# System dynamics simulation of soil water resources with data support from the Yucheng Comprehensive Experimental Station, North China

Changchun Zhou, Yi Luo and Melanie Zeppel

## ABSTRACT

System dynamics (SD) is one of the most suitable methods available to simulate and quantify the behaviour of complex systems due to it non-linear, multivariable, information feedback and temporally changing characteristics. This paper has improved on Khan *et al.*'s established model (see Khan *et al.* (2009) 'Analyzing complex behavior of hydrological systems through a system dynamics approach', *Environmental Modeling & Software* **24**, 1363–1372) by adding water production functions for three main crops (winter wheat, summer maize and cotton) based on soil water balance at the field level. Conclusions based on the simulation were as follows. (1) The model could simulate the dynamics of water balance components of winter wheat and summer maize relatively accurately through testing and validation. (2) Two to four irrigations were needed for the water-use requirement for winter wheat and summer maize when irrigation level was 75 mm each time. Cotton did not need to be irrigated except for the addition of 60 mm pre-sowing water. (3) Exploiting groundwater as far as possible and taking measures to reduce soil evaporation and at the same keeping irrigation unchanged was one of the best ways for sustainable utilization of water resources in the upper reaches of the Panzhuang District. (4) Water-use efficiencies were consistent with the regions' measured results showing that the model could simulate the water cycle in the field comparatively accurately.

**Key words** | movement law, soil water, system dynamics

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## INTRODUCTION

System dynamics (SD) is a theory of system structure and a methodology for representing complex systems and analysing their dynamic behaviour (Forrester 1961). It primarily explores how the behaviour pattern of a complex system changes with time (Khan *et al.* 2009). Its most important characteristic is to explain the endogenous structure of the system under research, to observe how the different elements of the system relate to each other, and to perform many experiments with changing relationships within the system when different choices are simulated (Simonovic 2002; Khan *et al.* 2009). The relationship between structure and behaviour forms the basis of information feedback and control in SD (Simonovic 2000). The application range of SD is very extensive, from company strategies to the dynamics of diseases, from the arms race of the cold war to the interaction between HIV and the human immune system (Simonovic 2002) and, in general, its application pervades various systems and extends to many fields (Wang *et al.* 1986).

In a rice field system, Khan *et al.* (2009) used SD to simulate water balance on a daily basis under aerobic conditions with provision of supplemental irrigation on demand. Advantages of their model were: (1) it combined with the mechanistic processes of the water balance based at a field scale; (2) it was a physically based conceptual model; and (3) it was dynamic (Zhou & Luo 2012). But the model had the following limitations: (1) its validity was verified only based on paddy fields without validation on other types of farmland; and (2) it was unable to reflect water-use

efficiency (WUE) without relating it to water production functions.

The ultimate purpose of water-saving agriculture is to improve the agricultural output efficiency of per unit water resources. In the field scale, this means increasing soil WUE (Li *et al.* 2000). Highly efficient utilization of water resources would be to increase crop yield and water productivity comprehensively (Gao 2009).

Therefore, based on three main crops (winter wheat, summer maize and cotton) and the field water balance of Yucheng Comprehensive Experimental Station (YCES) within Panzhuang Irrigation District, the model established by Khan *et al.* (2009) was improved by adding water production functions. Through use of a field scale simulation, our purpose was to establish the foundation for application of the model in the Panzhuang Irrigation District. We wanted to quantitatively analyse the composition of soil water consumption and suggest methods of increasing WUE in the region, and ultimately to realize a reasonable allocation of the water resources of the irrigation district.

The objectives of our study thus were as follows: (1) to validate the model and calculate cotton evapotranspiration (ET); (2) to study conditions of water consumption of winter wheat, summer maize and cotton within their growing seasons; (3) to discuss interactions among various water balance components through scenario simulation; and (4) to quantify water-use efficiencies of winter wheat, summer maize and cotton.

## METHODS

### Study area

The YCES (36°57′N, 116°36′E) belongs to the Chinese Ecosystem Research Network (CERN) and the China National Ecosystem Observation and Research Network (CNEN) (Figure 1). It is located geographically in the southwest of Yucheng County, Shandong Province. This area is the Yellow River alluvial plain, with an average altitude of 28 m, and is representative of typical conditions of the Huang-Huai-Hai Plain. The soil type is an alluvial deposit of the Yellow River and is mainly composed of aquox and salted aquox. The surface soil is rich in sandy loam (Table 1).
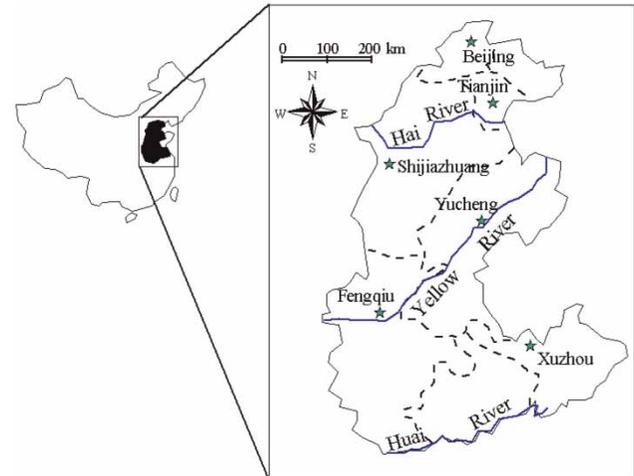


**Figure 1** | Location of the Yucheng Comprehensive Station in China (Fang *et al.* 2010).

**Table 1** | Soil textures (Liu & Luo 2010)

| Depth (m) | Sand (%) | Silt (%) | Clay (%) | Soil texture |
|-----------|----------|----------|----------|--------------|
| 0–20 | 13.17 | 68.54 | 18.29 | Sandy loam |
| 20–40 | 13.11 | 66.54 | 20.35 | Sandy clay loam |
| 40–60 | 14.42 | 70.40 | 15.18 | Sandy loam |
| 60–80 | 16.72 | 71.19 | 12.09 | Sandy loam |
| 80–100 | 27.15 | 62.84 | 10.01 | Sandy loam |
| 100–120 | 38.57 | 55.50 | 5.93 | Sandy loam |

Yucheng station is an agricultural experimental station with winter wheat and summer maize as the main crops, and has crop rotation characteristic of the North China Plain (NCP). Winter wheat is sown in mid-October and harvested in early June of the next year. Summer maize is sown in the middle of June and harvested in early October.

### Model development

#### Conceptual model

Considering the effective root zone as a single layer, the soil water balance at the field level can be expressed according to storage as given below (all parameters expressed in depth units) (Khan *et al.* 2009):

$$W_i = W_{i-1} + P_i + I_i + E_{gi} - \mathrm{ET}_i - P_{ai} - R_{si} \qquad (1)$$

where, $W_i$, $W_{i-1}$ are the soil water storage at the end of day $i$ and $i-1$, respectively; according to Liu & Luo (2010),

effective rooting depth is: winter wheat 1.5 m, summer maize 1 m, cotton 1.2 m; $P_i$ is the precipitation on day $i$; $I_i$ is the irrigation on day $i$; $E_{gi}$ is the capillary rise from the underlying water table on day $i$ depending on the depth of the water table; $ET_i$ is the actual evapotranspiration on day $i$; $P_{ai}$ is the percolation on day $i$; and $R_{si}$ is the runoff on day $i$ (Zhou & Luo 2012).

## ET calculation

Under unsaturated conditions (Khan *et al.* 2009; Zhou & Luo 2012), actual evapotranspiration is calculated by:

$$ET = K_S \times K_C \times ET_0 \qquad (2)$$

where $K_S$ is a dimensionless factor expressing the effects of limiting soil moisture conditions on crop evapotranspiration; $K_C$ is the single crop coefficient (Allen *et al.* 1998); and $ET_0$ is the potential evapotranspiration.

   $ET_0$ calculation: The concept and calculation formula of $ET_0$ are given in FAO Irrigation and Drainage Paper No. 56 (Allen *et al.* 1998). It is calculated by the Penman–Monteith equation using meteorological data from the YCES.

   $K_C$ determination: Based on Zhou & Luo (2012), crop coefficients of winter wheat and summer maize were from Liu (2007) and those of cotton were from The Cooperative Group of Contour Maps of Main Crops Water Requirements in China (1993).

   $K_S$ calculation: According to Allen *et al.* (1998),

$$K_S = \begin{bmatrix} 1 & \theta \geq \theta_{\text{threshold}} \\ \dfrac{\theta - \theta_{\text{wp}}}{\theta_{\text{threshold}} - \theta_{\text{wp}}} & \theta_{\text{wp}} \leq \theta < \theta_{\text{threshold}} \end{bmatrix} \qquad (3)$$

where $\theta$ is the volumetric water content; $\theta_{\text{wp}}$ is the water content at wilting point; $\theta_{\text{threshold}}$ is the threshold water content when water stress occurs:

$$\theta_{\text{threshold}} = (1 - p)\theta_{\text{fc}} + p\theta_{\text{wp}} \qquad (4)$$

$$p = b + 0.04(5 - ET_m) \qquad (5)$$

where $p$ is the fraction of total available water that a crop can extract from the root zone; and $\theta_{\text{fc}}$ is the water content

at field capacity; $b$ is the $p$ value under the standard conditions ($ET_m = 5$ mm/day), for winter wheat and summer maize, $b = 0.55$; for cotton, $b = 0.65$ (Allen *et al.* 1998); and $ET_m$ is the largest field evapotranspiration without water pressure.

## $E_g$ calculation

Capillary rise is estimated using the following exponential relationship (Li & Dong 1998; Khan *et al.* 2009):

$$E_g = ET \times e^{-aL} \qquad (6)$$

where $a$ is a parameter that relates to the capacity of the soil to transmit capillary fluxes; and $L$ is the depth of the water table below the root zone.

## $P_a$ calculation

Darcy's Law was used to calculate the percolation (Khan *et al.* 2009):

$$P_a = \frac{(h(\theta) - h) \times K(\theta)}{L} \qquad (7)$$

where $h(\theta)$ is negative pressure head; $h$ is the groundwater head; and $K(\theta)$ is the unsaturated hydraulic conductivity.

   $h(\theta)$ calculation: According to Wu (1993), $h(\theta)$ is calculated by the following soil water retention curve:

$$\theta = \frac{z \times u}{u + |h(\theta)|^b} \qquad (8)$$

where, $z$, $u$ and $b$ are coefficients.

   $K(\theta)$ calculation:

$$K(\theta) = K \times e^{-f \times h(\theta)} \qquad (9)$$

where $K$ is the saturated hydraulic conductivity; $f$ is the texture-specific empirical constant.

## $R_S$ calculation

When the soil becomes saturated after irrigation or precipitation, redundant water is discharged as surface runoff,

**Table 2** │ The values of variables and parameters of the model

| Category | Names and values |
|---|---|
| Shared parameters | Field capacity (m$^3$/m$^3$): 0.32 |
| | Water content at saturation (m$^3$/m$^3$): 0.42 |
| | [a]The soil retention curve: $\theta = \dfrac{0.473 \times 307.28}{307.28 + |h|^{0.904}}$ |
| | Unsaturated hydraulic conductivity = saturated hydraulic conductivity $\times \exp(-0.0198|h|)$ |
| Parameters of wheat and maize | Water content at wilting point (m$^3$/m$^3$): 0.12 |
| | [b]Values of $a$ and saturated hydraulic conductivity (mm/min): Wheat: 2001–2002: 1.45 and 12; 2002–2003: 0.6 and 0.035; 2003–2004: 5 and 0.012; 2003–2005: 1.7 and 0.015. Maize: 2000: 20 and 15; 2001: 1 and 0.125; 2003: 0.85 and 100; 2004: 120 and 0.035; 2005: 3 and 0.8 |
| Parameters of cotton | Water content at wilting point (m$^3$/m$^3$): 0.08 |
| | Values of $a$ and saturated hydraulic conductivity(mm/min): Cotton: 2003–2006: 2[c] and 30[d] |

$a$, capacity of the soil to transmit capillary fluxes.
[a]Soil retention and hydraulic conductivity curves are taken from Wu (1993).
[b]Value range of saturated hydraulic conductivity is from Wu (1993), Yin (2005) and Lai (2009).
[c]Li & Dong (1998).
[d]Yang (2005).

which is given by (Khan et al. 2009; Zhou & Luo 2012):

$$R_s = \begin{bmatrix} 0 & \theta \le \theta_S \\ W_i - \theta_S \times \text{RD} & \theta > \theta_S. \end{bmatrix} \tag{10}$$

where $\theta_S$ is water content at saturation; RD is the root depth; and the other parameters have been defined above.

Table 2 lists the values of variables and parameters of winter wheat, summer maize and cotton.

## Developing the system dynamics model

Based on the model established by Khan et al. (2009), water production functions were added using Vensim software (Figure 2). Water production functions of winter wheat, summer maize and cotton were from Liu (2007), Wu et al. (1998) and Yang (2005), respectively.

Winter wheat: $Y = -0.1633\,\text{ET}^2 + 167.22\,\text{ET} - 35,190$ (11)

Summer maize: $Y = (\text{ET}/4.573)^{2.02}$ (12)

Cotton: $Y = 6.031 \times \text{ET} - 1,738$ (13)

where ET is the actual evapotranspiration of crop on year, mm year$^{-1}$; and $Y$ is the economic yield of crop, kg hm$^{-2}$ year$^{-1}$.

## Model testing and validation

Model testing and validation aim at justifying the reliability of the model and providing confidence for model application (Shi & Gill 2005). As SD models seek to explain how and why the problematic dynamics are created, it is important that their structure should be a valid representation of real-life processes. This factor is very important because the purpose of a SD study is to evaluate policy alternatives in order to improve the behaviour. This purpose is quite different than that of a statistical/correlational 'forecasting' model. On the one hand, as far as the 'forecasting' model is concerned, the main (often the only) criterion of model validity is the match between output and real data, as the purpose of the model is to provide an accurate forecast. On the other hand, for the SD model, the main criterion of model validity becomes 'structure' validity, which refers to the validity of the set of relations used in the model to represent the real-life processes (Saysel & Barlas 2001). The validity of behaviour is also important, but it is different in two ways: first, behaviour validity is meaningful only after the structure validity is established (the 'right behaviour for the right reasons' principle). Second, a point-by-point match between the model behaviour and the real behaviour is not as important as it is in forecasting modelling. What is more

**Figure 2** | The stock-flow structure of the dynamic soil water balance model. *Note:* ET(sum) and soil water are level variables; ⟖⟶ is rate variable; ——▶ is material flow or information chain; ⬭: is source or leakage; others are auxiliary variable/constant variable/exogenous variable, and *b, u, z, f* are coefficients or parameters.

important in SD methods is that the model produces the major dynamic patterns of concern to the system (such as exponential growth, collapse, asymptotic growth, S-shaped growth, damping or expanding oscillations, etc.; Khan *et al.* 2009).

Testing the validity of the model structure usually uses indirect structure testing; extreme conditions and behaviour sensitivity tests are the two most powerful and practical ways of indirect structure tests (Barlas 1996; Sterman 2000).

Extreme-condition tests refer to assigning extreme values to selected model parameters or variables and comparing the model-generated behaviour to the expected behaviour of the real system under the same extreme condition (Saysel & Barlas 2001). Structural flaws or inconsistencies would be found by such tests if the model hides them (Barlas 1996).

Behaviour sensitivity test refers to determining sensitive model parameters and asking whether these sensitivities would make sense in real life (Saysel & Barlas 2001).

Model validation refers to using primary data from field data collection and from the existing literature to test the reliability and accuracy of the simulated results. In the present study, the data of soil volumetric water content from 2001 to 2005 were collected to validate the model. Soil water content moisture is measured once every 5 days and additional measurements are carried out after every rainfall and before and after irrigation.

Crop water requirement (ET) was an emphasis of the simulation. The simulated results were evaluated with the data measured by a weighing lysimeter at the YCES of the CAS from 2000 to 2005. The weighing lysimeter was built in the middle of a $1.0 \times 10^6 \, \mathrm{m}^2$ cultivated field in 1990 and put into use in 1991 (Luo *et al.* 2007). Yang *et al.* (2000) described in detail the structure, functions and principles of the lysimeter. The goodness-of-fit of the simulations was assessed with the help of three estimators, which are the Nash–Sutcliffe efficiency (NSE), $R^2$ and the root mean square error (RMSE).

$$NSE = 1 - \frac{\sum_{i=1}^{n} (ET_{obs} - ET_{cal})^2}{\sum_{i=1}^{n} (ET_{obs} - ET_{mean})^2} \tag{14}$$

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (ET_{obs} - ET_{cal})^2} \tag{15}$$

# RESULTS

## Model testing and validation

### Extreme condition I – No irrigation (rain-fed)

We took the wheat data from 2003 to 2004 as an example.

Soil water decreased 6.9%, ET and yield dropped by 22.0 and 31.4% under the scenario of no irrigation respectively. This finding illustrated that no irrigation significantly decreased yield.

### Extreme condition II – No irrigation and no precipitation

Compared with no irrigation (rain-fed) and the normal situation (irrigation and precipitation as usual), soil water decreased 8.7 and 15.0% and ET dropped 25.8 and 42.1% under the scenario of no irrigation and no precipitation, respectively. The results revealed that severe soil water deficit influenced booting and flowering of winter wheat and led to no yield.

In this paper, effects of parameters such as $p$, root depth (RD), water content at fc ($\theta_{fc}$), saturated hydraulic conductivity ($K$) and crop coefficient ($K_C$) on yield are analyzed primarily. The wheat data from 2003 to 2004 are still used as an example.

Table 2 results showed that abnormal fluctuations of winter wheat yields were not found as a result of minimal parameter change. Yield change was also related to water product function as well as parameters themselves and was most sensitive to change in crop coefficients.

The indirect structure tests revealed that the model structure produced meaningful behaviour under extreme parameters values and model behaviour displayed meaningful sensitivity to crop coefficients.

Figure 3 showed that the observed soil volumetric water content for the experimental field and the simulated values basically followed the same trend. The determination coefficients ($R^2$) between the observed and simulated values were 0.608, 0.792, 0.786 for winter wheat from 2002 to 2005 and 0.879, 0.769, 0.721 for summer maize in 2001, 2003, 2004, respectively and suggested that the improved SD model could simulate the dynamics of water balance components comparatively accurately.

For ET simulation, the estimation for the goodness-of-fit of winter wheat was 'good', and for summer maize was 'slightly inferior' (Figure 4 and Table 3).

## Cotton ET calculation

The SD model can be used to calculate cotton ET because water balance components of winter wheat and summer maize have been simulated comparatively accurately. Due to the lack of daily crop coefficient, we simulated them per month. For ease of comparison, growth periods were all set at 180 days. In total, 60 mm pre-sowing water was supplied 10 days before sowing. Antecedent soil water contents are from Yang (2005) in 2003 and 2004 and the China–Japan cooperation project of Yucheng Station in 2005 and 2006.

Simulation results showed that in 2003 water consumption of cotton was 496.2 mm. The simulated ET values were 675.0, 646.0 and 644.9 mm from 2004 to 2006, respectively. The 4-year mean ET value was 615.5 mm.

Water requirement intensity curve presented a parabola type change that was characteristic of cotton growing either openly or as plastic mulching cultivation; at seedling stage thr value was low, then rose and reached a peak at flowering stage, and then decreased.

## Soil water balance

Tables 4 and 5 listed the observed and simulated values of the water balance components of wheat and maize in their growing seasons from 2000 to 2005.

Irrigation range was 101.4–226.4 mm during wheat growing periods from 2001 to 2005. Therefore, two to three irrigations were needed for each season of winter wheat if the irrigation dose was 75 mm per each time; irrigation time was primarily when plants were turning green, head-flowering and/or grain-filling stage.

Compared with 86.5 mm in 2005, the irrigation value was zero in the maize growing seasons from 2000 to 2004. Therefore, maize usually did not need to be irrigated. If needed, irrigation took place mainly at the sowing or seedling stage. Rainfall in 2005 was actually more than that in 2000 and 2003, which indicated that the irrigation schedule of summer maize depended not
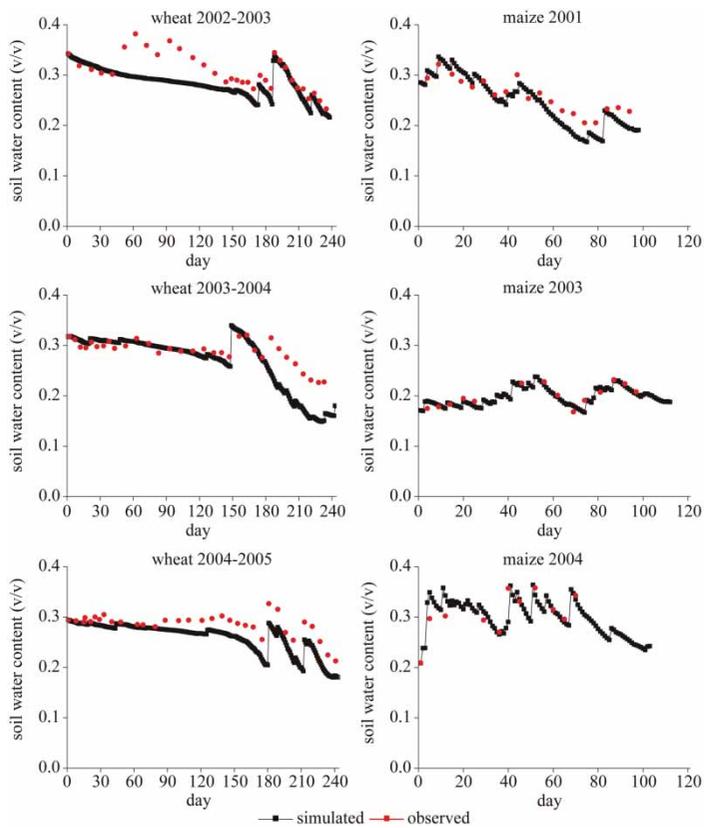
**Figure 3** | Comparisons of the observed and simulated soil volumetric water content values of winter wheat and summer maize.

only on total rainfall amount but also on rainfall time distribution.

Consequently, irrigation water requirement for winter wheat and summer maize ranged from 101.4 to 312.9 mm. Two to four irrigations were needed for winter wheat and summer maize if the irrigation dose was 75 mm per each time. We found that implementation of the optimized irrigation schedule, one application of surface irrigation during wet years, two in normal years and three in dry years for winter wheat and once for summer maize would achieve relatively high yields.

As shown in Tables 4 and 5, wheat water consumption was primarily from precipitation and irrigation, least consumption was due to capillary rise, and mid consumption was due to the contribution of soil water storage. Water consumption of maize was mainly from rainfall, secondly from irrigation and soil water storage, and least from capillary rise.

In the wheat growing seasons, less precipitation plus irrigation usually resulted in an increase in capillary rise.

Maize generally did not need to be irrigated, more rainfall resulted in more percolation and less capillary rise.

Soil water gradually decreased and was consumed primarily during the growth period of winter wheat. However, in the maize growing season, it seldom decreased as it was recharged by rainfall. Wheat and maize soil water primarily fluctuated with irrigation and rainfall, respectively.

As there were no observed values for cotton water balance components, we set the model parameters according to Li & Dong (1998) and Yang (2005). In this way, we obtained the values of cotton water balance components from 2003 to 2006 (Table 6).

As can be seen from Table 7, cotton water consumption was primarily taken from rainfall, secondarily from capillary rise, and thirdly from soil water storage. Usually the crop did not need to be irrigated. Thus, water was not the main limiting factor for cotton production in Yucheng City, as natural rainfall could satisfy the water requirement.
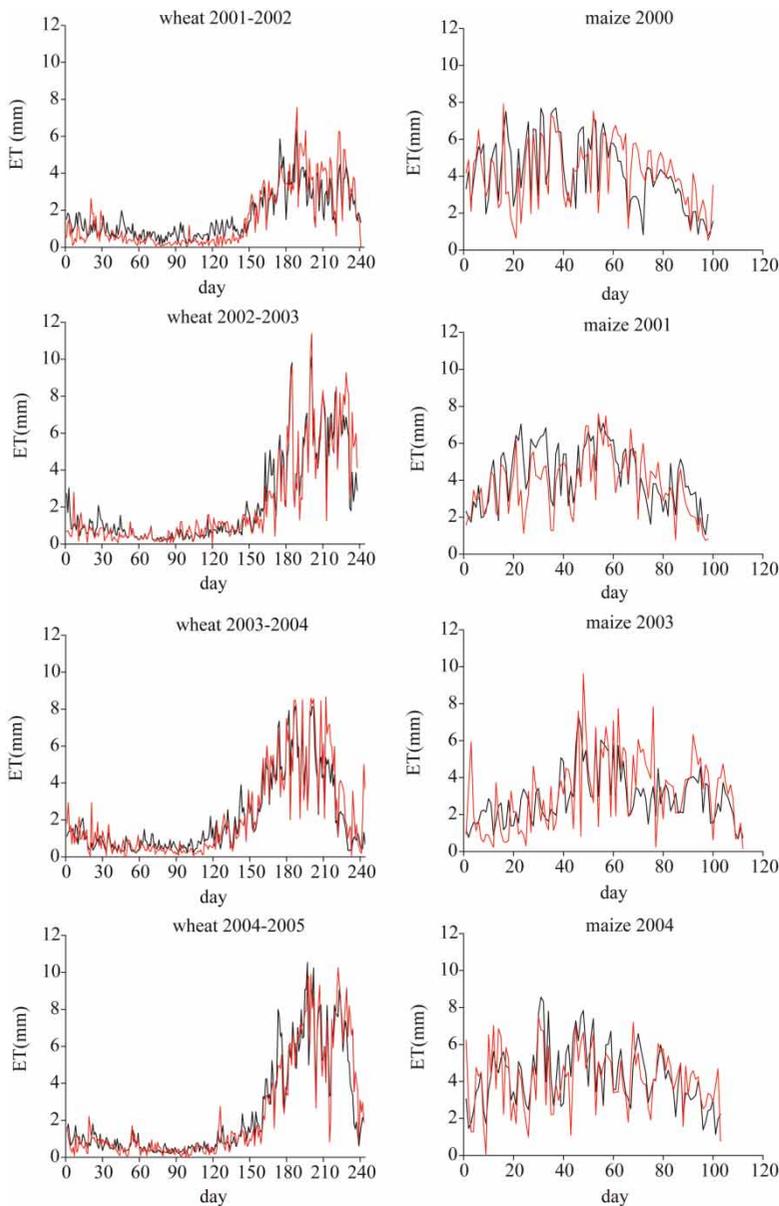
**Figure 4** │ The simulated and observed ET of winter wheat and summer maize.

The soil water consumption curves for cotton showed diversity and were related primarily to rainfall. In dry years, soil water consumption was so high that its curve indicated a decreasing trend; in wet years, soil water was recharged and showed an increasing trend; rainfall was uneven one year, soil water may have fallen initially and then risen (Figure 5).

Percolation was related to distribution of precipitation or irrigation, precipitation intensity and

antecedent soil moisture, there was a very large difference for percolation, although precipitation was almost the same in some years. In spite of this factor, there was comparatively good positive correlation between percolation and rainfall during the growth periods of maize and cotton. Percolation water was stored in subsoil or groundwater firstly, and then recharged to the crop rooting zone through water potential gradient or irrigation from groundwater extraction in the dry season of

**Table 3** | Yield sensitivity analysis on the parameter changes

| Parameter changes (%) | Yield changes (%) | Parameter changes (%) | Yield changes (%) | Parameter changes (%) | Yield changes (%) |
|---|---|---|---|---|---|
| $a+5$ | −0.00 | $p+5$ | +0.22 | RD+5 | +0.00 |
| $a+10$ | −0.00 | $p+10$ | +0.27 | RD+10 | +0.00 |
| $a+15$ | −0.00 | $p+15$ | +0.13 | RD+15 | +0.00 |
| $a$–5 | +0.00 | $p$–5 | −0.42 | RD–5 | −0.00 |
| $a$–10 | +0.00 | $p$–10 | −1.04 | RD–10 | −0.00 |
| $a$–15 | +0.00 | $p$–15 | −1.85 | RD–15 | −0.00 |
| $\theta_{fc}+2.5$ | −0.48 | $K+5$ | −0.00 | $K_C+1$ | +0.07 |
| $\theta_{fc}$–2.5 | +0.24 | $K$–5 | +0.00 | $K_C$–1 | −0.09 |
| $\theta_{fc}+5$ | −1.22 | $K+10$ | −0.16 | $K_C+2$ | +0.13 |
| $\theta_{fc}$–5 | +0.25 | $K$–10 | +0.17 | $K_C$–2 | −0.19 |

$\theta_{fc}$, water content at field capacity; $a$, capacity of the soil to transmit capillary fluxes; $K$, saturated hydraulic conductivity; $K_C$, single crop coefficient; $p$, fraction of total available water crop extracted from the root zone; RD, root depth.

**Table 4** | Assessment of the ET simulation

| Year | NSE | $R^2$ | RMSE |
|---|---|---|---|
| **(a) Winter wheat** | | | |
| 2001–2002 | 0.783 | 0.808 | 0.789 |
| 2002–2003 | 0.880 | 0.898 | 0.866 |
| 2003–2004 | 0.854 | 0.858 | 0.875 |
| 2004–2005 | 0.883 | 0.885 | 0.934 |
| **(b) Summer maize** | | | |
| 2000 | 0.316 | 0.477 | 1.254 |
| 2001 | 0.386 | 0.550 | 1.266 |
| 2003 | 0.364 | 0.388 | 1.584 |
| 2004 | 0.313 | 0.455 | 1.315 |

ET, evapotranspiration; NSE, Nash–Sutcliffe efficiency; $R^2$, determination coefficent; RMSE, root mean square error.

crop growth. In this way, water was used completely or partly.

It is very important to estimate accurately different water balance components of winter wheat, summer maize and cotton for utilization of reasonable water resources management strategies based on water supply and crop water requirement, in order to realize the aims of water-saving and of WUE increase.

## Water-use efficiencies of winter wheat, summer maize and cotton

Different irrigation levels and different configuration modes of water resources $(P+I+E_g+\Delta W)$ (where $\Delta W$ refers to the soil water content change in the wheat or

**Table 5** | The observed and the simulated values of soil water balance components of wheat

| Component (m) | 2001–2002 Observed | Simulated | 2002–2003 Observed | Simulated | 2003–2004 Observed | Simulated | 2004–2005 Observed | Simulated |
|---|---|---|---|---|---|---|---|---|
| $P$ | 115.2 | | 180.4 | | 198.2 | | 127.6 | |
| $I$ | 101.38 | | 124.65 | | 124.34 | | 226.43 | |
| ET | 387.07 | 397.31 | 505.61 | 516.84 | 528.76 | 500.68 | 569.52 | 584.59 |
| $E_g$ | 75.17 | 73.54 | 23.13 | 22.85 | 8.55 | 7.76 | 1.41 | 1.40 |
| $P_a$ | 12.22 | 12.20 | 3.8 | 3.37 | 0.61 | 0.44 | 30.48 | 3.09 |
| $R_S$ | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| $\Delta W$ | | +119.39 | | +192.31 | | +170.82 | | +232.25 |

+, Consumption of soil water.
$E_g$, capillary rise from underlying water table; ET, evapotranspiration; $I$, irrigation; $P$, precipitation; $P_a$, percolation; $R_S$, runoff; $\Delta W$, soil water content change.

**Table 6** │ The observed and simulated values of soil water balance components of maize

| Component (mm) | 2000 Observed | Simulated | 2003 Observed | Simulated | 2004 Observed | Simulated | 2005 Observed | Simulated |
|---|---|---|---|---|---|---|---|---|
| $P$ | 450.46 | | 303.4 | | 659.7 | | 575.2 | |
| $I$ | 0 | | 0 | | 0 | | 86.53 | |
| ET | 420.28 | 420.52 | 359.41 | 327.83 | 427.69 | 440.09 | 412.43 | 426.76 |
| $E_g$ | 0 | 0 | 55.02 | 55.39 | 0.26 | 0.50 | 19.48 | 19.03 |
| $P_a$ | 149.57 | 141.93 | 13.25 | 10.55 | 146.19 | 163.43 | 127.82 | 127.29 |
| $R_S$ | 0 | 0 | 0 | 0 | 0 | 219.06 | 0 | 0 |
| $\Delta W$ | | +111.99 | | −20.41 | | +162.38 | | −126.71 |

+, Consumption of soil water; –, recharge to soil water.

$E_g$, capillary rise from underlying water table; ET, evapotranspiration; $I$, irrigation; $P$, precipitation; $P_a$, percolation; $R_S$, runoff; $\Delta W$, soil water content change.

**Table 7** │ Cotton water balance components values

| Component (mm) | 2003 Simulated | 2004 Simulated | 2005 Simulated | 2006 Simulated |
|---|---|---|---|---|
| $P$ | 475.4 | 794.7 | 621.1 | 373.2 |
| $I$ | 0 | 0 | 0 | 0 |
| ET | 496.19 | 674.95 | 645.95 | 644.88 |
| $E_g$ | 10.38 | 323.74 | 60.45 | 13.74 |
| $P_a$ | 0.25 | 187.46 | 12.94 | 9.04 |
| $R_S$ | 0 | 261.31 | 0 | 0 |
| $\Delta W$ | +10.66 | +5.28 | −22.66 | +266.98 |

+, Consumption of soil water; –, recharge to soil water.

$E_g$, capillary rise from underlying water table; ET, evapotranspiration; $I$, irrigation; $P$, precipitation; $P_a$, percolation; $R_S$, runoff; $\Delta W$, soil water content change.

maize growing season) led to different water consumption levels and yields of crop, namely different water-use efficiencies.

The simulated mean WUE of winter wheat was 1.4 kg m$^{-3}$ (Table 8), mean WUE of summer maize was 2.1 kg m$^{-3}$ (Table 9) and cotton's mean WUE was 0.3 kg m$^{-3}$ (Table 10).

## DISCUSSION

### Interactions among various water balance components

The most important function of SD is to simulate the dynamic feedback of complicated problems in complex systems. The aim of the SD study was to evaluate all possible policy alternatives in order to improve behaviour in policy (Saysel & Barlas 2001). Through scenario simulation, interactions among various water balance components were revealed and provided a reference for water-saving and for improving field WUE. Winter wheat data from 2003 to 2004 were taken as an example.

An important concept of 'real water-saving' is introduced in order to realize the objective of sustainable utilization of water resources during the implementation of the World Bank-financed China Water Conservation Project. Real water-saving means reducing ET water consumption in the project area (in the hydrological cycle, only ET is real reduction of water amount). The essence of agricultural water-saving is to reduce inefficient consumption during crop growth. It has been documented that inefficient consumption can be the result of loss due to soil evaporation (Kang & Cai 1996; Tang et al. 2000; Shan et al. 2004).

In regions of North China, ratios of soil evaporation to ET were found to be 1:3 to 1:2 (Wang et al. 1992, 2007; Xiao et al. 1996; Zhou & Xu 1997; Liu & Wang 1999; Pei et al. 2000; Zhang & Yang 2000; Dong et al. 2001; Zhou 2003; Sun et al. 2004; Allen et al. 2005; Yu 2007). But, relatively little research has been undertaken as to what extent soil evaporation can be reduced.

### Decreasing 10 and 20% of the soil evaporation

When soil evaporation was decreased by 10% (we assume that transpiration was unchanged), soil water increased by
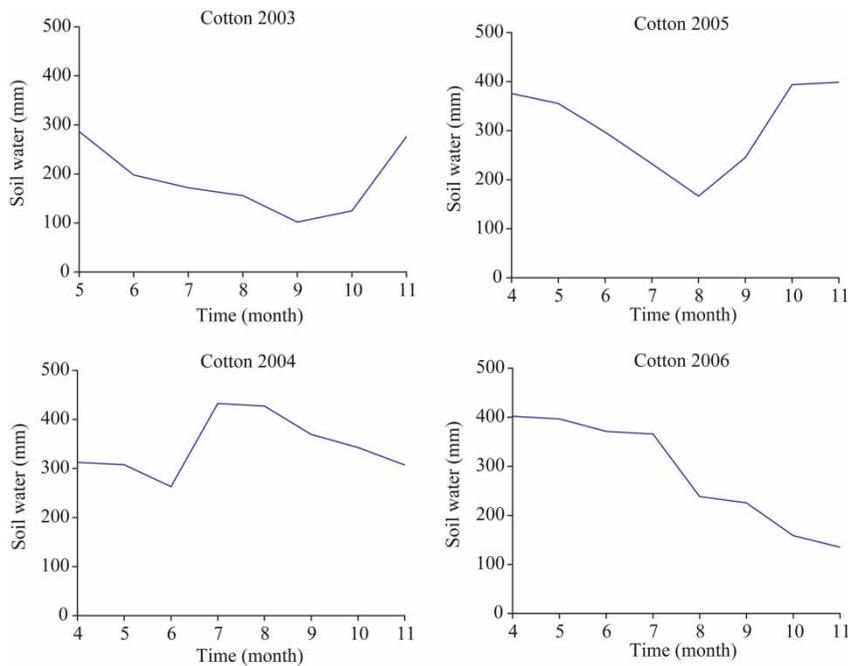
**Figure 5** | Changes of cotton soil water from 2003 to 2006.

**Table 8** | Water-use efficiency (WUE) of winter wheat

| Elements | 2001–2002 | 2002–2003 | 2003–2004 | 2004–2005 |
|---|---|---|---|---|
| $P + I + E + \Delta W$ (mm) | 409.51 | 520.81 | 501.12 | 614.68 |
| ET (mm) | 397.31 | 516.84 | 500.68 | 584.59 |
| Yield (kg/hm$^2$) | 5,470.48 | 7,614.71 | 7,597.6 | 6,758.13 |
| WUE (kg m$^{-3}$) | 1.38 | 1.47 | 1.52 | 1.16 |

*E*, capillary rise; ET, evapotranspiration; *I*, irrigation; $\Delta W$, soil water content change.

**Table 9** | Water-use efficiency (WUE) of summer maize

| Elements | 2000 | 2003 | 2004 | 2005 |
|---|---|---|---|---|
| $P + I + E + \Delta W$ (mm) | 562.45 | 338.38 | 603.52 | 554.05 |
| ET (mm) | 420.52 | 327.83 | 440.09 | 426.76 |
| Yield (kg/hm$^2$) | 9,256.35 | 5,597.61 | 10,147 | 9,536.08 |
| WUE (kg m$^{-3}$) | 2.20 | 1.71 | 2.31 | 2.24 |

*E*, capillary rise; ET, evapotranspiration; *I*, irrigation; $\Delta W$, soil water content change.

**Table 10** | Water-use efficiency (WUE) of cotton

| Elements | 2003 | 2004 | 2005 | 2006 |
|---|---|---|---|---|
| $P + I + E + \Delta W$ (mm) | 496.44 | 1,123.72 | 658.89 | 653.92 |
| ET (mm) | 496.19 | 674.95 | 645.95 | 644.88 |
| Yield (kg/hm$^2$) | 1,254.53 | 2,332.6 | 2,157.68 | 2,151.31 |
| WUE (kg m$^{-3}$) | 0.25 | 0.35 | 0.33 | 0.33 |

*E*, capillary rise; ET, evapotranspiration; *I*, irrigation; $\Delta W$, soil water content change.

0.9–1.4% in the wheat growing season; when soil evaporation decreased by 20%, soil water increased by 1.9–2.9%. Judging by the above figures, we are fully justified in the view that it is important to reduce soil evaporation as a means of water-saving.

Gradual reduction of water diversion from the Yellow River and in the future balancing water shortage needs downstream will probably reduce the amount of irrigation required upstream of the Panzhuang Irrigation District.

## Reducing 10 and 20% of the irrigation amount

When irrigation amount was reduced by 10%, the soil water dropped by 0.8%; when irrigation amount was reduced by 20%, soil water dropped 1.5%. Therefore, it was necessary to keep the irrigation levels unchanged as far as possible.

Groundwater application amount will rise in the upper reaches of the irrigation district represented by Yucheng Station when the irrigation amount is unchanged and surface water is transported to the lower reaches, which causes an increase in groundwater depth.

## Increasing 10 and 20% of the groundwater depth

When groundwater depth was increased 10%, soil water dropped by 0.04%; when groundwater depth increased 20%, soil water dropped 0.07%. Groundwater depth is shallow in Yucheng Station, the variable range is 1–4 m and the mean value is 2.3 m. Hence, the influence of an increase of 10 and 20% in the groundwater depth for the soil water was small.

From the above discussion, we infer that exploiting groundwater as far as possible and taking measures to reduce soil evaporation at the same time under the condition of keeping irrigation amount unchanged was one of the best strategies for sustainable utilization of water resources upstream of the Panzhuang District.

## Model validation and analysis

Growth under scenario Extreme condition I, no irrigation, was found to significantly decreased yield, a result that was comparable with experimental results of Zhang *et al.* (2004). Under the scenario of Extreme condition II, severe soil water deficit influenced booting and flowering of winter wheat and led to no yield, a finding similar to the experimental result of Yucheng Station.

Based on the behaviour sensitivity test, change of yield was most sensitive to change of crop coefficients, which agreed with results of Satti *et al.* (2004).

For ET simulation, the goodness-of-fit result of winter wheat was 'good', summer maize was found to be 'slightly inferior' (Figure 4 and Table 3), a finding that was consistent with the calculated results of Liu & Luo (2010) who used the dual crop coefficient (DCC) method proposed in FAO-56 for calculating the actual daily ET of the main crops (winter wheat and summer maize) in the NCP.

To sum up, the model was valid and simulated results were credible through validation and analyses.

## Cotton evapotranspiration

Cotton ET was 496.2 mm in 2003, which was very close to the simulated result of Yang (2005) (527.4 mm) using the COTTON2K model. The 4-year mean ET value was 615.5 mm. Cheng *et al.* (1994) held that mean annual water consumption of cotton was 500–700 mm in the Huang-Huai-Hai Plain. According to the co-operative group of contour maps describing the water requirements of main crops in China (1993), multi-year average water requirement was 671 mm for northern Shandong Province. Consequently, simulated results were credible.

## Crop water-use efficiency

According to the Equation (11) and Table 7, wheat water consumption was about 500 mm when yield and WUE were the largest. This result was consistent with finding by Hong & Xie (1997), Wu *et al.* (1998) and Liu (2007).

The simulated mean WUE of winter wheat was 1.4 kg m$^{-3}$, a value that matched well the observed values of the lysimeter in recent years. This value was higher compared with Wu *et al.* (1998) who had a calculated result of 1.1 kg m$^{-3}$, based on lysimeter data from 1986 to 1996. However, there was on a small difference in comparison with WUE (1.4–1.6 kg m$^{-3}$) for Luancheng Station, Hebei Province (Zhang *et al.* 2002).

Mean WUE of summer maize was 2.1 kg m$^{-3}$, which was consistent with the result calculated by Li *et al.* (2004) for conditions without irrigation treatment. Our calculated mean WUE was higher when compared with that calculated by Wu *et al.* (1998) (1.9 kg m$^{-3}$) based on lysimeter data from 1989 to 1994. Our results were also higher compared with WUE values for wheat and maize under the well managed experimental sites in the NCP, and which ranged from 1.0 to 1.9 km m$^{-3}$ (Wang *et al.* 2002; Deng *et al.* 2006). But compared to maize WUE of straw mulching (Zhang *et al.* 2002; Yu *et al.* 2004), our simulated result was similar.

The mean WUE for cotton was 0.3 kg m$^{-3}$, a value that was basically the same as the experimental results of Zuo *et al.* (2010) in Lingxian, Shandong Province.

Field WUE matched the results measured for the region, and showed that the model could simulate the transformation process of field water amount comparatively accurately. At the same time, it proved that SD was an appropriate technique for simulating complex problems in integrated water resources and seeking best management

solutions while keeping track of the whole system response, and was consistent with Khan *et al.* (2009).

## Methods of increasing WUE

The above results illustrated that WUE had room for improvement in Yucheng Station, although some improvement had been achieved in the past 30 years. There are several measures and research priorities needed in order to further increase WUE at the field level.

Irrigation should be improved, as crop water consumption strongly depends on irrigation in dry years. Experimental results of the different regions indicated that water consumption was due to, from highest to lowest: flood irrigation > furrow irrigation > border irrigation > sprinkler irrigation > trickle irrigation. Therefore, the improvement of irrigation methods is an effective way to use water resources reasonably and increase its economic benefit (Cheng *et al.* 1994).

In order to reduce soil evaporation, measures may be adopted which include: low-pressure water–groundwater pipeline conveyance systems or 'small white dragon' (plastic hoses); mulching of plastic film or straw, intertillage for moisture conservation, etc. The notion of 'real water-saving' proposed and implemented by the World Bank was to decrease the field ET (soil evaporation; Department of Irrigation, Drainage and Rural Water Supply of Ministry of Water Resources, China Irrigation and Drainage Development Center 2007). The ET approach focused on actual water consumption of crops, encouraged more efficient use of water and adopted more water-saving technologies and methods, thus it could significantly improve the sustainable utilization of the water resources in agricultural areas, especially in the NCP. As a result, ET-based water resources management should be promoted by governments (The International Bank of Reconstruction and Development, the World Bank 2009).

No-tillage (NT) basically has been implemented in both winter wheat and summer maize in Yucheng Station. According to research by Xu *et al.* (1999), NT was a good option as it could maintain relatively high soil moisture during the early part of the growing season and reduce percolation losses of irrigation in the growth period, but led to increased risk of waterlogging in wet years. Subsoiling

tillage promoted infiltration; in wet years it could effectively utilize natural precipitation to recharge groundwater through increasing drainage, but in dry years crop seedling growth might face the potential threat of drought. The subsoiling practice of cotton is possibly a good choice due to plenty of rainfall in summer. Whether NT should be implemented for winter wheat and subsoiling tillage should be carried out for summer maize need to be further researched.

In recent years, computer simulation techniques offered the most reliable method of calculating soil water balance components in that they permitted a relatively detailed analysis in a short time. At the same time, agricultural system models used in computer simulation had been used to study soil water balance and WUE under the different soil, climate and management conditions in the NCP (Yu & Wang 2001). Wang *et al.* (2001) analysed the effect of irrigation management on crop growth and soil evaporation using a process-based model Water Atmosphere Vegetation Energy and Solutes (WAVES), and concluded that mulching can reduce soil evaporation up to 50% and save about 80 mm of water during a wheat growth period in the NCP. Mo *et al.* (2005) simulated regional WUE of 1.2–1.6 kg m$^{-3}$ for winter wheat and 1.1–1.9 kg m$^{-3}$ for summer maize using the Soil-Vegetation-Atmosphere-Transfer (SVAT) model with remotely sensed data, and confirmed that their studies would implicate a new view for regional agricultural and water resources management by assessing regional crop yield, water consumption and WUE consistently based on modelling biophysical processes with the aid of remote sensing. Yang *et al.* (2006) used a Decision Support System for Agrotechnology Transfer (DSSAT)-wheat model to simulate water use of winter wheat, and was found to save 76 mm of ET (WUE is improved from 1.3 to 1.5 kg m$^{-3}$) and 99.5 mm irrigation water without much yield reduction based on a 12-year simulation period. Irrigation practice was according to the following three principles: (1) as a moderately low growth in the leaf area index (LAI) of wheat does not result in low yield, moderate water deficits in March can save water, and therefore, the aim should be to avoid irrigation in March; (2) depending on the soil water condition, irrigation in mid-November is recommended to obtain a good

growth of LAI and to create a moderate condition for water stress in March; and (3) after the start of the growth of the ears (around 15 April), water deficits should be avoided to ensure there is no influence on ear growth and grain filling. Fang *et al.* (2010a) applied a 2-year experiment with four irrigation levels to calibrate and validate the Root Zone Water Quality Model (RZWQM) and ran the model by utilizing weather data from 1961 to 1999 to explore irrigation scheduling. They thought it possible to achieve the highest WUE and the least water drainage by allocating 80% of water to the critical wheat growth stages and 20% at maize planting. Based on long-term weather conditions, Chen *et al.* (2010) studied the effects of climate variations and irrigation on crop yield and WUE using the Agricultural Production Systems Simulator Model (APSIM), and analysed the different irrigation amounts in the wet, medium and dry seasons. Applying the Crop Environmental Resource Synthesis (CERES) wheat and maize models, Guo *et al.* (2010) found that yield and WUE for wheat and maize were both affected by the projected climates, and they believed that wheat response to $CO_2$ fertilization was higher than in maize. These modelling studies extend experimental results in space and time and recommend improvements in irrigation efficiency and water productivity thereby providing useful guidance for management of limited water resources (Fang *et al.* 2010b).

In the NCP, agricultural water supply will unavoidably decrease with the increasing demands of domestic and industry. In order to cope with the above challenge, it is crucial to enhance agricultural WUE at field and regional scales via innovative management and research.

## CONCLUSIONS

The model established by Khan *et al.* (2009) was improved by adding water production functions. Tests and validation of the model were carried out using the observed data. Results showed the observed and simulated data generally matched well, and that the model could reflect the transformation process of field water balance. The objective of describing the different water balance components with

relatively high precision was achieved, which would provide reference for water-saving, especially for increasing WUE in the NCP.

The simulation results are as follows:

1. Results of testing and validation showed that the model could simulate components of soil water system comparatively accurately.
2. As there were no daily crop coefficients, ET values of cotton were simulated based on a monthly scale. The analysis indicated that results were credible.
3. Two to four irrigations were needed for water consumption requirements for winter wheat and summer maize if the irrigation amount given was 75 mm each time. Cotton did not need to be irrigated except for 60 mm water pre-sowing.
4. The strategy of exploiting groundwater as far as possible and taking measures to reduce soil evaporation at the same time under the condition of keeping irrigation unchanged was one of the best ways of sustainable utilization of water resources in the upper reaches of the Panzhuang Irrigation District.
5. Mean values of WUE of winter wheat, summer maize and cotton were 1.4, 2.1 and 0.3 $kg\,m^3$ in Yucheng Station, upstream of the irrigation district, respectively. Water-use efficiencies were consistent with the actual calculated results for the region, and again showed that the model could reflect the transformation process of field water amount comparatively accurately.

## ACKNOWLEDGEMENTS

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