiation values during 2000–2004. Regression analysis indicated that the estimation agreed fairly well with measurements with a slope of 0.94, interception 0.85 MJ/m<sup>2</sup>/d, and coefficient of determination 0.73. The calculated net radiation overestimated the measurements by 4.1%. However, comparisons of the calculated net radiation values to observations for the different growth seasons showed significant differences (Table 2). Thus, separate calibrations were done for each growth season to minimize the differences. Subsequently, the calibrated constants  $a$  and  $b$  and the daily sunshine duration data were used to compute solar radiation input to SWAT model for each individual growth season.

**Table 2** Comparison of the total estimated and measured net radiation values during the growth seasons of 2000–2004

Crops and growth seasons	Measured (MJ/m <sup>2</sup> )	Calculated (MJ/m <sup>2</sup> )	Relative error
Wheat, 2000–2001	1667.5	2011.6	0.21
Wheat, 2001–2002	2022.6	2079.4	0.03
Wheat, 2002–2003	1850.9	2032.8	0.10
Wheat, 2003–2004	2335.8	1984.0	–0.15

### Crop parameters

The cropping system in the region consists of two harvests per year (winter wheat–summer maize). Summer maize is usually planted around June 10 and harvested late September; winter wheat is planted around October 10 and harvested by the end of the following May or early June. The period of June 10–September 30 is considered as the growing season of the summer maize, and October 10–May 10 the growth season of the winter wheat. Potential heat units (PHUs) for winter wheat were calculated for each growth season. The base temperature was taken as 0 °C and the optimal temperature of 25 °C (Ritchie and Otter, 1985). The winter wheat is a perennial crop in the region. However, the SWAT model discontinues accumulation of PHU at the end of each calendar year and starts a new accumulation of PHU at the beginning of a new calendar year. Subsequently, the code of SWAT was modified to allow continuous accumulation of PHU over the whole growth season. The winter wheat experiences dormancy during winter time for which the accumulation of PHU stops. To recognize the dormancy period, SWAT was run to produce the daily PHU output for each growth season first and then accumulated the daily PHU values over the entire growth season. On the basis of the PHU accumulation and LAI observation data, optimal LAI curves were developed. Starting with the initial shape coefficients, the measured LAI and biomass data of the wet plots were used to refine the shape coefficients of the LAI curves. Value of the radiation use efficiency (RUE) was chosen from the crop data base of the SWAT2000. The growth seasons and the corresponding total PHU are given in Table 3.

### Soil data

SWAT estimates soil wilting point based on the clay content, bulk density, and soil saturation water content for each soil layer but requires available water content (AWC) as an input. With the wilting points and large amount of measured soil water content profiles, the AWC values for each layer were determined. The relevant soil parameters are given in Table 4. The initial soil water content profiles for each plot were measured within 3 days of the sowing date.

### Groundwater data

The depth to water table (DTW) was observed at 2-day intervals. Variation of the DTW from May 2002 to October 2006 was significant. It averaged 2.43 m, with a maximum of 5.12 m, a minimum of 0.32 m, and a standard deviation of 0.70 m. A water table rise is usually caused by recharge from irrigation or precipitation and a decline by irrigation withdrawals or upward supply to crop root zone. During the rainy season, the storm may cause a rapid rise in ground-

**Table 3** Planting and harvest dates of the winter wheat and the total PHU

Crops and growth season	Plots	Planting	Harvest	PHU (°C)
Wheat, 2002–2003	A1–D8	10/07/2002	06/08/2003	1893.9
Wheat, 2003–2004	A1–D8	10/20/2003	06/10/2004	1913.4
Wheat, 2004–2005	A1–D8	10/08/2004	06/08/2005	1821.0

Note: PHU, Plant Heat Unit; A1–D8, plot names.

**Table 4** Soil parameters used in the simulation

Depth (mm)	50.0	150.0	300.0	450.0	600.0	700.0	800.0	1200.0	1400.0	1800.0
Bulk density (g/cm <sup>3</sup> )	1.45	1.45	1.50	1.45	1.46	1.50	1.45	1.45	1.45	1.45
Soil AWC (mm/mm)	0.26	0.25	0.26	0.24	0.24	0.24	0.22	0.22	0.22	0.22
$K_{sat}$ (mm/h)	150.0	150.0	150.0	150.0	150.0	150.0	150.0	150.0	150.0	150.0
Content of organic carbon (%)	2.5	2.0	1.0	0.5	0.0	0.0	0.0	0.0	0.0	0.0
Content of clay (%)	11.8	11.8	18.8	18.8	18.5	18.5	19.5	14.0	15.7	15.7
Content of silt (%)	66.7	66.7	67.8	67.8	70.6	70.6	70.6	70.6	70.6	70.6
Content of sand (%)	21.5	21.5	13.4	13.4	10.9	10.9	9.9	15.4	13.7	13.7

Notes: AWC, available water content;  $K_{sat}$ : saturated soil water conductivity.

water table. Daily values of the water table were used as input to SWAT model.

### SWAT2000 model configuration

SWAT divides an entire watershed into subbasins on the basis of hydrological response units (HRU) and then simulates hydrological processes at each subbasin and routes the flows of each subbasin down to the watershed outlet for total river outflow. In this study, the experiment consisted of 32 experimental plots and each of the plots could be considered as a HRU. To run the SWAT2000 for the 32 experimental plots, a virtual basin was created with each of the four treatments in Table 1 as a subbasin and each of the plots in the subbasin as a HRU. Separate management files were written for each HRU or a group of HRUs that had the same operation practices.

### Evaluation of the simulation results

Nash–Sutcliffe efficiency (NSE), RMSE (root mean square errors) to observations standard deviation ratio (RSR), and standard regression (Moriasi et al., 2007) were used to evaluate the simulated values with the observed ones. NSE ranges between  $-\infty$  and 1.0, with NSE = 1 being the optimal value. Values between 0.0 and 1.0 are generally viewed as acceptable levels of performance, whereas a value <0.0 shows that the mean observed value is a better predictor than the simulated value, which indicates unacceptable performance. RSR incorporates the benefits of error index statistics and a scaling/normalization factor, so that the resulting statistic and reported values can apply to various constituents. RSR varies from an optimal value of 0, which indicates zero root mean square error (RMSE) or residual variation and therefore perfect model simulation, to a large positive value. The lower RSR value, the lower the RMSE is, and the better the model simulation performance is. The slope and y-intercept of the best-fit regression line can indicate how well-simulated results match measured data. The slope indicates the relative relationship between simulated and measured values. The y-intercept indicates the presence of a lag between model predictions and measured data, or that the data sets are not perfectly aligned. A slope of 1 and y-intercept of 0 indicate that the model perfectly reproduces the magnitudes of measured data. The slope and y-intercept are commonly examined under the assumption that the measured and simulated values are linearly related, which implies that all of the error variance is contained in simulated values and that the measured data

are error free (see Moriasi et al., 2007 for detailed calculation of NSE, RSR, and standard regression).

## Results and discussion

### Water stress to crop growth

The SWAT model first calculates the crop leaf growth and biomass under non-stress condition, i.e., the optimal growth. Then, the optimal LAI and biomass are adjusted with stress factors such as water, temperature, nitrogen, and phosphorous (Neitsch et al., 2002):

$$\gamma_{reg} = 1 - \max(wstrs, tstrs, nstrs, pstrs) \quad (11)$$

In this study it is assumed that crop grows under optimal nitrogen and phosphorous conditions. The water and temperature stresses are considered only.

As indicated in the theoretical document of SWAT2000 model,  $wstrs$  is given as

$$wstrs = 1 - \frac{E_{t,act}}{E_t} \quad (12)$$

where  $E_{t,act}$  is the actual plant evapotranspiration,  $E_t$  is the maximum plant transpiration on a given day.  $wstrs$  ranges between 0.0 and 1.0. When  $wstrs$  equals to 0.0, plant transpires at potential rate.

SWAT2000 assumes that water stress happens when available soil water content drops to  $AWC/4$ :

$$reduc = \exp \left[ 5 \left( \frac{1}{4} \frac{SW_l}{AWC_l} - 1 \right) \right] \text{ when } SW_l \leq \frac{1}{4} AWC_l \quad (13)$$

$$reduc = 1.0 \text{ when } SW_l > \frac{1}{4} AWC_l \quad (14)$$

where  $reduc$  is the water uptake reduction factor,  $SW_l$  is the volumetric soil water content above the wilting point,  $AWC$  is the available soil water content, the letter  $l$  is the number of the soil layers. Eqs. (13) and (14) assume that water extraction slows down when the available moisture falls to or below 25% AWC, regardless of differences of soil types or crops. However, the availability of water varies according to soil types and crops. The rate of root water uptake is in fact influenced more directly by the potential energy level of the soil water (soil matric potential and the associated hydraulic conductivity) than by water content. A certain soil matric potential corresponds in different soil types with different soil water contents. Generally, it can be stated that finer textured soils (clay) tend to have less proportion of the

total available water that does not stress crop water use than the more coarse textured soils (sand) do (Allen et al., 1998). Cabelguenne and Debaeke (1998) introduced into EPICphase, the French version of EPIC model, a soil water removal function that takes into account the soil texture and layers, the rooting pattern of the crop, the fraction of apparent available water beyond which crop transpiration is affected, and the intensity of extraction beyond the limit of  $-1.5$  MPa. For different crops, soils, and phenological phases, the availability of soil water to crop growth is different, and hence the different response of crop growth to soil water stress. The CERES (Crop and Environment Research Synthesis) crop models use different water stress indices to different organs at different phenological phases (Ritchie and Otter, 1985). Allen et al. (1998) also listed the threshold values for different crops. For winter wheat, it is 0.55. Thus, considering the crop response to soil water conditions in the study site, this study used 0.55 as the threshold value of soil water stress instead of 0.25 used in SWAT2000.

In the SWAT model, a compensation factor for plant transpiration *EPCO* was introduced to compensate water stress from the lower layers to root uptake in the current layer (Neitsch et al., 2002). *EPCO* varies between 0.0 and 1.0. When it equals to 0.0, no water from the lower soil layer will compensate the water deficit in the current layer. When *EPCO* equals 1.0, the water deficit in the current layer can be fully compensated by the available water in the lower layers. *EPCO* is actually an index that regulates the soil water distribution over the profile through the root uptake. It is related to the soil hydraulic properties of the profile. A sensitivity test of *EPCO* shows that the water stress dropped sharply with the value of *EPCO* increasing from 0.10 to 0.50. When *EPCO* = 0.50, water stress disappeared almost com-

pletely. The sensitive response of water stress to *EPCO* shows the need of calibrating it against field data.

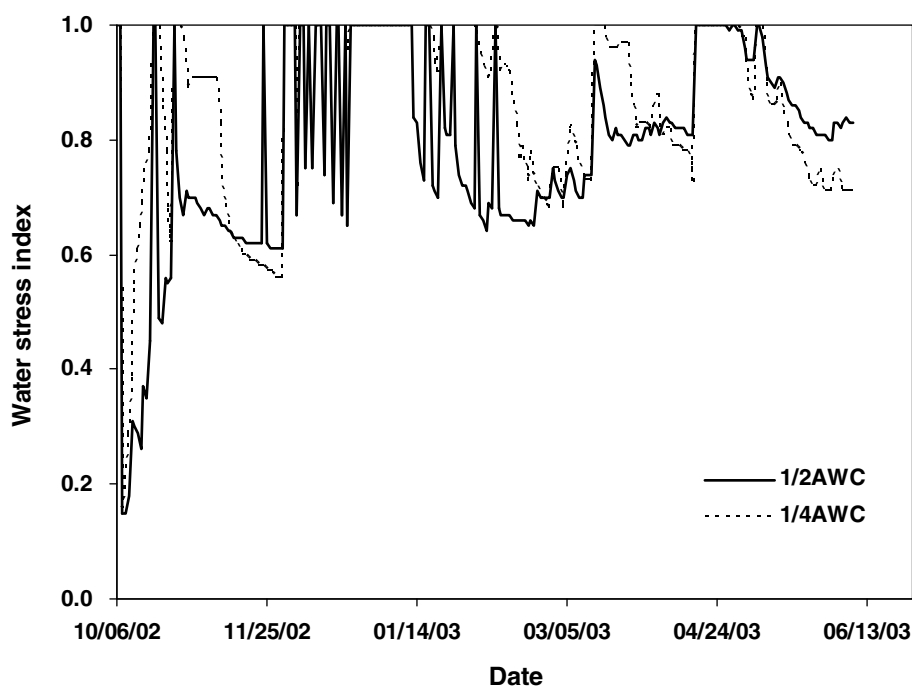
In this paper, calibrations of the crop growth and soil water parameters were done using the data from the wet treatments (less water stress) while calibration of the *EPCO* was conducted using the data from the dry treatments (higher water stress) for the 2003–2004 growth season. For other growth seasons (2002–2003 and 2004–2005), the soil parameters and *EPCO* values remained the same during the simulations. Simulation of the water stress process with both stress threshold values of 0.25AWC and 0.50AWC indicated significant differences between them (Fig. 2). With the threshold value of 0.25AWC, water stress happened much less frequently and with smaller intensity than with the 0.50AWC.

## Crop growth

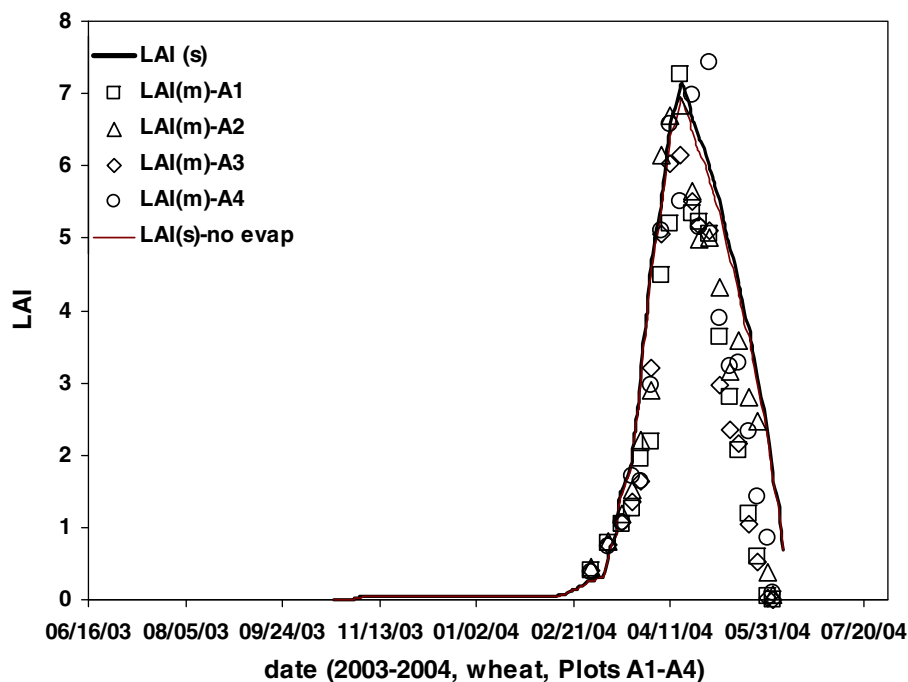
### LAI

Figs. 3a and 3b show comparisons of the simulated LAI values against observations for plots A1–A4 for treatment I (no irrigation) and plots B5–B8 for treatment IV (irrigation when soil water content drops to 80% of field capacity, see Table 1), respectively, during the growth season 2003–2004.

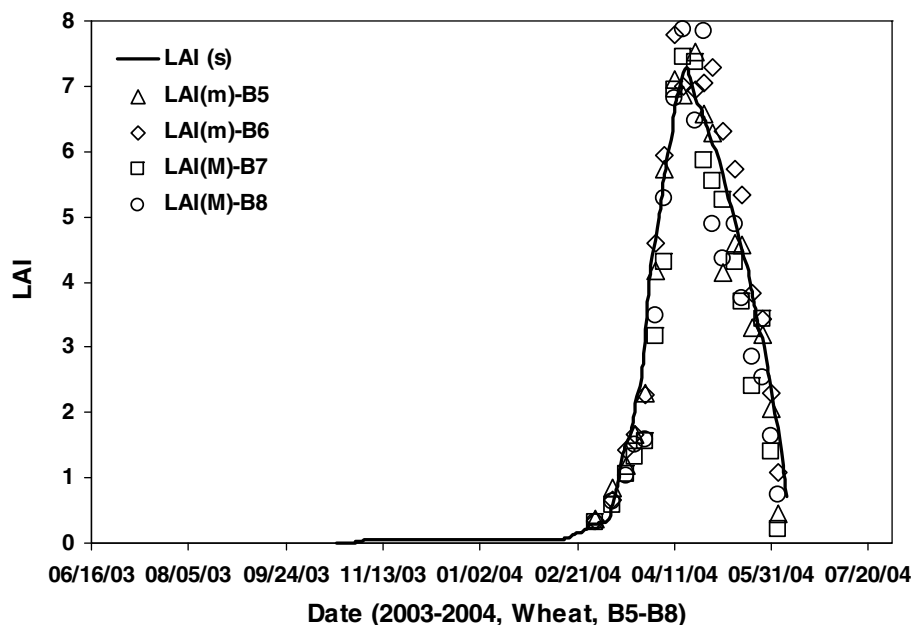
In order to evaluate the LAI simulation in different periods of the growth season, the growth season of winter wheat is partitioned into two continuous stages. Stage-1 indicates the growth period before maximum LAI values, and stage-2 the period after the maximum LAI value. Analyses of NSE, RSR, and standard regression were done for the growth season, stage-1, and stage-2, respectively. The water stress courses of plots A1–A4 in treatment I during the growth season had similar pattern and magnitude. No



**Figure 2** Comparison of water stress index between different stress thresholds (2002–2003, wheat, plot A1, *EPCO* = 0.15): AWC: available water content; *EPCO*: the plant uptake compensation factor.



**Figure 3a** Comparison of simulated LAI values against the measured ones of winter wheat: s: simulated values; m: measured values; no evap: groundwater evaporation is not included in soil water balance; A1–A4: plot names.



**Figure 3b** Simulated and measured LAI for winter wheat: s: simulated values; m: measured values; B5–B8: plots names.

water stress was found in the crop in plots B5–B8 in treatment IV during the growth season (Table 5).

Following Moriasi et al. (2007), performance rating of the reported statistics NSE and RSR are classified into four levels: very good (V), good (G), satisfactory (S), and unsatisfactory (U). As shown in Table 5, the predicted LAI values for stage-1 are very good. For stage-2, the predicted LAI values for the B5–B8 plots are very good, but those for the A1–A4 plots are unsatisfactory. Winter wheat in plots A1–A4 experienced

water stress almost during the whole season, especially during stage-2. The significant difference between the simulated LAI values and observations during the senescence phase might be attributed to SWAT’s neglecting water stress to leaf growth since senescence dominated. To remedy this deficiency, Cabelguenne et al. (1999) introduced the impact of water and nitrogen stresses on the leaf senescence to take into account accelerated leaf loss from a development stage due to the build-up of water stress.

**Table 5** Statistical results of the predicted LAI values against observations

Items	Treatments and plots		NSE	RSR	slope	y-intercept <sup>a</sup>	R <sup>2</sup>
LAI	A2, A3	Stage-1 + stage-2	0.60(S)	0.64(S)	0.89	1.37	0.84
		Stage-1	0.89(V)	0.33(V)	0.99	0.46	0.93
		Stage-2	0.29(U)	0.84(U)	0.79	2.21	0.91
	B5, B6, B7, B8	Stage-1 + stage-2	0.97(V)	0.17(V)	0.85	0.81	0.92
		Stage-1	0.97(V)	0.17(V)	0.91	0.52	0.94
		Stage-2	0.97(V)	0.16(V)	0.77	1.28	0.91
Biomass	Treatment I A2, A3	Stage-1 + stage-2	0.98(V)	0.15(V)	0.95	-555.43	0.95
		Stage-1	0.94(V)	0.24(V)	0.76	61.55	0.97
		Stage-2	0.98(V)	0.15(V)	1.14	-3253.50	0.84
	Treatment III B5, B6, B7, B8	Stage-1 + stage-2	0.97(V)	0.17(V)	1.04	-888.57	0.93
		Stage-1	0.91(V)	0.30(V)	0.70	121.14	0.94
		Stage-2	0.97(V)	0.16(V)	1.24	-3712.70	0.80
Yield	All treatments and plots	2003–2004	-4.44(U)	2.33(U)	0.18	680.10	0.48
		2002–2003	-0.11(U)	1.05(U)	0.28	4121.50	0.15

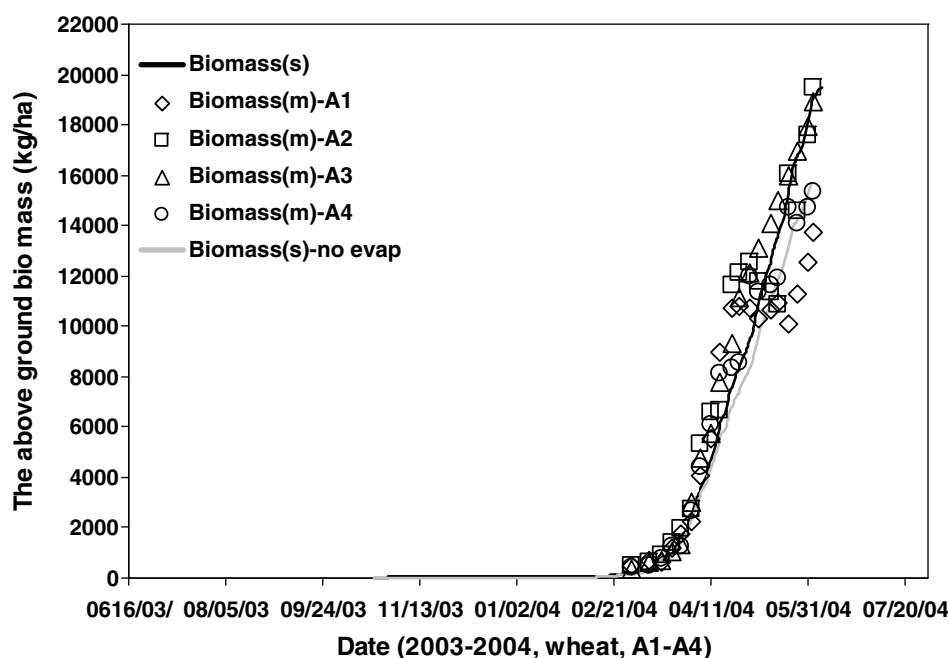
Notes: NSE: Nash–Sutcliffe efficiency; RSR: RMSE (root mean square error) to observations standard deviation ratio; R<sup>2</sup>: coefficient of determination; Stage-1 indicates the crop growth period before maximum LAI; Stage-2 indicates the crop growth period after maximum LAI; (V), very good; (S), satisfactory; (U), unsatisfactory; A2, A3, B5–B8: plot names.

<sup>a</sup> Unit, LAI: dimensionless; Biomass: kg/ha; Yield: kg/ha.

With regard to the entire growth season, the predictions of LAI values for plots B5–B8 are very good, and those for plots A1–A4 satisfactory (the coefficient of determination is 0.84). Standard regression indicates that the predicted LAI values of A1–A4 agree very well with observations during stage-1, but are much higher than the observed LAI values during stage-2 with a slope of 0.79 and a positive y-intercept 2.21. For plots B5–B8, the correlation of the

predicted LAI values to observations are better than those for plots A1–A4. The coefficients of determination indicate that the predicted LAI values account for more than 90% of the variance of observations for most of the cases.

In the generic growth module of the SWAT model, the LAI development depends upon the accumulation of plant heat units and the environmental stress indexes and has no relation to the biomass accumulation. This brings great flexibil-



**Figure 4a** Comparison of measured above-ground biomass to simulated one for treatment I (Plots A1–A4): Biomass: above-ground biomass; s: simulated values; m: measured values; no evap: groundwater evaporation is not included in soil water balance; A1–A4: plots names.

ity to calibration of shape coefficients for the optimal LAI curves. In reality, LAI and biomass production are coupled by positive feedback. The denser the wheat canopy, the more photosynthetically active radiation (PAR) is intercepted and more biomass is produced, and the greater the LAI value. Breaking up the coupling effect makes the model calibration easier, and this paper also showed very good calibration results. The environmental factors pose influences not only on the leaf growth, but also on the leaf senescence (Cabelguenne and Debaeke, 1998). But, SWAT models the leaf senescence solely as a function of the plant heat unit and ignores the impact of all other environmental factors. In this study, the slow senescence processes of treatment I over the three growth seasons might be attributed to this simplification.

### Biomass and yield

Figs. 4a and 4b show comparisons of the simulated above-ground biomass values to observations for plots A1–A4 of treatment I and plots B5–B8 of treatment IV. As seen in Table 5, the statistical results of NSE and RSR are very good for all plots and all stages. The coefficients of determination are more than 0.90 for stage-1 and the growth season, and more than 0.80 for stage-2 of the plots. The slope values and y-intercepts indicate significant deviation of the predicted values to the observations in the late stage-1 and early stage-2. The predictions underestimated the observations. However, for the entire growth season, the regression analysis produces very good results (Figs. 4a and 4b).

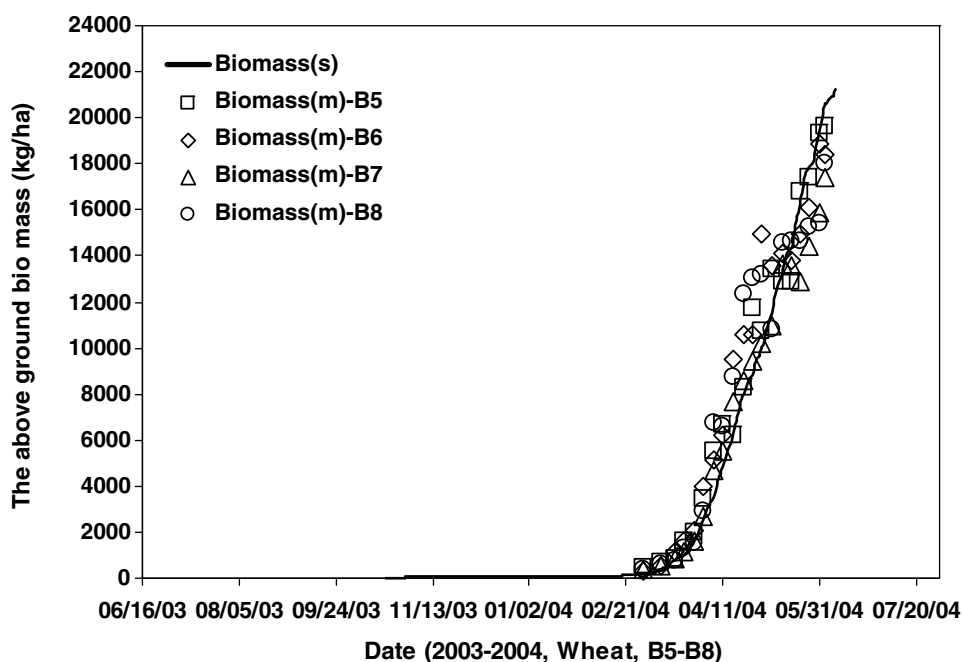
Table 5 also shows the statistical data for the simulated and the observed yield comparisons. The NSE and RSR of two growth seasons are categorized as unsatisfactory. Their slopes deviate from the 1:1 line significantly, the y-inter-

cepts are very big, and the coefficients of determination are quite low. The model overestimated the crop yield under soil water stress conditions.

The simulated wheat yield was compared to observations for the growth seasons 2002–2003 and 2003–2004. For the growth season 2002–2003, the mean, standard deviation, and coefficients of variation for the simulated and observed yields are 5621.0 and 5419.4 kg/ha, 368.82 and 518.5 kg/ha, and 0.07 and 0.10, respectively. Those for the 2003–2004 growth season are 7729.2 and 5233.2 kg/ha, 298.1 and 1166.5 kg/ha, and 0.04 and 0.22, respectively. The simulated yields are much higher than observations, or even are as much as twice of observations for some plots. The simulated wheat yields showed smaller variations among different water supply conditions than those of the observed yields. Several studies have reported poor yield prediction using the EPIC model (Moulin and Beckie, 1993; Toure et al., 1995; Steduto et al., 1995; Debaeke et al., 1996; Mearns et al., 1999). Since its crop growth module is based on the one from EPIC, SWAT appears to have similar problems in crop yield prediction as well.

SWAT calculates crop yield as a product of Harvest Index (HI) and above-ground biomass. Daily HI was calculated on the basis of an optimal HI and a fraction of PHU (Neitsch et al., 2002). A single relationship of the HI to the fraction of PHU is used without considering different sensitivity of the HI values to water or nitrogen stress at different phenological stages. The value of the HI is further reduced by the water use ratio (WUR) in the SWAT model, however, the approach is not documented in the theoretical document of SWAT2000 (Neitsch et al., 2002). According to the source code of SWAT2000, computation of the WUR is given by

$$wur = 100 \times \frac{swh}{swp} \quad (15)$$



**Figure 4b** Comparison of measured above-ground biomass to simulated one for treatment IV (Plots B5–B8): Biomass: above-ground biomass; s: simulated values; m: measured values; B5–B8: plots names.

where  $sw_h$  and  $sw_p$  are the accumulated actual and potential evapotranspiration, respectively. The accumulation starts when the PHU accumulation exceeds 0.50 and ends at  $fr_{ph_u.sen_sce}$  when senescence dominates leaf growth. If  $fr_{ph_u.sen_sce}$  is less than 0.50, the accumulation does not happen and WUR is taken as 100. The simulation results indicate that when the wheat evapotranspiration rate drops from the potential to 50%, the HI decreases by 0.02% or 5% only. Meanwhile, the water stress impacts the HI in the same way during the entire growth season without differentiating the phenological stages. To consider the water stress differences among phenological stages, Cabelguenne et al. (1999) divided the entire developmental period of the crops into different physiological phases. For winter wheat, four physiological phases were defined on the basis of accumulated degree-days. The relationship of the water stress to HI was reformulated to consider its variations among the different physiological phases. The refinement is reported to have improved the simulation results (Cabelguenne et al., 1999). Similarly, future versions of SWAT need to consider new advancements relevant to crop growth to improve its performance in crop physiological simulation and to produce more reliable results, especially for agricultural watersheds where crop yield and yield response to deficit irrigation management are critical.

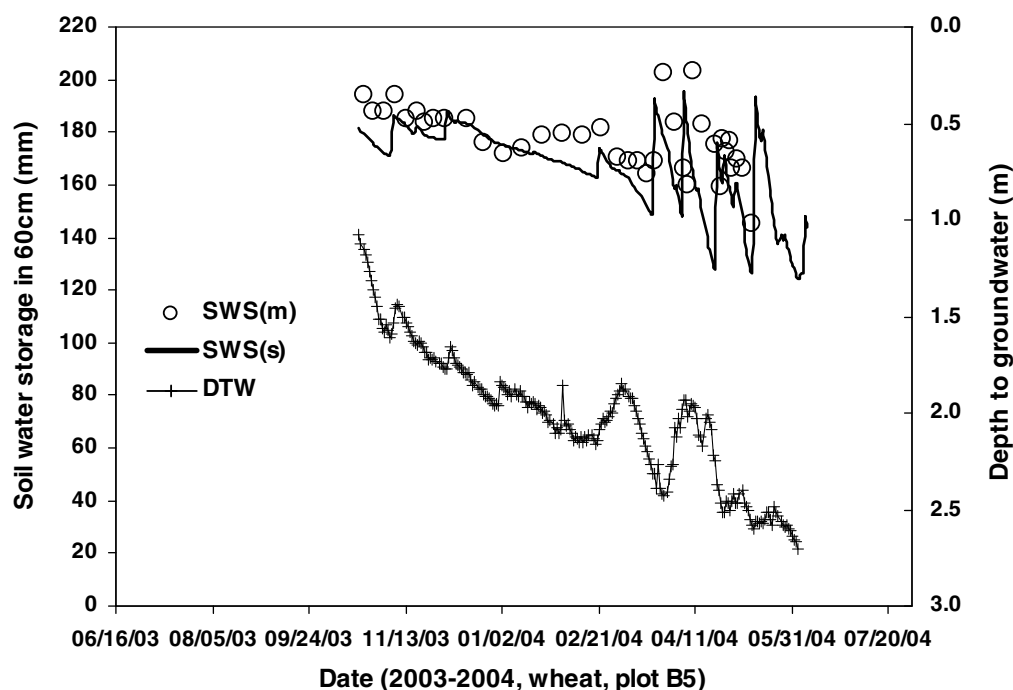
## Evapotranspiration

The Penman–Monteith equation was employed to calculate the wheat evapotranspiration rates. The simulated ET rates of plot B5 over the 2003–2004 growth season were compared to the observed ET rates from a weighing lysimeter (for detailed descriptions of the weighing lysimeter, see Luo et al., 2003; Yang et al., 2000). Comparison of the

evapotranspiration processes showed very good agreement between them. Linear regression analysis showed the y-interception of only 0.015 mm/d, and the coefficient of determination up to 0.88. The NSE is 0.87 and RSR 0.33, and both fall into the category of ‘very good’ (Moriasi et al., 2007). The simulated ET rates underestimated the observed values slightly. This might be attributed to lysimeter measurement errors as Skaggs et al. (2006) reported that ET rates in the volumetric lysimeters were very high owing to their oasis effects. In this study, the simulated total wheat ET over the growth season was 452 mm while the lysimeter observed total ET was 490 mm, with a difference of less than 10%.

## Soil water and groundwater evaporation

The impact of groundwater evaporation on soil profiles was investigated by comparing the simulated soil water storages in the upper 60.0 cm soil to the observed ones. During the 2003–2004 growth season, a total irrigation water supply of 194.0 mm was applied to each of the plots B5–B8, the highest amount among all the plots. The irrigation supply, together with the total seasonal rainfall of 202.1 mm was retained in the upper 60.0 cm soil to maintain relative high soil moisture. SWAT simulations of the plots B5–B8 showed occurrence of percolations from the unsaturated profile at the beginning of the season. This might be partly due to the initial soil profile input and soil parameter calibration. There was no groundwater evaporation in this treatment because of the quite wet soil profile. Overall, there was a very good agreement between the simulated and measured soil water storages. As an example, Fig. 5a shows the comparison of the simulated soil water storage values for plot B5 against the measured ones.



**Figure 5a** Comparison of simulated soil water storage in the upper 60 cm to the measured one: SWS: soil water storage, DTW: depth to groundwater, s: simulated values, m: measured values; B5: plot name.

Comparisons of the simulated soil water storage in the upper 60cm against the measured ones for plot A1 for treatment I (no irrigation) are shown in Fig. 5b during the growth season 2003–2004, and in Fig. 5c during 2004–2005, respec-

tively. In later stages of the growth season, the predicted values of soil water storage were much less than the observed ones when groundwater evaporation was not included. But, when the groundwater evaporation was

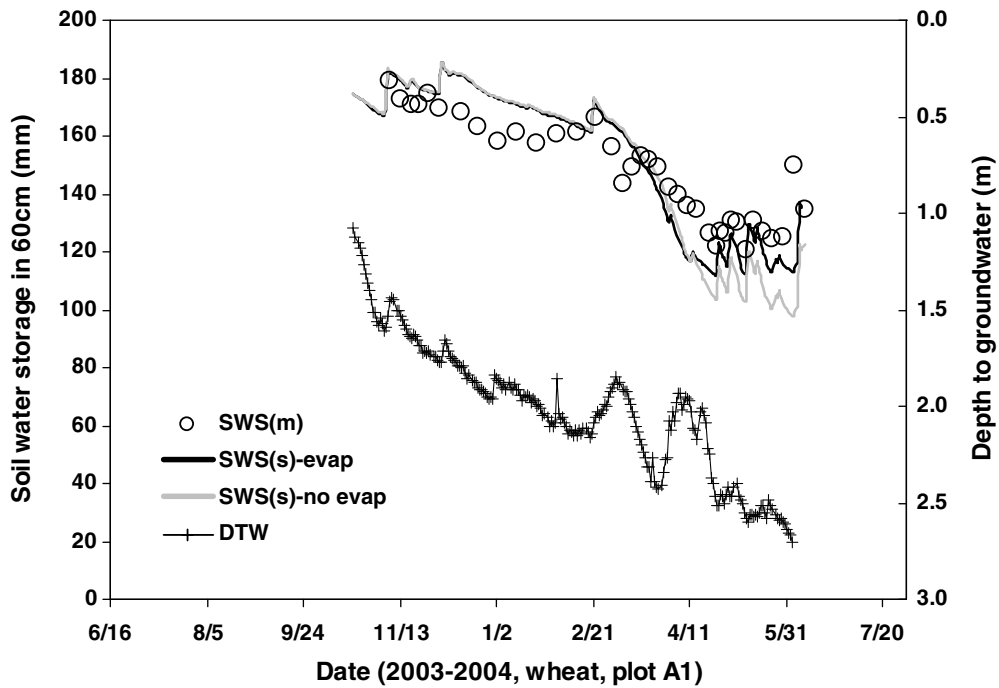


Figure 5b Comparison of simulated soil water storage in the upper 60 cm to the measured one: SWS: soil water storage; DTW: depth to groundwater; s: simulated values; m: measured values; evap: groundwater evaporation is included in soil water balance; no evap: groundwater evaporation is not included in soil water balance.

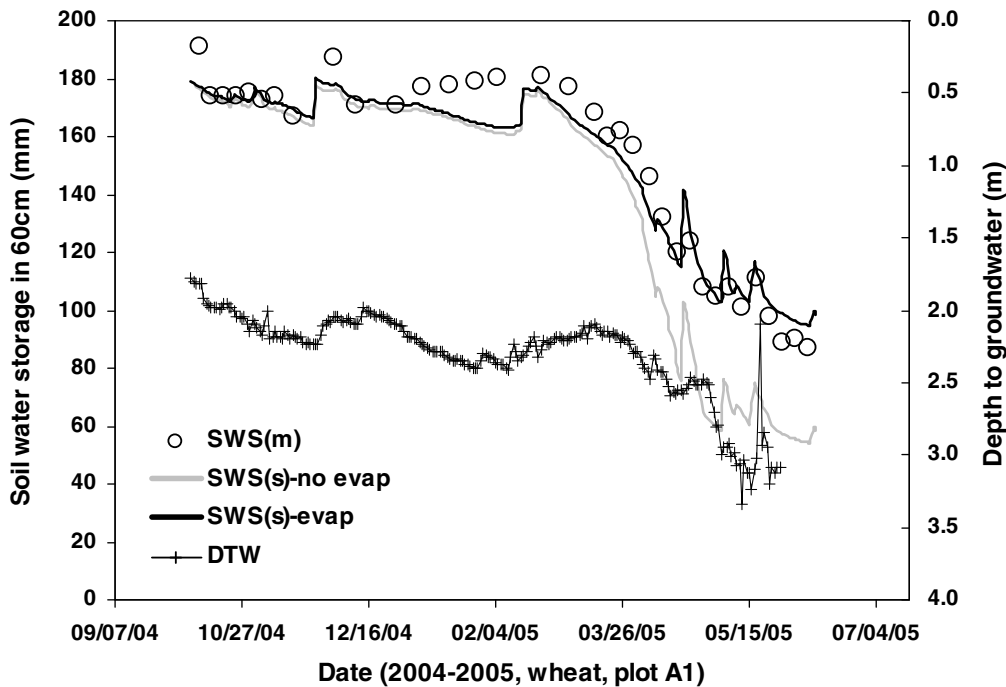
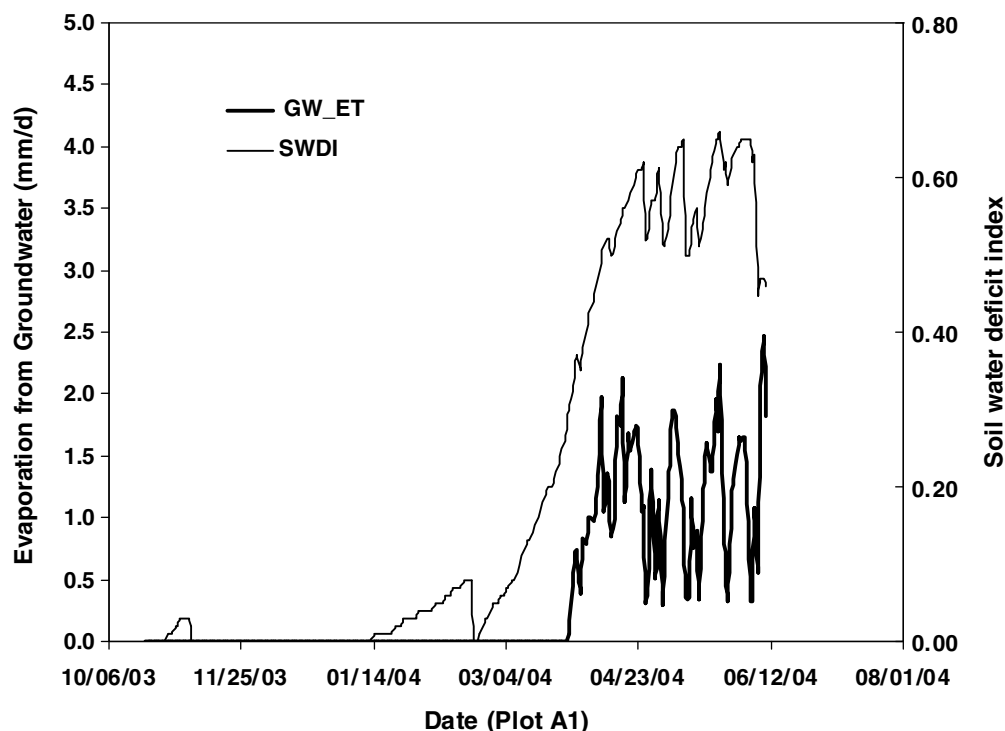


Figure 5c Comparison of simulated soil water storage in the upper 60 cm to the measured one: SWS: soil water storage; DTW: depth to groundwater; s: simulated values; m: measured values; evap: groundwater evaporation is included in soil water balance; no evap: groundwater evaporation is not included in soil water balance.



**Figure 6** Soil water deficit index and groundwater evaporation during the growth season: GW\_ET: groundwater evaporation; SWDI: soil water deficit index; A1: plot name.

included, the soil water storage simulation was improved significantly.

Fig. 6 shows the daily groundwater evaporation and the soil water deficit index. As can be seen, the groundwater evaporation was triggered by the high soil water deficit index. The groundwater evaporation in plot A1 was 41.8 mm during the 2002–2003 growth season, 84.0 mm in 2003–2004, and 40.0 mm in 2004–2005, which accounted for approximately 17.3%, 22.2%, and 14.0% of the total wheat ET during those years, respectively. This is similar to the finding by Yang et al. (2000) at the same site from October 1998 through June 1999. Yang et al. reported that the winter wheat lysimeter measurement included 16.6% of total evapotranspiration from the groundwater evaporation for a water table depth of 1.6–2.4 m.

### Impact of groundwater evaporation on crop growth

The impact of groundwater evaporation on winter wheat water use and growth was investigated by comparing ET and above-ground biomass of winter wheat when groundwater evaporation was not included in soil water balance to that when groundwater evaporation was included. Table 6 shows the comparison of the ET rates and above-ground biomass with the groundwater evaporation (GW\_ET) included for plot A1 of treatment I. For the growth seasons of 2002–2003 and 2004–2005, the wheat ET did not show obvious differences between simulations with the groundwater evaporation included and not included. However, for the growth season 2003–2004, the differences were significant. And, biomass production increased significantly when the

**Table 6** Impacts of groundwater evaporation on the ET and biomass production of winter wheat

Growth season	Groundwater Evaporation	ET(mm)	GW_ET (mm)	Biomass (kg/ha)	Biomass reduction (%) <sup>a</sup>
2002–2003	Included in soil water balance	241.19	41.80	13250.88	22.6
	Not included	240.38		10805.53	
2003–2004	Included in soil water balance	393.39	87.64	19487.65	24.2
	Not included	336.72		15684.99	
2004–2005	Included in soil water balance	297.40	33.29	13150.06	9.0
	Not included	280.59		12061.86	

Notes: GW\_ET, groundwater evaporation during the growth season.

<sup>a</sup> Compared to that when GW\_ET is not included in soil water balance.

groundwater evaporation was included. For the growth seasons of 2002–2003 and 2003–2004, biomass increased by over 20% when groundwater evaporation was included, indicating the importance of groundwater evaporation in the crop growth simulation under dry conditions. This might have implied that application of SWAT model to arid or semiarid regions where groundwater is shallow should consider the effect of groundwater evaporation on crop growth.

### Inter seasonal variation of the crop parameters

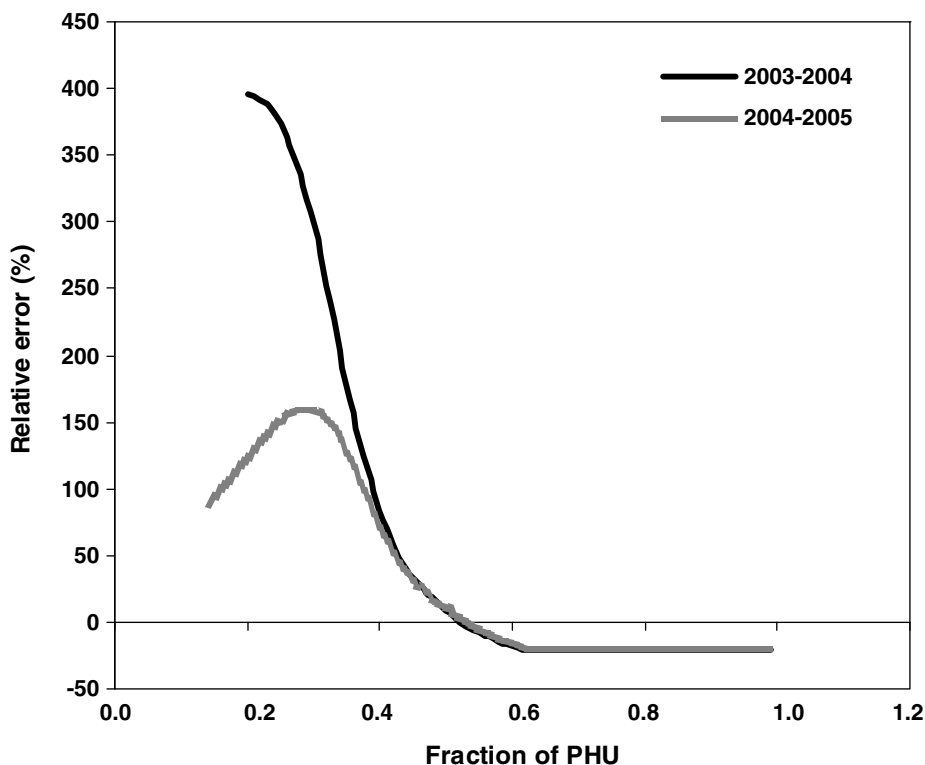
The maximal LAI values and the fractions of PHU during the senescence period differed significantly among the three growth seasons of 2002–2005 (see Table 7). The optimal curves of the 2003–2004 and 2004–2005 seasons were compared with those of the 2002–2003 season (base line). The relative errors were calculated and plotted in Fig. 7. During the early phenological phase, the relative errors were as high as 400%. This is probably due to the fact that a variety of environmental factors have influence on phenological

development and the relevant growth processes. For example, Miralles et al. (2001) reported that the phyllochron varied among the different sowing dates. At the earlier phenological phases, the phenol-thermal index decreased with the delayed sowing dates, but increased at the later phases. The optimal LAI curve approach does not consider such phenomena. Another recurring quest in the wheat phenological research in recent decades has been to better understand the role of temperature and to improve the thermal time concept (McMaster, 1997). Most wheat phenological modeling is based on the concept of thermal time, which is further modified by factors such as photoperiod, water stress, nutrient stress, upper temperature thresholds, and varying base temperatures (Weir et al., 1984; Ritchie and Otter, 1985; McMaster et al., 1992; Rickman et al., 1996). Cabelguenne et al. (1999) divided the wheat growth into 4 different phases in the EPICphase model to improve the simulation of biomass, HI, and other relevant processes. The inter-seasonal variability of the calibrated crop parameters shows that the simplified approach of the LAI develop-

**Table 7** LAI curve shape coefficients

Growth seasons	PHU (°C)	LAI <sub>max</sub>	fr <sub>phu,1</sub>	fr <sub>lai,1</sub>	fr <sub>phu,2</sub>	fr <sub>lai,2</sub>	fr <sub>phu,sen</sub>	$\alpha$
2002–2003	1893.9	5.0	0.25	0.03	0.45	0.71	0.62	0.70
2003–2004	1913.4	8.5	0.25	0.15	0.45	0.94	0.48	0.70
2004–2005	1821.0	7.5	0.25	0.08	0.45	0.92	0.50	0.70

Notes: PHU, Plant Heat Unit; LAI<sub>max</sub>, the maximum LAI (leaf area index); fr<sub>phu,1</sub>, fraction of PHU at point 1; fr<sub>lai,1</sub>, fraction of LAI at point 1; fr<sub>phu,2</sub>, fraction of PHU at point 2; fr<sub>lai,2</sub>, fraction of LAI at point 2; fr<sub>phu,sen</sub>, fraction of PHU when senescence dominates leaf development;  $\alpha$ , constant.



**Figure 7** The relative error of the optimal LAI curves against that of 2003–2004.

ment in the current generic growth module of SWAT needs to be improved. Transferring the growth parameters from one growth season to other seasons, or use of the suggested parameters from other sources should be done with great caution. Further refinement of the crop growth module is needed to improve the applicability of SWAT to agricultural watersheds.

## Conclusions

As a physically-based, comprehensive hydrological model, SWAT has been widely used for simulation of hydrological processes, crop growth, and transport of sediment and nutrients at both the process and watershed scales. But little has been reported to test the performance, variability and transferability of the SWAT parameters in the crop growth, soil water, and groundwater modules at the field scale. Using the field experimental data of the winter wheat in the lower reaches of the Yellow River Basin, this paper evaluated the crop growth, soil, and groundwater modules of SWAT2000. Overall, the crop growth and soil water modules of the SWAT2000 performed well in simulating wheat LAI, biomass, and soil water moisture. However, under some conditions, the performance of the SWAT modules was unsatisfactory. Specifically, this paper concludes the following:

- (1) The current representation of the water stress in SWAT needs to be modified to be more sensitive to specific soil types, crops, and their developmental phases.
- (2) SWAT overestimated the LAI values during the senescence period because of its neglect of the effects of other environmental factors such as water and nitrogen, on leaf senescence.
- (3) Compared to observed yields, SWAT simulations overestimated the wheat yields significantly partially due to improper computation of the harvest index.
- (4) Addressing the inadequate representation of groundwater evaporation in SWAT, this paper presents a revised groundwater evaporation formula that incorporates the coupling of the soil profile dynamics with groundwater table changes. Groundwater evaporation replenished soil water profiles and in turn reduced water stress to crop growth, leading to increased biomass production compared to that without groundwater supply. The test results show that the revised groundwater formula significantly improved the simulations of soil water storage and wheat biomass production under dry soil conditions.
- (5) Calibrations of the crop parameters in SWAT indicated large variations of the SWAT parameters among the different growth seasons in the lower reaches of the Yellow River Basin.

SWAT is one of the widely used, comprehensive hydrologic models in the analysis of agricultural watersheds. Compared to a number of crop growth models, it considers the spatial heterogeneity of the study watershed. But as shown in this paper, the current version of SWAT has a number of limitations, particularly for agricultural watershed analysis such

as crop yield simulation and irrigation management. While SWAT was developed as a watershed-scale model, it is also desirable to incorporate the latest advancement of crop growth modeling in future versions of SWAT to improve its crop growth module. When it is used in agricultural watersheds, especially when used for crop yield simulation and irrigation management, the model parameters should be carefully calibrated against field data. Meanwhile, the groundwater module needs to be extended so that it can simulate the crop–soil–groundwater interactions. Incorporating these improvements to SWAT with carefully designed experimental data will make it a more accurate and robust model for agricultural research and management.

## Acknowledgements

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