WHEAT

Estimation of Winter Wheat Evapotranspiration under Water Stress with Two Semiempirical Approaches

Yongqiang Zhang,* Qiang Yu, Changming Liu, Jie Jiang, and Xiying Zhang

ABSTRACT

Winter wheat (*Triticum aestivum* L.) is one of most important crops in the North China Plain. However, soil water deficit (SWD) often occurs due to lack of precipitation in its growing season. In this study, we introduce two semiempirical approaches, a recharge model and the crop coefficient (K_c)–reference evapotranspiration (ET_0) approach, to estimate wheat actual evapotranspiration (ET_a) under no SWD and slight and severe SWD conditions. The recharge model allocated ET_0 to reference evaporation and reference transpiration as a function of leaf area index. In the model, ET_a is limited by soil water content, and crop water extraction for ET_a is distributed through the soil profile as exponential functions of soil and root depth. The K_c–ET_0 approach regarded ET_a under the SWD condition as a logarithmic function of soil water availability. Under no SWD condition, the recharge model simulated 10-d ET_a with a root mean square error (RMSE) of 5.58 mm and a bias of 0.95 mm compared with measurements from a large-scale weighing lysimeter. The two approaches both estimated seasonal evapotranspiration (ET) well compared with the *adjusted* ET (from the soil water balance and the recharge model–simulated deep drainage). The recharge model, which simulated the seasonal ET with the RMSE of 27.8 mm and the bias of −8.0 mm, was better than the K_c–ET_0 approach (RMSE = 31.7 mm and bias = −33.1 mm). The seasonal pattern of soil water stress coefficient (K_s) showed that there were faster water losses at grain-filling stage than at other stages.

The North China Plain (NCP), one of the most important centers of agricultural production in China, contains about 22% of the cultivated land in the country but less than 4% of the water resources (Jin et al., 1999). Winter wheat is one of the most important crops in the NCP. Serious water shortage problems exist in the winter wheat season, and the situation has been aggravated by an increase in agricultural and industrial demand for groundwater over the last 20 yr (Zhang et al., 2001). Another reason the groundwater table is persistently declining is that NCP farmers irrigate excessively by pumping groundwater, which unnecessarily maximizes crop transpiration and soil evaporation and increases the proportion of nonbeneficial soil water consumption (Zhang et al., 2002). Irrigation management based on ET estimations would allow limited groundwater supplies to be used more efficiently for wheat production.

To calculate crop ET over seasonal time, it is essential to simplify ET-estimated methods in the NCP due to lack of enough weather, soil, and crop physiological data. Thus, it is convenient and suitable to use empirical approaches to estimate crop ET_a. These methods are mainly based on the K_c–ET_0 approach and on soil water balance (SWB) calculation (Rana and Katerji, 2000). When limited by soil water content, water uptake for crop transpiration from a point in a soil profile is an exponential function of soil and root depth (Novak, 1987).

The K_c–ET_0 approach estimates crop ET_a as a fraction of the ET_0 (Allen et al., 1998). The K_c–ET_0 approach is simple because the method calculates ET_a only by estimating ET_0 and K_c as well as K_s (Doorenbos and Pruitt, 1977, p. 144; Kerr et al., 1993; Kang et al., 2000). Reference evapotranspiration can be estimated from pan evaporation data (Doorenbos and Pruitt, 1977, p. 144). It is also estimated with more data-intensive methods, e.g., the modified Penman equation and the modified Penman–Monteith formula (Doorenbos and Pruitt, 1977, p. 144; Allen et al., 1989; Allen, 2000). The crop coefficient, K_c, can be determined by the ratio of crop ET_a under no SWD condition to ET_0. The soil water stress coefficient, K_s, is mainly estimated by a relationship to the average soil moisture contents or matric potential in a soil layer. And, it can usually be estimated by an empirical formula based on soil water contents or relative soil available water contents (Jensen et al., 1970). Poulovassilis et al. (2001) assumed that K_s is an exponential function of the soil water content. Kang et al. (2000) found that K_s is highly related to soil water availability (A_w) in a logarithmic function. The K_c–ET_0 approach has been successfully applied at many locations (Kang et al., 2000; Abdelhadi et al., 2000; Allen, 2000; Poulovassilis et al., 2001; Sepaskhah and Andam, 2001; De Medeiros et al., 2001; Liu et al., 2002). Actual evapotranspiration can also be estimated from ET_0, soil water content, and leaf area index (LAI) (Campbell and Norman, 1998; Kendy et al., 2003). Reference evapotranspiration is partitioned into reference evaporation from soil and reference transpiration from plants, and the ratio of reference evaporation to refer-

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Published in Agron. J. 96:159–168 (2004).
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Abbreviations: A_w, soil water availability; ET, evapotranspiration; ET_a, actual evapotranspiration; ET_0, reference evapotranspiration; K_c, crop coefficient; K_s, soil water stress coefficient; LAI, leaf area index; NCP, North China Plain; RMSE, root mean square error; SWB, soil water balance; SWD, soil water deficit; SWS, soil water storage.

ence transpiration depends on the development stage of the leaf canopy, expressed as τ, the dimensionless fraction of incident beam radiation that penetrates the canopy (Campbell and Norman, 1998). When limited by soil water content, water uptake for crop transpiration from a point in a soil profile is an exponential function of soil and root depth (Novak, 1987). The ET-estimated approach is applied in a recharge model (Kendy et al., 2003).

Based on the principle of conversion of mass in one-dimension soil, the SWB approach estimates ET from runoff, drainage, irrigation, precipitation, and change of soil water content of SWB equation. In arid and semiarid areas with small slopes, runoff can be neglected (Holmes, 1984). Drainage has to be measured, calculated, or assumed to be zero. Lysimeter is used to measure drainage (Khan et al., 1993). There are many methods of calculating deep drainage. For the loam soils in the NCP, the tipping-bucket method has been used successfully (Kendy et al., 2003). Some researchers suggest that it can be neglected in dry regions (Holmes, 1984), but actually, it depends on the soil depth, slope, permeability, and surface storage (Jensen et al., 1990; Parkes and Li, 1996) and needs to be considered in some particular cases, depending also on the climate and weather (Katerji et al., 1984). In some situations, it is so important that its direct measurement can be used to estimate ET on a weekly or greater scale (Allen et al., 1991, p. 444).

Here, we applied the K_c–ET_0 approach and the recharge model to estimate seasonal ET_a under different irrigation treatments in a winter wheat field in the NCP. We then compared ET_a results from the two semiempirical approaches with seasonal ET_a data obtained from SWB calculations adjusted from deep drainage (Cavero et al., 2000) and compared ET_a results from the recharge model with ET_a data from a large-scale lysimeter under no SWD condition. The purposes of the study were mainly as follows:

1. To estimate seasonal ET_a, K_c, and K_s in a field of the NCP.
2. To test the K_c–ET_0 approach and the recharge model by the large-scale lysimeter measurement and the SWB calculation.

MATERIALS AND METHODS

Site Description

Experiments were conducted at the Luancheng Agroecosystem Station (37°53′ N, 114°41′ E; altitude 50.1 m), one of the agricultural ecosystem stations of the Chinese Ecological Research Network. It is located in a high-yield farming plain in the NCP with fertile loam soil. The soil characteristics of the station are given in Table 1. Rotation cropping of winter wheat and summer maize (*Zea mays* L.) is one of most extensive planting systems. The growing season for winter wheat is from early October to mid-June, and summer maize is planted at the end of winter wheat season and harvested in late September.

Precipitation in the NCP mostly occurs from July to September because of a semiarid monsoon climate. Mean annual precipitation, temperature, and global radiation in the station over the past 20 yr are 480.7 mm, 12.2°C, and 524.2 kJ cm^{-2}, respectively. Mean precipitation over 1984–2001 was 300.0 mm in the summer maize season, which can satisfy most water consumption of maize. Drought often occurs during the winter wheat season. Average precipitation, which basically does not satisfy the need of wheat, is only about 130 mm in the wheat season. Irrigated groundwater is pumped so much that the groundwater table in the NCP is dramatically declining. Annually, the declined rate in the station was about 0.7 m yr^{-1} for the last 20 yr (Zhang et al., 2001).

Experimental Treatments and Measurements

Experiments on winter wheat were conducted in three consecutive winter wheat seasons in 1998–2001. The experimental field was split into 15 plots using concrete curbs to obtain five irrigation treatments with three repetitions, e.g., SWD at reviving stage (Treatment A), SWD at jointing stage (Treatment B), SWD at grain-filling stage (Treatment C), no SWD treatment (Treatment D), and severe SWD condition (Treatment E) (Table 2). The split wall is 24.5 cm thick and extends to 1.5 m beneath the surface to prevent runoff. The total area of each plot was 5×10 m $=$ 50 m^2. Preliminary research showed that there was slight SWD when soil water storage (SWS) in the 0- to 120-cm soil depth (most roots accumulate in this soil depth) was decreased to about 55 to 60% of field capacity because in this condition, stomatal conductance and leaf potential were slightly decreased. When SWS was less than 55% of field capacity, wheat was in the severe SWD condition. In our experiment, for slight SWD treatments (Treatments A, B, and C), irrigation was applied when SWS (0–120 cm depth) was lower than 55% of field capacity. For the no SWD treatment, SWS (0–120 cm depth) was kept higher than 60% of field capacity for the whole growing season. For the severe SWD treatment, SWS (0–120 cm depth) was lower than 55% of field capacity because of no irrigation input and little precipitation after the reviving stage.

Winter wheat cultivar Gaoyou no. 503 was sown by hand at the rate of 150 kg ha^{-1}, with 20-cm row sparing in early October of each year. Before sowing, each plot was irrigated with about 80 mm of water containing 300 kg ha^{-1} ammonium phosphate and 150 kg ha^{-1} urea. Treatment A was conducted

Table 1. Characteristics of soil at Luancheng Station (Zhang and Yuan, 1994).

Depth	Texture	Bulk density	Effective porosity	Field capacity	Wilting point	Saturated hydraulic conductivity
cm		g/cm^3	% by volume			m/d
0–25	Loam	1.39	49	36	9.6	1.1
25–40	Loam	1.50	46	35	11.4	0.43
40–60	Loam	1.46	46	33	13.9	0.73
60–85	Loam	1.49	46	34	13.9	0.71
85–120	Silty clay loam	1.54	46	34	12.9	0.020
120–165	Clay loam	1.63	42	39	13.9	0.003
165–210	Silty clay loam	1.55	44	38	16.4	0.016

Table 2. Levels of the ratio of average soil water content (θ_a) to average field capacity (θ_{fc}) at crop root depth after different irrigation treatments for winter wheat at Luancheng Station (1998–2001).

Crop	Treatment	Growth stage and irrigation treatment (θ_a /θ_{fc})				
		Overwintering	Reviving	Jointing	Heading	Grain filling
Winter wheat	A	1.0	–†	0.8	0.8	0.8
	B	1.0	0.8	–	0.8	0.8
	C	1.0	0.8	0.8	0.8	–
	D	1.0	1.0	1.0	1.0	1.0
	E	1.0	–	–	–	–

† Dashes indicate that there was no irrigation applied.

on 26 Mar. 1999, coinciding with resumption of weak growth after the overwintering stage (Table 3).

Soil water content was measured with a neutron probe (Inst. of Hydrol., Oxfordshire, UK). One access tube was installed in each of the 15 experimental plots. Soil water content was measured at 20-cm intervals from a depth 20 cm to 200 cm or 180 cm approximately every 5 d, and gravimetric soil water content in 0- to 20-cm depth was measured by taking 3.5-cm soil cores with a hollow steel drill. Precipitation was measured on-site daily by summing hourly tipping-bucket measurements. Irrigation was applied from a soft plastic pipe, which was connected with a volumetric flow meter (Ninggang-MC, Ningbo Watermeter, Ningbo, China) to measure water application at each irrigation event.

Daily ET was measured with a large-scale weighing lysimeter (The Institute of Geographical Science and Natural Resources Research, Chinese Academy of Sciences, Beijing), with 0.02-mm precision. The lysimeter, which is 1.5×2 m = 3 m^2 in area and 2.5 m deep, contains about 14 000 kg of soil, and it is located about 10 m from the site of our experimental plots. The soil characteristics in the lysimeter were the same as the surrounding field (Table 1), and irrigation conditions in the lysimeter were similar to those under no SWD condition of our experiments (similar to Treatment D) (Table 2). Zhang et al. (2002) describe the lysimeter in more detail.

Daily maximum temperature (°C), daily minimum temperature (°C), wind velocity at 2-m height (m s^{-1}), relative humidity (%), solar radiation hours, and pan evaporation (mm d^{-1}) were collected by an autometeorological observation system at Luancheng Station.

Crop measurements were taken weekly. The green leaf area was determined from 10 randomly selected plants harvested from the sampling area of each plot. Length and maximum width of wheat leaves were measured at different times during the season, and leaf area was calculated by multiplying the leaf length by the leaf width and by a coefficient 0.83, which was calibrated by a CI-203 electronic leaf area meter (CID, Camas, WA). Due to lack of workers, we only collected partial LAI data from the experimental plots in 1998–1999 and 2000–2002. Fortunately, all LAI data were collected in 1999–2000. We did not measure wheat root depths directly but instead used experimental results from Zhang (1999).

Recharge Model

We utilized the recharge model to estimate precipitation- and irrigation-generated areal recharge from commonly available crop and soil characteristics and climate data (Kendy et al., 2003). There are three processes in the recharge model during each time step. First, precipitation or irrigation is added to the top layer and then distributed downward in a simple *tipping-bucket* routine. Next, water is redistributed by solving for downward flux (infiltration) from each soil layer in which soil water content was measured. Flux from the bottom layer was considered soil water drainage. The contribution to ET_a from each layer was then determined. The ET_a under no SWD and SWD conditions is separated into evaporation and transpiration, which is controlled by the crop growth indicators root depth, LAI, and soil water content. Finally, the new soil moisture content is calculated as the water balance residual. Kendy et al. (2003) described the modeling procedure in detail. For crop ET, it was calculated as follows.

Evapotranspiration from each layer was calculated and subtracted from soil water storage. Actual evapotranspiration is a fraction of ET_0, which consists of reference evaporation from soil and reference transpiration from plants. Daily ET_0 was obtained by multiplying daily Class A pan evaporation by a pan coefficient of 0.7, which was determined for semiarid environments by Jensen et al. (1990).

The ratio of reference evaporation to reference transpiration depends on the development stage of the leaf canopy, expressed as τ, the dimensionless fraction of incident beam radiation that penetrates the canopy (Campbell and Norman, 1998):

$$\tau = \exp(-K_b \times \mathrm{LAI}) \qquad [1]$$

where K_b is the dimensionless canopy extinction coefficient, with a value of about 0.4. Accordingly, ET_0 is allocated to:

$$E_0 = \tau \times \mathrm{ET}_0 \qquad [2]$$

and

$$T_0 = (1 - \tau)\mathrm{ET}_0$$

where E_0 is reference evaporation from soil and T_0 is reference transpiration from plants. Total actual evaporation (E_a) and transpiration (T_a) from the entire soil profile are modeled as:

$$E_a = E_0\left[1 - \left(\frac{\theta}{\theta_{wp}}\right)^{-b}\right] \text{ and } T_a = T_0\left[1 - \left(\frac{\theta}{\theta_{wp}}\right)^{-b}\right] \qquad [3]$$

where θ is the calculated moisture content after infiltration, θ_{wp} is the soil moisture content at wilting point, and b is the inverse of the pore-size distribution index, λ, which Brooks and Corey (1966) use to describe soil water retention. According to Maidment (1993), λ ranges from about 0.04 for clay to about 1.1 for sand. The term is dimensionless. The

Table 3. Growth stages of winter wheat under no soil water deficit condition in each winter wheat season at Luancheng Station in 1998–2001.

Season	Sowing	Emergence	Tillering	Overwintering	Reviving	Jointing	Heading	Flowering	Grain filling	Harvest
1998–1999	3 Oct.	10 Oct.	12 Nov.	1 Dec.	3 Mar.	10 Apr.	1 May	5 May	10 May	10 Jun.
1999–2000	9 Oct.	15 Oct.	14 Nov.	3 Dec.	5 Mar.	10 Apr.	30 Apr.	4 May	11 May	11 Jun.
2000–2001	12 Oct.	18 Oct.	15 Nov.	5 Dec.	6 Mar.	11 Apr.	1 May	4 May	10 May	8 Jun.

parameter b is about 4 for transpiration (representing the entire soil profile, which is predominantly loam) and about 0.3 for evaporation (representing the sandy, plowed surface layer). Preliminary experiments at Luancheng Station indicate that ET may remove water from as deep as 3 m in the soil profile. Transpiration removes water from all layers that contain plant roots. Although evaporation removed most water from surficial layers, evaporation was considered in the root depth. Water uptake, S, from a point z in a soil profile with an exponential root distribution can be expressed as (Novak, 1987):

$$S(z) = T_a \frac{\delta \exp\left[-\delta\left(\frac{z}{z_r}\right)\right]}{z_r[1 - \exp(-\delta)]} \quad [4]$$

where z_r is the current-time root depth in the soil profile and δ, the water use distribution parameter, distributes water use over z (depth). It is an empirical constant that determines the curvature of the exponential function, from almost linear (δ approaching 0) to increasingly curved (Riha et al., 1994). For most crops, δ values range from about 0.5 to 5.0.

For a soil layer with roots extending from depth z_1 to z_2, the fraction contribution to total actual transpiration can be obtained by integrating Eq. [4] from z_1 to z_2:

$$u_f^t = \left(\frac{1}{1 - \exp(-\delta)}\right)\left\{\exp\left[-\delta\left(\frac{z_1}{z_r}\right)\right]\left[1 - \exp\left(-\delta\frac{z_2 - z_1}{z_r}\right)\right]\right\} \quad [5]$$

where u_f^t represents the transpiration uptake fraction. The sum of u_f^t values over all layers in a soil profile is equal to 1.0. We use essentially the same equation for u_f^e to allocate evaporation to soil layers, substituting soil layer depths for root depths. Because evaporation is more concentrated near the land surface than is transpiration, δ for evaporation is about 10. Actual evaporation and transpiration from a single soil layer, i, during one time step (time, 1 d) are:

$$E_{a(i)} = u_f^e E_a \Delta\text{time} \quad \text{and} \quad T_{a(i)} = u_f^t T_a \Delta\text{time} \quad [6]$$

Crop Coefficient–Reference Evapotranspiration Approach

Another semiempirical approach, K_c–ET_0 method (Doorenbos and Pruitt, 1977, p. 144), was here used to estimate crop ET_a. A target crop ET_a under no SWD condition, which is obtained from K_c and ET_a was calculated as

$$ET_a = ET_0 K_c \quad [7]$$

Under soil water stress conditions, ET_a is influenced by the soil water condition and the target crop as

$$ET_a = K_c K_s ET_0 \quad [8]$$

The ET_0 in the K_c–ET_0 approach was calculated with the FAO Penman–Monteith equation. And, it was applied using 24-h time steps and had the form:

$$ET_0 = \frac{0.408\,\Delta(R_n - G) + \gamma\frac{900}{T + 273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34\,u_2)} \quad [9]$$

where R_n is the net radiation above the crop canopy (MJ m^{-2} d^{-1}), G is soil heat flux density (MJ m^{-2} d^{-1}), T is air temperature at 2-m height (°C), u_2 is wind velocity at 2-m height (m s^{-1}), e_s is saturation vapor pressure (kPa), e_a is actual vapor pressure (kPa), $e_s - e_a$ is the saturation vapor pressure deficit (kPa), Δ is the slope vapor pressure curve (kPa °C^{-1}), and γ is the psychrometric constant. In applications having 24-h calculation time steps, G is presumed to be 0, and e_s is computed as $[e^0(T_{max}) + e^0(T_{min})]/2$, where $e^0(\ )$ is the saturation vapor function and T_{max} and T_{min} are daily maximum and minimum air temperatures, respectively.

The FAO Penman–Monteith equation predicts ET_0 from a hypothetical grass reference surface that is 0.12 m in height and has a surface resistance of 70 s m^{-1} and albedo of 0.23. The equation provides a standard to which ET in different periods of the year or in other regions can be compared and to which the ET from other crops can be related. Standardized equations for computing all parameters in Eq. [9] are given by Allen et al. (1994a, 1994b, 1998).

The large-scale weighing lysimeter was fully irrigated. Thus ET with the lysimeter measurement was regarded as crop ET_a under no SWD condition. And, K_c was calculated according to ratio of the lysimeter-measured ET_a to ET_0. Thus, K_c was determined.

The soil water stress coefficient, K_s, is a logarithmic function of A_w, which was calculated according to Haan et al. (1994)

$$K_s = \ln(A_w + 1)/\ln(101) \quad [10]$$

As a percentage, A_w was calculated according to

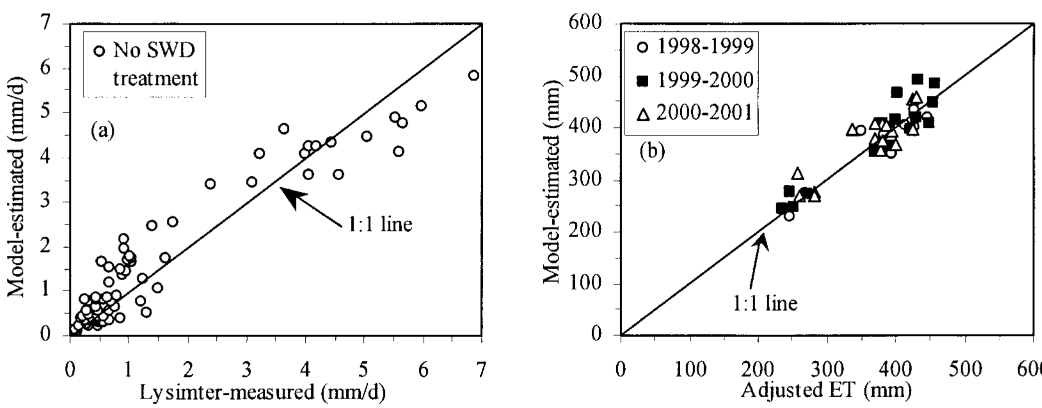

Fig. 1. (a) Comparison between the recharge model--estimated and lysimeter-measured averaged daily evapotranspiration (ET) from 10 d and (b) comparison of the recharge model--estimated and adjusted seasonal ET at Luancheng Station. Adjusted ET was calculated from the soil water balance and the simulated deep drainage with the recharge model. The diagonal line represents the 1:1 relationship. Part (b) includes all water treatments. SWD, soil water deficit.

Table 4. Adjusted seasonal evapotranspiration (ET) values as a function of estimated values of ET and lysimeter-measured 10-d ET as a function of estimated values of ET.

	Linear regression	N†	Slope	y intercept	R^2	Bias‡	RMSE§
						mm	
Seasonal ET	Recharge model–adjusted ET	40	0.94 (0.06)¶**	32.23 (24.1)#	0.84	−8.03	27.8
	K_c–ET_0 approach††– adjusted ET	40	1.01 (0.14)**	0.76 (51.2)	0.59	−33.1	31.7
10-d ET	Recharge model–lysimeter	69	1.05 (0.04)**	−1.81 (0.10)	0.90	0.95	5.58

** Slope significantly different from 1 at the 99% confidence level.
† N, observed number.
‡ The means of simulated minus measured values.
§ RMSE, root mean square error.
¶ Values in parentheses are the standard errors of the estimates.
# y intercept not significantly different from zero at the 95% confidence level.
†† K_c–ET_0 approach, crop coefficient–reference evapotranspiration approach.

$$A_w = 100\left(\frac{\theta_a - \theta_{wp}}{\theta_{fc} - \theta_{wp}}\right) \quad [11]$$

where θ_a is average soil water content in the layers of the root depth and θ_{fc} and is average field capacity at the same root depth.

Soil Water Balance Equation

Seasonal ET (mm) in each plot was determined from the SWB equation

$$ET = P + I + R + SD - D \quad [12]$$

where P is precipitation (mm), I is irrigation (mm), R is runoff/run-on (mm), SD is soil water depletion (mm), and D is drainage (mm) below the rooting depth considered (1.8 m). Runoff/run-on was assumed to be insignificant because the field was level-smoothed to zero slope and bordered with cement walls and irrigation volume per application was less than or equal to field capacity. Soil water depletion was calculated as the difference between the beginning and ending total soil water contents for the season. Drainage below the rooting depth very often has to be calculated. It was calculated using the tipping-bucket method as described in Kendy et al. (2003). And, a good agreement between simulated drainage and drainage observed to the groundwater table was found at our experimental station, which determined that it was reasonable to simulate drainage below winter wheat rooting depth with the recharge model. The estimated ET with the SWB equation was referred to as *adjusted* ET (Cavero et al., 2000).

Statistical Analysis

The mean SWB adjusted ET values were compared with the mean simulated ET values with the two semiempirical approaches under different irrigation treatments. Standard

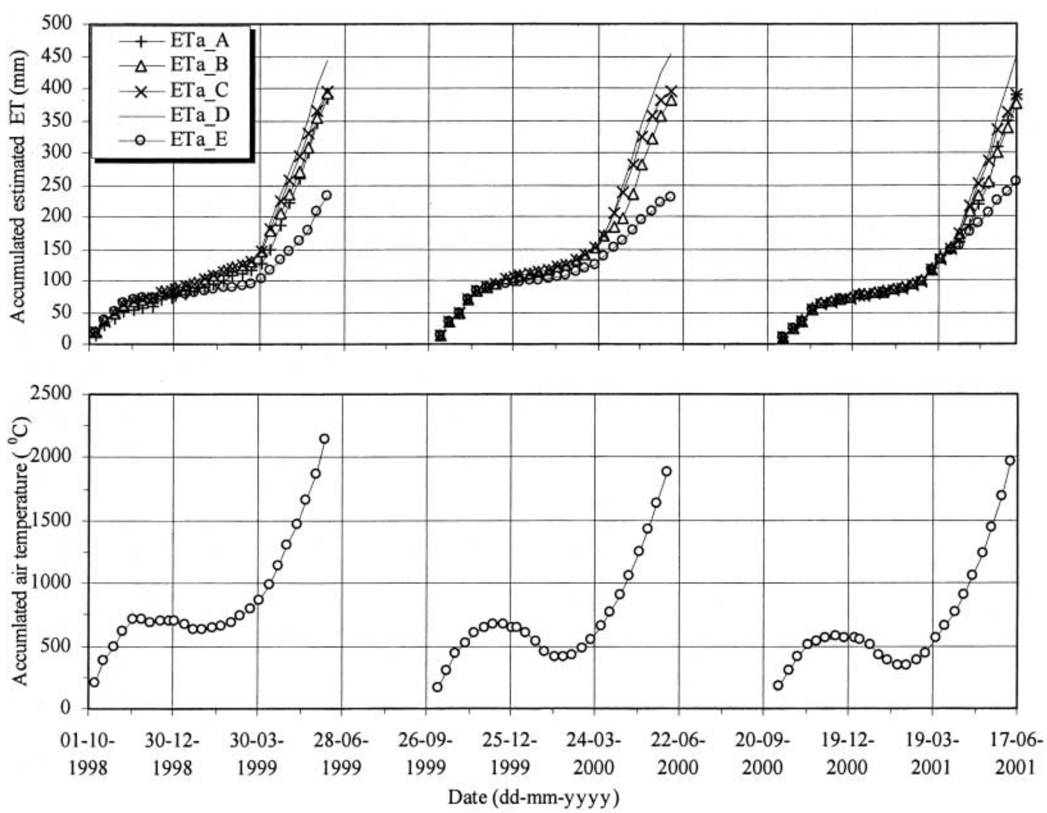

Fig. 2. Accumulation of estimated actual evapotranspiration (ETa) with the recharge model under different irrigation treatments and accumulation of daily average air temperature at Luancheng Station in the three consecutive winter wheat seasons, 1998–2001. ETa_A, ETa_B, ETa_C, ETa_D, and ETa_E are estimated ETa values with the recharge model under the five irrigation treatments (A, B, C, D, and E), which are shown in Table 2.

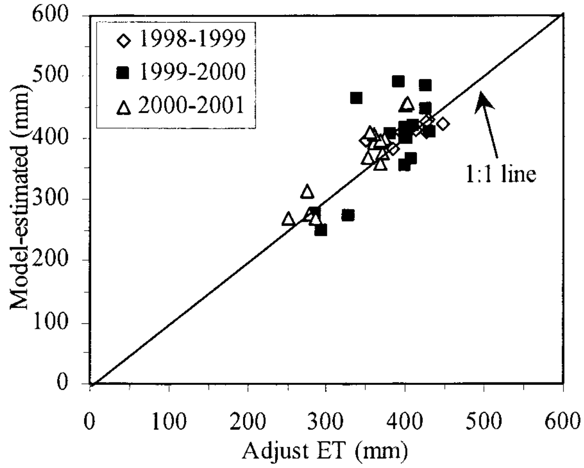

Fig. 3. Comparison of crop coefficient (K_c)–reference evapotranspiration (ET_0) approach to estimate ET with adjusted seasonal ET at Luancheng Station in the three consecutive seasons, 1998–2001. Adjusted ET was calculated from the soil water balance and the simulated deep drainage by the recharge model. The diagonal line represents the 1:1 relationship. All soil water deficit (SWD) treatments are included, except for the no SWD treatment.

deviations of K_c and K_s were calculated using MS-EXCEL 2000, and two-tailed Pearson correlation analysis was done with SPSS 11.0. Bias and a RMSE of simulated ET vs. adjusted ET were also used to evaluate the performance of the two approaches (Cavero et al., 2000):

$$\text{Bias} = \frac{1}{N}\sum_{i=1}^{N}(S_i - M_i) \quad [13]$$

where S is simulated ET and M is the adjusted ET for the ith observation and N is the number of observations.

RESULTS AND DISCUSSION

Estimation of Evapotranspiration with the Recharge Model

The daily ET_a estimated with the recharge model was compared with the lysimeter-measured values under no SWD condition (Fig. 1a). The daily ET_a was averaged from 10 d. It was well correlated with the measurements from the lysimeter where enough irrigation was applied, and low values of bias (0.95 mm) and RMSE (5.58 mm) indicated a good agreement between measured and estimated values of 10-d ET. Simulation with the recharge model indicated that there was drainage below the rooting depth for some treatments, especially for the no SWD treatment (Fig. 1b.). There was a good agreement between seasonally estimated and adjusted ET_a as indicated by values for bias (−8.0 mm) and RMSE (27.8 mm). The two comparisons show that the recharge model could successfully simulate both 10-d ET_a (slope = 1.05) and seasonal ET_a (slope = 0.94) (Table 4).

Seasonal patterns of modeled cumulative ET_a, shown for the three consecutive seasons in Fig. 2, were similar under the different irrigation treatments, except that ET_a accumulated more slowly under severe SWD treatments than under other treatments after reviving stage. The accumulated ET_a increased quickly before overwintering stage, slowly from overwintering stage to reviving stage, and quickly after reviving stage. The seasonal pattern is mainly determined by air temperature and wheat growing stage. Before overwintering, rapidly accumulating air temperature made wheat sprout, come into leaf, and tiller, and high radiation and vapor pressure deficit made soil evaporation accumulate quickly. During overwintering, low air temperature restricts wheat growth while low radiation and low radiation and vapor pressure deficit made soil water evaporate slowly. After that stage, wheat turned green and its LAI began to increase quickly. Thus, accumulated ET_a increased dramatically.

Estimation of Evapotranspiration with the Crop Coefficient–Reference Evapotranspiration Approach

The seasonal ET_a estimated with the K_c–ET_0 approach was compared with the adjusted seasonal ET_a (Fig. 3). Relatively low values of bias (−33.1 mm) and RMSE (31.7 mm) indicated a good agreement between adjusted

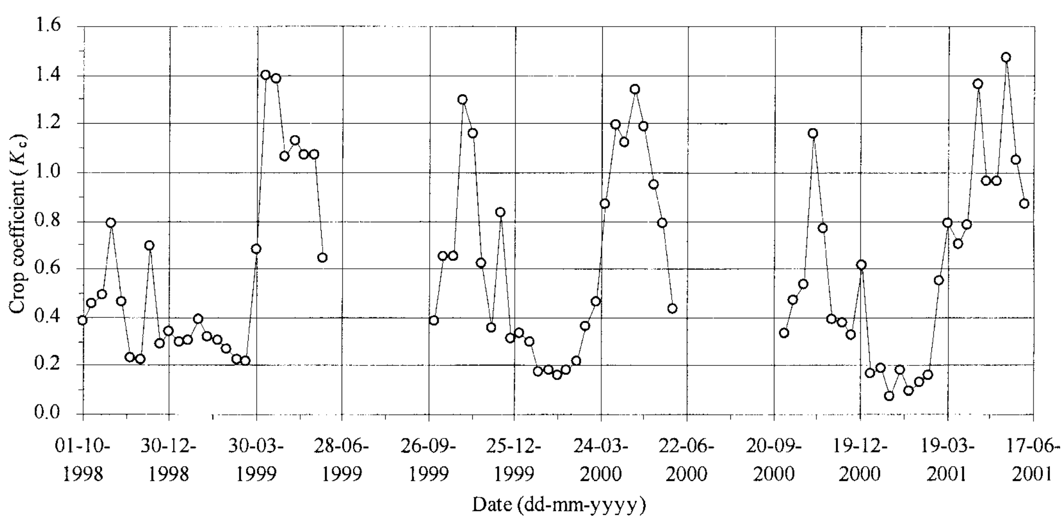

Fig. 4. The seasonal pattern of average crop coefficient (K_c) for winter wheat at Luancheng Station in the three consecutive winter wheat season, 1998–2001. K_c was determined from lysimeter-measured actual evapotranspiration and reference evapotranspiration.

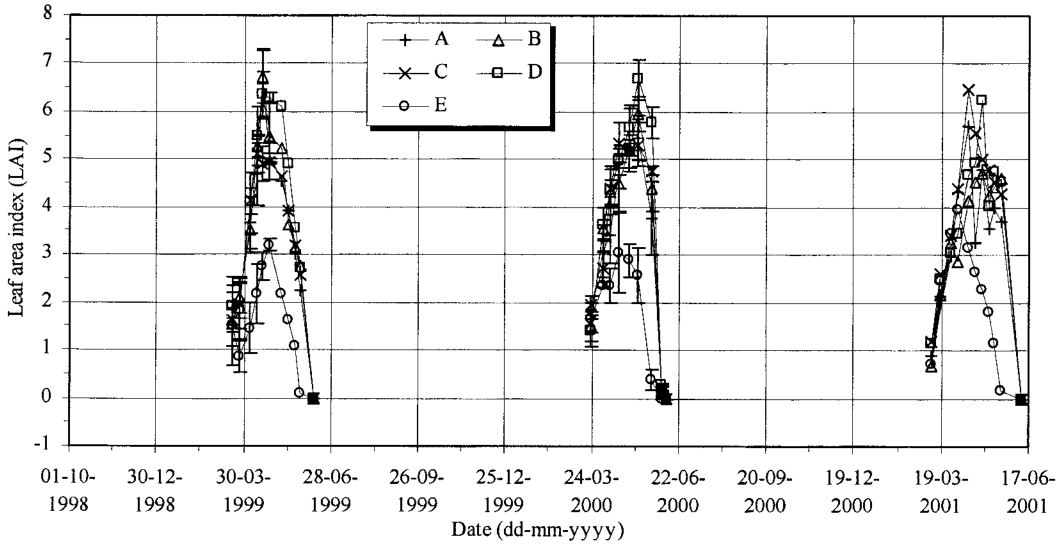

Fig. 5. The seasonal pattern of leaf area index (LAI) for winter wheat under different irrigation treatments at Luancheng Station in three consecutive seasons, 1998–2001. Error bars, which represent standard deviation from average LAI, are not shown from 7 May 1999 to 10 June 1999 and in 2000–2001 owing to lack of collecting all LAI data from the experimental plots. Treatments A, B, and C represent slight soil water deficit (SWD) conditions, Treatment D represents no SWD condition, and Treatment E represents severe SWD condition. Irrigation applications of the five treatments are shown in Table 2.

and K_c–ET_0 approach–estimated seasonal ET (Table 4). Figure 4 shows the seasonal pattern of average K_c in the three consecutive seasons from 1998–2001. For K_c, there were two peak stages and one lowest stage over the season. The first peak appeared at tillering stage, with an average value about 0.96; the second peak appeared during heading to grain-filling stage, with the highest average value about 1.16; the lowest K_c at overwintering stage was about 0.32 (Table 5). From emergence to fillering stage, wheat ET_a increases quickly because of rapidly increasing LAI and high soil evaporation. At overwintering stage, ET_a was very small owing to low soil evaporation, which was up to about 68.9% of total ET_a (Liu et al., 2002). From heading to grain-filling stage, wheat water requirements were very high due to high LAI (Wang et al., 2001). At maturity, K_c dramatically declined to 0.65 owing to declined LAI (Fig. 5). Thus, for K_c, there exists two peak stages and one lowest stage.

The soil water stress coefficient, K_s, changes from 0 to 1 according to Eq. [10], and it shows how A_w changes in the root depth to limit crop ET_a. Before reviving stage, K_s declined slowly while after the stage, it declined quickly under the four SWD treatments (Fig. 6). And for all of the SWD treatments, K_s at grain-filling stage declined more evidently than at the other stages even when much irrigation or precipitation was applied at the stage. The evident decline in K_s was caused by much ET_a and the highest K_c from heading to grain-filling stage. After grain-filling stage, K_s continuously declined and touched the bottom at maturity because there was little irrigation or precipitation input at that time even if LAI was very low due to leaf senescence.

Comparison of the Two Semiempirical Approaches

The results of the seasonal ET showed that the recharge model and the K_c–ET_0 approach both simulated ET very well. The recharge model (RMSE, 27.8 and Bias, −8.0) is better than the K_c–ET_0 approach (RMSE, 31.7 and Bias, −33.1) in estimating seasonal ET because it used a 1-d time step. But, the step of the K_c–ET_0 approach is 10 d because FAO Penman–Monteith equation calculates ET_0 in 10 d or one month. And, the recharge model used δ, the water use distribution parameter, which distributes water use over the multilayer soil profile to determine the curvature of the water uptake function. In the recharge model, ET_a is calculated depending on the pan evaporation, LAI, and the soil water content in the crop root depth; in the K_c–ET_0 approach, ET_a is determined by ET_0, K_c, and A_w. The recharge model and the K_c–ET_0 approach are both based on ET_0 estimation. There was a good agreement between 0.7 × pan evaporation and ET_0 calculated with the FAO Penman–Monteith equation (Fig. 7) though ET_0 in the two approaches was calculated in different ways. The recharge model separated ET_a into total actual evaporation and transpiration in a multilayer soil while the K_c–ET_0 approach estimated ET_a depending on two coefficients, K_c, and K_s, instead of dividing ET_a into total actual evaporation and transpiration.

Table 5. The average crop coefficient (K_c) for winter wheat at Luancheng Station during the three consecutive seasons, 1998–2001, based on reference evapotranspiration (ET_0) and lysimeter-measured actual evapotranspiration (ET_a).

Crop	Sowing	Emergence	Tillering	Overwintering	Revival	Jointing	Heading	Flowering	Grain filling	Harvest
Winter wheat	0.37	0.53	0.96	0.32	0.38	1.13	1.12	1.09	1.16	0.65

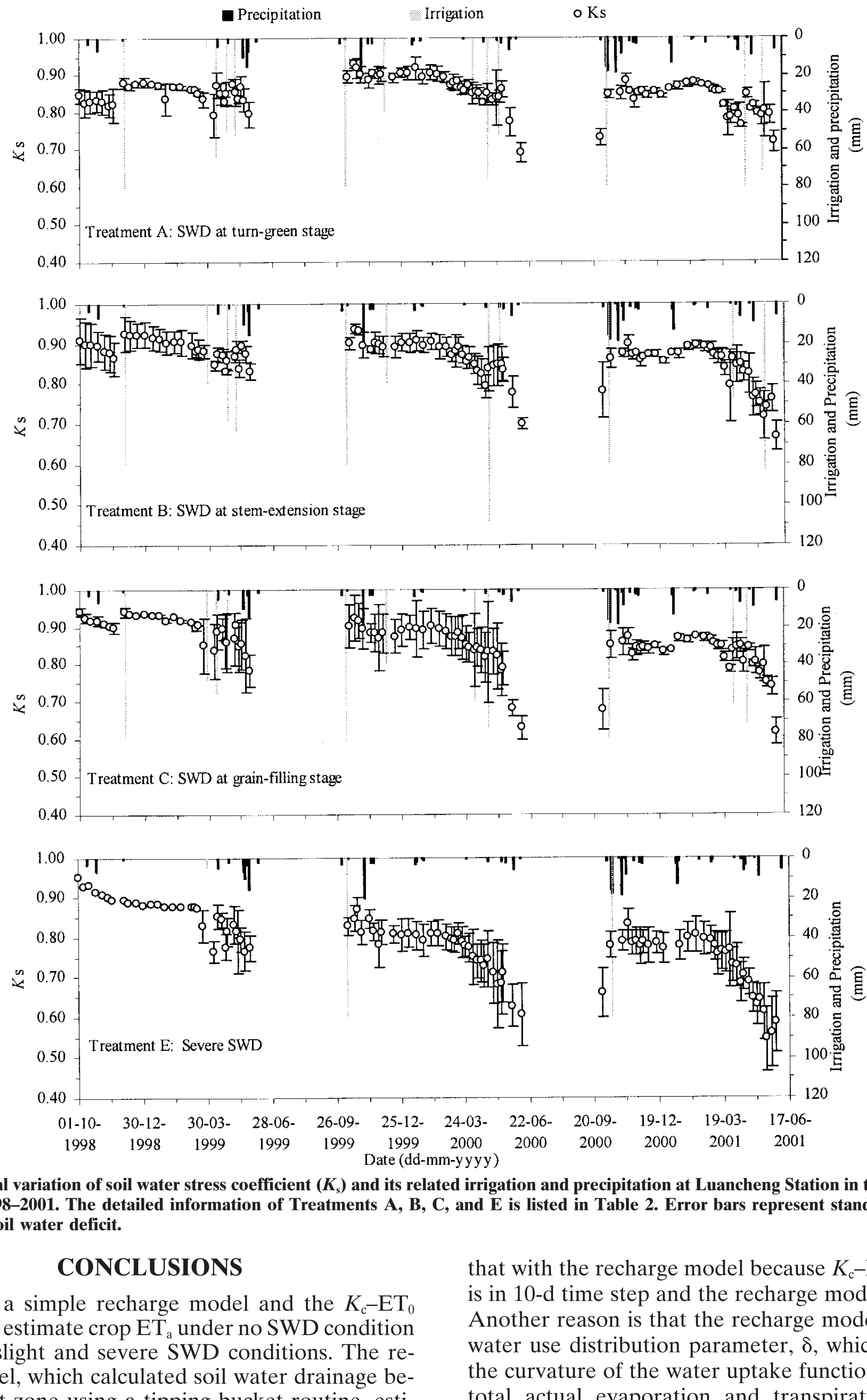

Fig. 6. Seasonal variation of soil water stress coefficient (K_s) and its related irrigation and precipitation at Luancheng Station in three consecutive seasons, 1998–2001. The detailed information of Treatments A, B, C, and E is listed in Table 2. Error bars represent standard deviation of K_s. SWD, soil water deficit.

CONCLUSIONS

We used a simple recharge model and the K_c–ET$_0$ approach to estimate crop ET$_a$ under no SWD condition and under slight and severe SWD conditions. The recharge model, which calculated soil water drainage below the root zone using a tipping-bucket routine, estimated 10-d ET$_a$ and seasonal ET$_a$ well. The K_c–ET$_0$ approach also estimated seasonal ET$_a$ well while estimated accuracy with the K_c–ET$_0$ approach is lower than that with the recharge model because K_c–ET$_0$ approach is in 10-d time step and the recharge model in 1-d step. Another reason is that the recharge model applied the water use distribution parameter, δ, which determines the curvature of the water uptake function, to estimate total actual evaporation and transpiration over the multilayer soil profile. In the wheat season, K_c had two peak stages—tillering stage and during heading to grain-filling stage. At grain-filling stage, K_s declined more

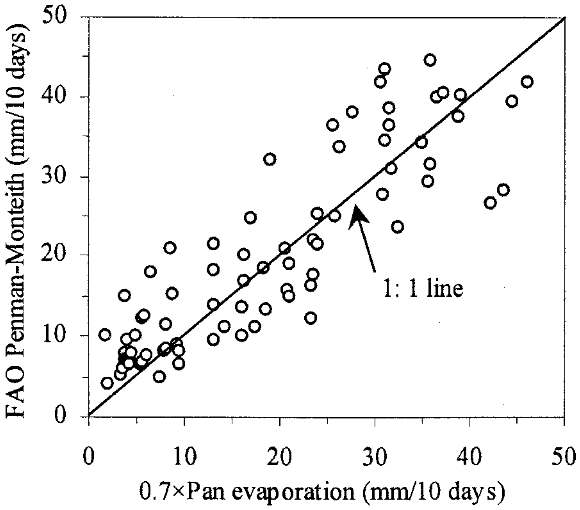

Fig. 7. Comparison between 10-d potential evapotranspiration calculated by the FAO Penman–Monteith method and estimated as a fraction of Class A pan evaporation, 1998–2001. **Correlation is significant at the 0.01 level (two-tailed); Pearson correlation coefficient is 0.88.

evidently than at other stages owing to much crop ET_a and the highest K_c.

Both approaches are suitable for estimating crop ET over 10 d, especially seasonal crop ET, instead of estimating diurnal change of ET. For short-term ET estimation (minutes or hours), it is suitable to use micrometeorological methods, e.g., the energy balance and Bowen ratio method, the aerodynamic method. and the eddy correlation method (Rana and Katerji, 2000). In general, the two approaches we used can successfully estimate crop ET over 10 d.

ACKNOWLEDGMENTS

This research was jointly funded by the Innovation Knowledge Project of the Institute of Geographic Sciences and Natural Resources Research of the Chinese Academy of Sciences (Grant no. CXIOG-C003-03), the Innovation Knowledge Project of Chinese Academy of Sciences (Grant no. KZCX-SW-317-02), and the Project of the Hebei Plain Water-Saving Agriculture and Sustainable Utilization of Groundwater (Grant no. 01220703D). The authors would like to acknowledge two anonymous referees for their valuable comments. Special appreciation is extended to the associate editor (Dr. William A. Payne) for his critical review and constructive suggestions, which resulted in a great improvement in the quality of the paper. The authors thank Dr. Marv Shaffer at USDA-ARS Great Plains Systems Research Unit for his correction of the paper. Finally, the first author would thank Dr. Eloise Kendy for much helpful discussion on the recharge model.

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