Evaluation of dual crop coefficient approach on evapotranspiration calculation of cherry trees

Tong Guodong[1], Liu Honglu[2*], Li Fahu[1]

(1. *College of Water Resources and Civil Engineering, China Agricultural University, Beijing* 100083, *China*;
2. *Beijing Water Science and Technology Institute, Beijing* 100044, *China*)

Abstract: A simple way to estimate tree evapotranspiration is needed for orchard irrigation schedules and water management practice, and the dual crop coefficient (DCC) approach provides such a method. Plot experiments on cherry trees were conducted in an orchard of Beijing, China, from 2011 to 2013, to test the suitability and reliability of the DCC method. The calculated results from the DCC method were compared with those directly measured by water balance (WB) and sap flow (SF) methods. Results showed that total evapotranspiration in the whole growth period of cherry trees obtained by WB, SF and DCC methods was 560.0-569.3 mm, 544.7-569.8 mm and 564.1-574.6 mm, respectively. The Nash-Sutcliffe efficiency (*NSE*) and the ratio of root-mean-square error to the standard deviation of measured data (*RSR*) showed that the calculated total evapotranspiration by DCC method was consistent to that measured by the WB method at above "Satisfactory" level ($0.50 < NSE \leq 0.65$ and $0.60 < RSR \leq 0.70$), and at "Very good" level ($0.75 < NSE \leq 1.00$ and $0 < RSR \leq 0.50$) when compared to the SF method. However, the performance of the DCC method on monthly evapotranspiration was worse than on total evapotranspiration, and the consistency mostly was classified as "Unsatisfactory" ($NSE \leq 0.50$ and $RSR > 0.70$) for the monthly evapotranspiration and as "Satisfactory" for the total evapotranspiration, respectively when compared with the WB and SF methods. Crop coefficients for the whole growth period were similar for all three methods, but the crop coefficient suggested by the DCC method was larger at the beginning and the late growth stages but smaller at the vigorous growth stage of cherry trees than those measured by using the WB and SF methods. It can be concluded that the DCC method is an effective tool to estimate total evapotranspiration in the whole growth period of cherry tree, but an improvement on accuracy of estimating monthly evapotranspiration of cherry trees is required.

Keywords: dual crop coefficient method, crop coefficient, evapotranspiration, sap flow method, water balance method

1 Introduction

Cherry trees are an economically important tree species in the North China Plain. Appropriate irrigation

on cherry orchards is necessary so as to improve fruit yield and quality in this drought-prone area.

Actual crop evapotranspiration (ET_c) estimation is fundamental to establishing an effective irrigation schedule[1]. Many methods have been developed to estimate ET_c and its components. They are mainly divided into two major categories, that is, using field measurements and empirical calculations. Field measurement methods measure ET_c value directly or indirectly using instruments, while empirical calculation methods estimate ET_c using empirical models[2]. Water balance (WB) and sap flow (SF) are two common field measurement methods to determine ET_c values. These methods can be used in a small field or large basin and its

measurement time can range from days, weeks, to years[3].

The WB method has been widely applied to fruit trees, field crops, and greenhouse crops[4-7]. However, using the WB method to accurately measure all terms in the water balance equation is difficult, even though its principle is simple. Water balance measurement is usually representative only for a small area, and a high spatial variability on soil water content will result in sampling difficulty, and make extrapolation to a larger scale problematic[8].

The SF method is often used in orchards or forests to measure evapotranspiration for single trees[9]. Studies have proved that sap flow technique can provide useful data to calculate tree ET_c and to separate the components of transpiration and soil evaporation[10,11]. The accuracy of this technique maybe is affected by a drift in data obtained at night[9] or the scaling up of ET_c values from a single tree to an area[12]. The radial gradient of sap flow in sapwood also can result in measurement errors[13]. The WB and SF methods are often used to validate other approaches or models on ET_c estimation[3,14,15].

The dual crop coefficient (DCC) method, recommended by FAO-56[1], is a convenient and common empirical model to estimate ET_c under different climate conditions. In this approach, the effects of crop transpiration and soil evaporation are represented by a basal crop coefficient K_{cb} and a soil evaporation coefficient K_e, respectively. Compared to the single crop coefficient approach, the DCC method usually can obtain a more accurate estimation of ET_c value especially under sparse vegetation cover, though the calculation procedure is more complex[16,17].

Many studies have used the DCC method to estimate the ET_c value and its components in field[18,19], greenhouse[20,21], and orchard crops[22,23]. Since the basal crop coefficient K_{cb} in DCC method is based on experience, there may be some deviations when applied in different regions or crops. This has been reported for a range of crops[20,24]. Some studies have shown that the ET_c value estimated by DCC method differs significantly from the measured data[25,26].

There are few studies on the feasibility and accuracy

of the DCC method in estimating ET_c value of cherry trees in the North China Plain, though this is essential when planning schedules based on the DCC method. The objectives of this study are: 1) to the determine ET_c value of cherry trees using the WB and SF methods to calculate its crop coefficient; and 2) to evaluate the feasibility and accuracy of the DCC method on ET_c estimation of cherry tree on a daily and seasonal basis in the North China Plain.

2   Materials and methods

2.1   Experimental site

This study was conducted between 2011 and 2013 at the Beijing Irrigation Experiment Station (39°20′N, 114°20′E, and ASL 12 m) of China Agricultural University, located in the Tongzhou District of Beijing. This site has a temperate continental monsoon climate, with a mean annual rainfall of 565 mm and evaporation of 1140 mm. Rainfall events mainly occur in July and August, which accounts for 60% to 70% of total annual rainfall. The yearly averaged air temperature and relative humidity in the station is 11.5°C and 56.8%, respectively, and groundwater depth is greater than 12 m. The soil in the station is silt loam, with a field capacity of 30 cm^3/cm^3 and a dry bulk density of 1.55 g/cm^3.

2.2   Experimental design and measurement

One hundred and eight seven-year-old sweet cherry trees, which were transplanted in 2007, were distributed with a spacing of 3 m×4 m in the orchard of the experimental station as shown in Figure 1.
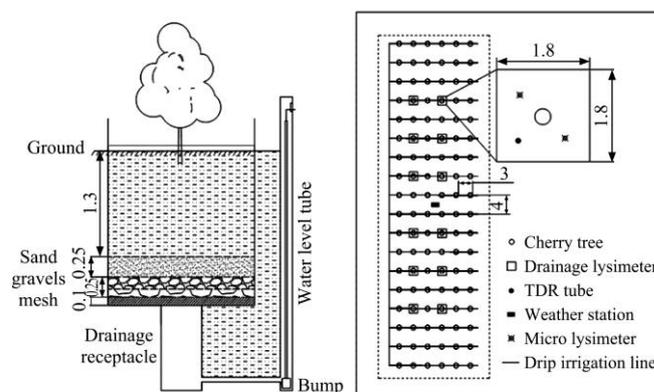
Figure 1   Experimental arrangement and schematic diagram of lysimeter (m)

A Watchdog 2000 weather station was located in the middle of the orchard. A lysimeter was filled evenly

with local soil for the upper depth of 1.3 m at a bulk density of 1.55 g/cm^3. The bottom 0.55 m of the lysimeter was filled with sand and gravel as a filter layer (Figure 1). A total 12 drainage lysimeters with a length $\times$ width $\times$ depth of 1.8 m $\times$ 1.8 m $\times$ 1.9 m were set up at the experimental site when sweet cherry trees were transplanted, and each drainage lysimeter was planted with one cherry tree.

A drip irrigation system was employed to irrigate cherry trees. Two emitters per tree with a total flux rate of 16 L/h were used. The irrigation water was groundwater and the irrigation schedule was planned according to local climate conditions and crop species (Table 1). Organic fertilizer (15 kg) and compound chemical fertilizer (0.2 kg) were applied to each tree every autumn. The flowers bloomed at the end of April and leaves fell at the end of October, with a total growth period of about 180 d.

Table 1   Irrigation time and quantity during 2011-2013

Date (d/m/y)	31/5/2011	22/6/2011	12/7/2011	4/9/2011	23/9/2011	14/10/2011	Total
Irrigation quantity/mm	40	40	40	40	40	40	240
Date (d/m/y)	17/5/2012	11/6/2012	2/7/2012	27/8/2012	20/9/2012	12/10/2012	Total
Irrigation quantity/mm	40	40	40	40	40	40	240
Date (d/m/y)	14/5/2013	17/6/2013	23/7/2013	21/8/2013	28/9/2013	21/10/2013	Total
Irrigation quantity/mm	40	40	40	40	40	40	240

During 2011-2013, the physiological indices of cherry trees such as tree trunk diameter, tree height, leaf area index, photosynthetic rate, and stomatal conductance were measured every month or at various growth stages. The fruit yield and its quality were measured after harvest.

Common weather parameters such as temperature, relative humidity, radiation, wind speed, and precipitation were automatically monitored in real time by the weather station. Soil water content, soil evaporation rate, deep percolation, and trunk sap flow flux were monitored according to normal procedures.

A 1.5 m long TRIME-TDR monitoring tube (IMKO, Ettlingen, Germany) was installed in each lysimeter 0.8 m from each cherry tree for soil water monitoring. Soil water content was measured every 2-4 d at a depth interval of 0.1 m for a depth of 0-1.3 m, and additional observations were carried out before and after irrigation or heavy rain events.

Two weighing micro-lysimeters, 15 cm in length and 9 cm in internal diameter, were installed on diagonal lines in each drainage lysimeter to measure soil evaporation (Figure 1). The micro-lysimeter maintenance and soil evaporation measurements were performed according to the Irrigation Experiment Standard (SL13-2004) of China[27].

Two sap flow probes, 30 mm long and 1 mm in diameter, were installed on every tree planted in the drainage lysimeters. These were placed on the north side of the tree trunk at the height of 30 cm above the ground, to avoid direct sun exposure. The sap flow probes were insulated and shielded with aluminum foil to minimize temperature fluctuations in sapwood. Sap flow flux was monitored in real time by a data collection system, and its value was collected and stored every 30 min.

2.3   Evapotranspiration calculation

2.3.1   WB method

Actual evapotranspiration for WB method was calculated according to the following equation:

$$ET_c = P + I + W - \Delta S - R - D \tag{1}$$

where, ET_c is actual evapotranspiration, mm; P is effective precipitation, mm; I is irrigation amount, mm; W is groundwater recharge amount into the root zone of cherry tree, mm; R is runoff, mm; D is percolation amount into below the root zone, mm; ΔS is the change in soil water storage between two consecutive times in the lysimeter, mm. ΔS can be calculated by:

$$\Delta S = S(t_2) - S(t_1) \tag{2}$$

where, $S(t_1)$ and $S(t_2)$ are water storage amounts (mm) in the measured soil depth at time t_1 and t_2, respectively.

In this study, W and R were negligible due to deep groundwater level and lysimeter boundary blockage, therefore Equation (1) was reduced to:

$$ET_c = P + I - \Delta S - D \qquad (3)$$

2.3.2   SF method

The sap velocity J (cm/s) and sap flux F (cm^3/h) of single tree were calculated based on the empirical relationships proposed by Granier[28]:

$$J = 119 \times 10^{-4} \times \left[\frac{\Delta T_{(0)}}{\Delta T_{(u)}} - 1 \right]^{1.23} \qquad (4)$$

$$F = J \times S_A \times 3600 \qquad (5)$$

where, $\Delta T_{(0)}$ is assumed to correspond to the zero flow condition that usually occurs in the dawn, ^{o}C; $\Delta T_{(u)}$ is the temperature difference between two sensors, ^{o}C; S_A is the cross-sectional area of conducting sapwood, cm^2.

Actual evapotranspiration ET_c was calculated by:

$$ET_c = \frac{F}{A} \times 10 + E_s \qquad (6)$$

where, E_s is soil evaporation between two consecutive measured times, as was measured by micro-lysimeter installed in drainage lysimeters, mm; A is the area of the tree canopy, cm^2; F is the sap flux of single tree, cm^3/h.

2.3.3   DCC method

The DCC method estimates actual evapotranspiration ET_c from the following equation[1]:

$$ET_c = (K_s \times K_{cb} + K_e) ET_0 \qquad (7)$$

where, ET_0 is reference crop evapotranspiration (mm) between two consecutive measured times, calculated based on Penman-Monteith equation according to weather data[1]; K_s is water stress or salinity stress reduction coefficient (dimensionless), and it was assumed to be 1 because there was no water stress under conditions of this study; K_{cb} is basal crop coefficient (dimensionless).   The recommended K_{cb} values for cherry trees are 0.5, 0.9 and 0.7 at their initial, middle, and end development stages respectively.   These K_{cb} values were adjusted based on meteorological data according to the method described by Allen et al[1]; K_e is soil evaporation coefficient (dimensionless), and its value was calculated according to the method of Allen et al.[1]

2.4   Statistical analysis and consistency evaluation

The calculated ET_c value from the DCC method was compared with those measured by WB and SF methods, using a linear regression and determination coefficient (R^2).   Further evaluations on the consistency between

the calculated ET_c value from DCC method and those measured by WB and SF methods were performed by calculating the Nash-Sutcliffe efficiency (NSE) and the ratio of root-mean-square error (RMSE) to the standard deviation of measured data (RSR)[29].

The NSE is a normalized statistic value that determines the relative magnitude of the calculated data compared to the measured data, and its value is ≤1.0, where 1.0 is the optimal value.   The RSR value varies from the optimal value of 0 to a large positive value.   The larger the NSE and the lower the RSR values, the better the model at estimating the actual measurement[30].   The NSE and RSR values can be calculated according to the following equations:

$$NSE = 1 - \frac{\sum_{i=1}^{n} (ET_i^{obs} - ET_i^{cal})^2}{\sum_{i=1}^{n} (ET_i^{obs} - ET_{mean})^2} \qquad (8)$$

$$RSR = \frac{\sqrt{\sum_{i=1}^{n} (ET_i^{obs} - ET_i^{cal})^2}}{\sqrt{\sum_{i=1}^{n} (ET_i^{obs} - ET_{mean})^2}} \qquad (9)$$

where, ET_i^{obs} is the ith measured ET_c value by the WB or SF methods, ET_i^{cal} is the ith calculated ET_c value by the DCC method, ET_{mean} is the averaged value of measured ET_c data, and n is total number of measured or calculated data.

According to Moriasi et al[31], the consistency between the calculated value and the measured value can be classified as 4 levels: 'Very Good' (NSE = 0.75-1.00 and RSR = 0-0.50), 'Good' (NSE = 0.65-0.75 and RSR = 0.50-0.60), 'Satisfactory' (NSE = 0.50-0.65 and RSR = 0.60-0.70), and 'Unsatisfactory' (NSE ≤ 0.50 and RSR > 0.70).

3   Results and discussion

3.1   Reference crop evapotranspiration

Daily reference crop evapotranspiration rate (ET_0) of cherry tree was calculated in 2011-2013, based on meteorological data and the Penman-Monteith equation[1] (Figure 2).   The daily ET_0 increased from Jan. to about May and then gradually decreased with time. It showed a typical bell shape within a year and a good consistency from year to year (Figure 2).   The maximum ET_0 value occurred in May or June because of vigorous tree growth,

strong radiation, high air temperature, and relatively low rainfall. Some relatively small ET_0 values in May-July of 2013 probably were caused by low air temperature, low radiation, and high humidity in this period. The average daily ET_0 value in the growth season of cherry trees from May to October in the three years tested was 3.31 mm/d, 3.41 mm/d, and 3.24 mm/d for 2011-2013, respectively.
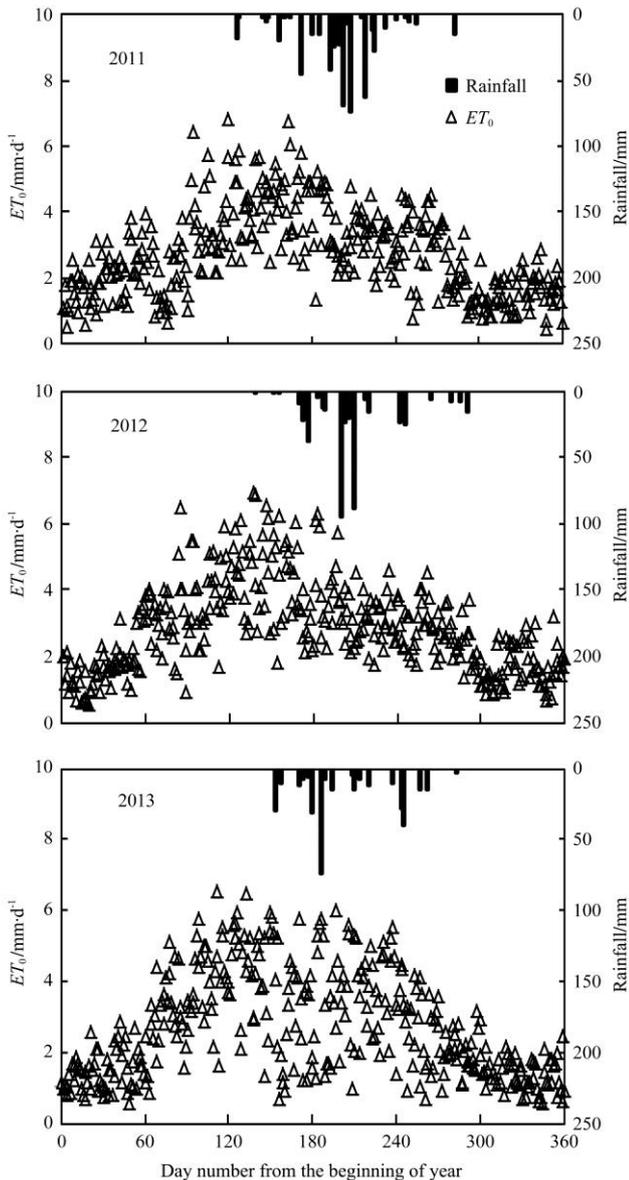
Figure 2   Daily reference crop evapotranspiration rate and rainfall amount in 2011-2013

The rainfall measurements were 515.3 mm, 448.7 mm, and 348.2 mm in 2011-2013; these were 8.8%, 20.6%, and 38.5% lower than the average annual rainfall amount in this region. The rainfall during the experimental period was equivalent to a drought year with slight to moderate levels according to probability analysis result.

3.2   Evapotranspiration estimation

3.2.1   WB method

Table 2 shows water balance components in the drainage lysimeter for every month during the growth season of cherry trees during 2011-2013. The total evapotranspiration in the whole growth period of cherry trees measured by the WB method was 569.3 mm, 563.4 mm, and 560.0 mm respectively in 2011, 2012, and 2013. The evapotranspiration in 2013 was 38 mm and 35 mm less than that in 2011 and 2012 respectively (Table 2). Monthly evapotranspiration and daily evapotranspiration rate both increased rapidly with growth time at the initial stage of growth period, and then gradually decreased. The peak value was in July or August (Table 2). The average evapotranspiration rate for the whole growth period was 3.1 mm/d, 3.1 mm/d, and 3.0 mm/d in 2011, 2012, and 2013, respectively.

Deep percolation in the growth season of 2011 was 13.7% and 403.0% greater than that in 2012 and 2013, respectively. Soil evaporation was correspondingly 8.1% and 13.6% larger than the other two years because of the annual rainfall of 515.3 mm in 2011, which was 14.4% and 48.0% greater than that for 2012 and 2013, respectively (Table 2). The ratio of soil evaporation to tree transpiration decreased gradually with growth time in 2011 but it generally increased in 2012 and 2013 (data not shown), which maybe also was caused by the higher rainfall in 2011. Their averaged values in whole growth period were 0.89, 0.78, and 0.73 for 2011, 2012 and 2013 respectively. Generally, rainfall, deep drainage, soil evaporation, and tree transpiration in every month showed a trend of first increase and then decrease during the whole growth period, with the peaks in July or August when climate was hottest and crop growth was most vigorous. For field crops such as wheat and maize as well as some shrubs, soil evaporation is influenced by crop canopy density[32,33]. Crop transpiration rate is lower at the initial stage of the growth period due to low leaf area index, and soil evaporation accounts for a great portion of evapotranspiration at this stage[21]. With the increasing of crop canopy and leaf area index, the amount of soil area shaded by plants increases. This decreases the effects of solar radiation and subsequently soil

evaporation rate[19].   On the other hand, crop transpiration rate usually increases with crop growth development, reaching a peak value when the crop canopy is fully developed, then decreasing with the

decline of crop growth.   However, soil evaporation in the drainage lysimeter was less affected by tree canopy, because of the height between the cherry tree canopy and the ground and because of weeding (Table 2).

Table 2   Water balance components and evapotranspiration on a monthly basis in 2011-2013

Year	Month	Irrigation /mm	Rainfall /mm	Drainage /mm	Evaporation /mm	Transpiration /mm	Evapotranspiration /mm	Daily evapotranspiration rate/mm·d^{-1}	Change on soil water storage/mm
2011	5	40.0	28.2	13.4±3.4	39.2±4.1	28.9±8.2	68.1±8.2	2.2±0.3	−13.3±4.3
	6	40.0	71.3	3.2±1.1	61.4±5.8	66.9±12.3	128.3±12.3	4.3±0.4	−20.2±4.4
	7	40.0	271.0	84.8±14.6	72.2±8.1	59.0±14.2	131.2±14.2	4.2±0.5	95.0±16.5
	8	0	111.8	28.7±9.3	45.7±3.3	71.1±11.4	116.8±11.4	3.8±0.4	−33.7±5.3
	9	80.0	18.3	29.1±10.2	27.6±2.0	56.1±7.3	83.7±7.3	2.8±0.2	−14.5±3.3
	10	40.0	14.7	7.3±1.2	22.1±1.1	19.1±3.1	41.2±3.1	1.3±0.1	6.2±2.2
	Total	240.0	515.3	166.3±18.0	268.0±20.0	301.3±27.5	569.3±27.5	3.1±0.2	19.7±4.1
2012	5	40.0	2.2	0	39.1±1.6	35.2±5.3	74.3±5.3	2.4±0.2	−32.1±4.3
	6	40.0	79.4	45.1±11.3	35.1±6.0	71.1±7.8	106.2±7.8	3.5±0.3	−31.9±4.9
	7	40.0	258.6	75.3±16.2	54.1±8.3	78.1±9.2	132.2±9.2	4.3±0.3	91.1±7.6
	8	40.0	23.3	2.2±1.0	52.6±5.6	66.1±8.1	118.7±8.1	3.8±0.2	−57.6±4.1
	9	40.0	54.8	23.7±6.3	40.1±4.5	46.1±7.2	86.2±7.2	2.9±0.2	−15.1±2.6
	10	40.0	32.2	0	26.6±3.7	20.2±6.1	46.8±6.1	1.5±0.1	25.4±3.3
	Total	240.0	450.5	146.3±20.4	248.0±18.8	316±29.4	563.4±29.4	3.1±0.3	−19.2±3.0
2013	5	40.0	0	0	20.2±3.3	63.2±7.1	83.4±7.1	2.7±0.3	−43.4±5.7
	6	40.0	65.2	0	29.4±4.1	64.2±7.8	93.6±7.8	3.1±0.3	11.6±1.6
	7	40.0	154.1	29.3±7.0	61.4±8.4	70.4±9.9	131.8±9.9	4.3±0.4	33.0±4.1
	8	40.0	28.6	0	66.1±7.1	68.1±9.6	134.2±9.6	4.3±0.3	−65.6±7.6
	9	40.0	97.3	4.0±1.3	35.1±1.6	41.2±6.4	76.3±6.4	2.5±0.2	57.0±6.6
	10	40.0	3.1	0	24.3±1.2	16.4±5.3	40.7±5.3	1.3±0.1	2.4±0.0
	Total	240.0	348.3	33.7±6.4	236.6±19.6	323.4±26.6	560.0±26.2	3.0±0.3	−5.4±1.1

Note: [†]denotes average value±standard error; [‡]"−" refers to the reduction of soil water storage.

3.2.2   SF and DCC methods

Figure 3 shows the daily evapotranspiration rates measured by the SF method and calculated by DCC method for cherry trees in 3 different growth seasons. Both the measured and calculated evapotranspiration rates showed a similar trend of rapid increase and then gradual decrease during the whole growth period (Figure 3).   Daily evapotranspiration rate measured by the SF method was 0.6-6.9 mm/d, 0.6-6.3 mm/d, and 0.7-6.1 mm/d in 2011, 2012, and 2013, respectively, and the corresponding values calculated by the DCC method were 0.6-6.0 mm/d, 0.9-5.8 mm/d, 1.0-5.4 mm/d.   Total actual evapotranspiration obtained by SF and DCC methods respectively were 544.7-569.8 mm and 571.6-574.6 mm during the 3 experimental years.

3.3   Consistency evaluation

3.3.1   Comparison on total evapotranspiration and daily evapotranspiration rate

Total evapotranspiration measured by the WB method

was 24.6 mm greater than that measured by SF method in 2011 but was 6.0 and 4.6 mm smaller in 2012 and 2013, respectively.   It was 5.3, 7.8, and 4.1 mm smaller than that calculated by the DCC method, respectively, in 2011, 2012, and 2013.   The relative difference between WB and SF methods was 0.8%-4.5%, and that between WB and   DCC   method   was   within   0.7%-1.4%. Correspondingly, the total evapotranspiration calculated by the DCC method was 29.9 mm and 1.8 mm greater in 2011 and 2012 but 0.5 mm smaller in 2013 respectively than that calculated by the SF method, and its relative difference was within 0.1%-5.5%.   The difference in total evapotranspiration in whole growth period obtained by all 3 methods was less than 5.5%, which indicated a high agreement among 3 methods on estimating total evapotranspiration of cherry trees.

Daily evapotranspiration rates obtained by the 3 methods showed a relatively greater difference, especially at the beginning stage or the late stage of the growth period.
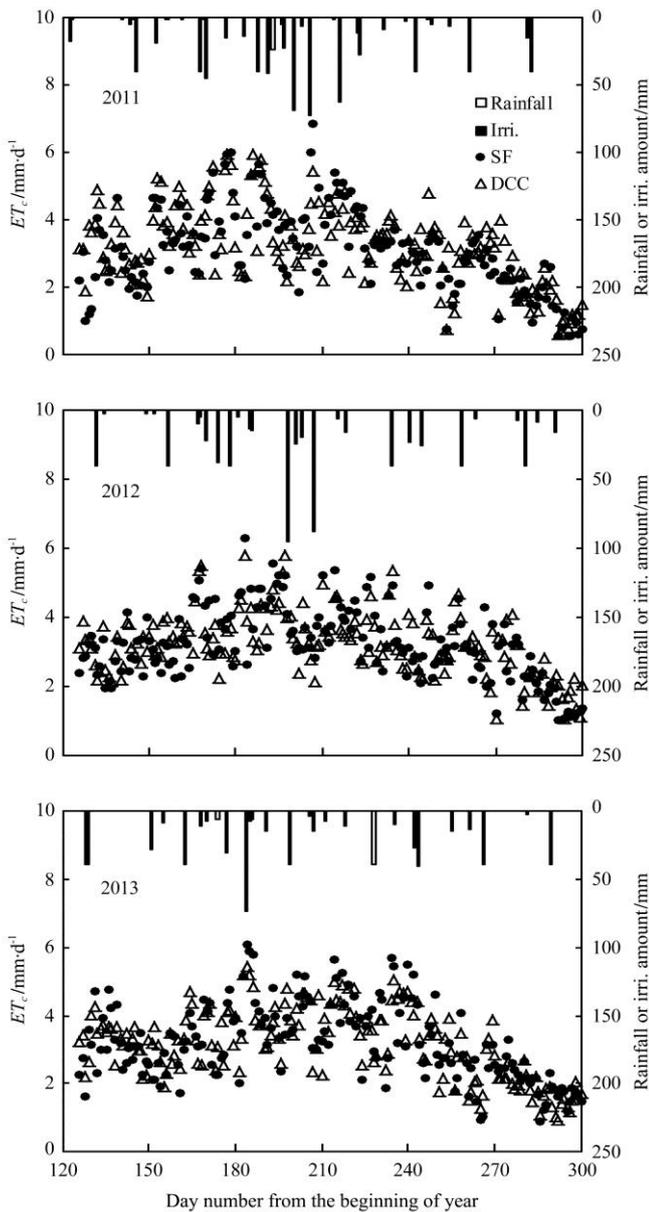
Figure 3   Daily crop evapotranspiration rate obtained by sap flow (SF) method and dual crop coefficient approach (DCC) during the growth seasons in 2011-2013

The daily evapotranspiration rates in May and October that calculated by the DCC method were greater than those by SF and WB methods but a contrary tendency existed in July and August. Compared with the WB method, the relative difference of daily evapotranspiration rate measured by the SF method was −9.3%-38.5%, and that calculated by the DCC method was −12.5%-50.0%. The relative difference between the SF and DCC methods on daily evapotranspiration rate was −5.6%-23.1%. These data possibly hint that a more precise estimate of evapotranspiration rate is necessary at the beginning stage or the late stage of tree growth period. Generally, the average daily evapotranspiration rate over the 3 growth periods of cherry trees measured by the WB method was smallest, being about 6.1% lower than the SF method and 4.8% lower than the DCC method. The rate measured by the SF method was almost equal to that calculated by the DCC method, with the former being only 1.4% lower than the latter.

The comparison between daily evapotranspiration rates obtained by WB, SF, and DCC methods are shown in Figure 4. Statistical analysis showed that the linear regression coefficient between evapotranspiration rates measured by WB and SF methods was 0.939 (R^2=0.578[***]) for all 3 experimental years, and those between WB and DCC methods and between SF and DCC methods were 0.952 (R^2=0.427[***]) and 0.986 (R^2=0.681[***]), respectively. Figure 4 shows that daily evapotranspiration rates obtained by WB, SF, and DCC methods were mostly similar to each other.
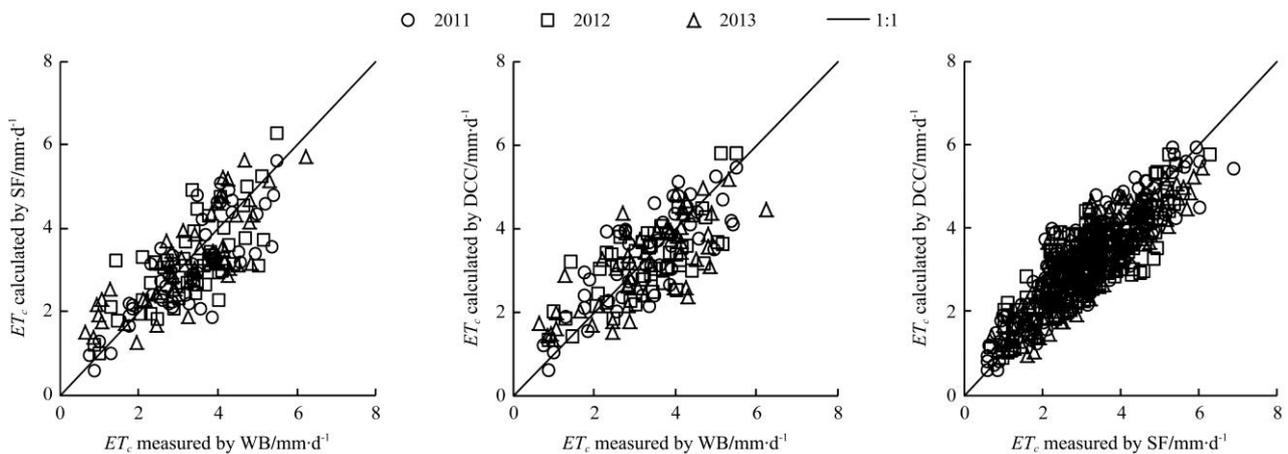
Figure 4   Comparison of daily evapotranspiration rates obtained by water balance (WB), sap flow methods (SF), and dual crop coefficient approach (DCC)

3.3.2   Consistency between calculated and measured total actual evapotranspiration

Table 3 shows the *NSE* and *RSR* values comparing the consistency of evapotranspiration calculated by DCC method with those measured by WB and SF methods. These show that the consistency of total evapotranspiration in the whole growth period of cherry tree between the DCC and WB methods was at the "Satisfactory" or "Good" level, and that between the DCC and SF methods was rated as "Very good". This means that the calculated total evapotranspiration during the whole growth period using the DCC method was very close to the values measured by the WB and SF methods.

Table 3   Consistency classification for evapotranspiration calculated by dual crop coefficient (DCC) method compared with that measured by water balance (WB) or sap flow (SF) methods

Year	Month	$NSE_{DCC\text{-}WB}$ [†‡]	$RSR_{DCC\text{-}WB}$	Classification	$NSE_{DCC\text{-}SF}$	$RSR_{DCC\text{-}SF}$	Classification
	5	-0.19	1.09	US [¶]	0.55	0.67	S
	6	0.21	0.89	US	0.72	0.53	G
	7	-0.32	1.15	US	0.67	0.57	G
2011	8	-0.32	1.15	US	0.58	0.65	S
	9	0.73	0.52	G	0.51	0.70	S
	10	0.22	0.89	US	0.54	0.68	S
	Total	0.68	0.56	G	0.81	0.43	VG
	5	-0.68	1.30	US	0.44	0.75	US
	6	0.04	0.98	US	0.55	0.67	S
	7	-0.46	1.21	US	0.55	0.67	S
2012	8	-0.13	1.06	US	0.63	0.61	S
	9	-0.76	1.33	US	0.54	0.68	S
	10	-0.49	1.22	US	0.47	0.73	US
	Total	0.54	0.68	S	0.76	0.49	VG
	5	0.26	0.86	US	0.42	0.76	US
	6	0.04	0.98	US	0.58	0.65	S
	7	-0.30	1.14	US	0.62	0.62	S
2013	8	0.09	0.95	US	0.67	0.57	G
	9	0.06	0.97	US	0.54	0.68	S
	10	-0.07	1.03	US	0.46	0.73	US
	Total	0.71	0.54	G	0.79	0.46	VG

Note: [†]*NSE* and *RSR* refer to Nash-Sutcliffe efficiency and the ratio of root-mean-square error to the standard deviation of measured data, respectively; [‡]subscripts *DCC-WB* and *DCC-SF* refer to dual crop coefficient and water balance methods as well as dual crop coefficient and sap flow methods, respectively; [¶]VG, G, S and US refer to "Very good", "Good", "Satisfactory", and "Unsatisfactory", respectively.

The evaluation classification in Table 3 indicates that the performance of DCC method on monthly evapotranspiration was worse than that on total evapotranspiration for the whole growth period, which is similar to the results found by other researchers[29,34,35]. Moriasi et al thought this was possibly because of different sample sizes in the two time scales[31], but it may also be because of the mean value ET_{mean} in Equation (8) and Equation (9). The ET_c has a greater fluctuation and subsequently a greater difference between the measured ET_i^{obs} and the averaged ET_{mean} value during the whole growth period than in a month. The *NSE* value was therefore greater but the *RSR* value was smaller during the whole growth period than in a month (Table 3). The consistency between monthly evapotranspiration from the DCC method and from the WB method was mostly classified as "Unsatisfactory", and the consistency between values from the DCC and from SF methods was mostly rated as "Satisfactory" (Table 3). This indicates that the monthly evapotranspiration calculated by the DCC method was more similar to that measured by the SF method than the WB method. This consistency evaluation is consistent with above comparison analysis results.

3.3.3   Suitability analysis of crop coefficient suggested by DCC method

The crop coefficient (K_c) calculated by the WB and SF methods and that suggested by the DCC method are presented in Figure 5 for cherry trees during 3 growth seasons. The variation patterns of K_c values obtained by

the three methods generally showed a similar trend during the growth period of cherry trees, this being first an increase and then a decrease with growth time at a maximum value in July or August (Figure 5). The variation fluctuation of the K_c value obtained by the DCC method with growth time was smaller than that obtained by the WB and SF methods, and it was within the range of the latter 2 methods (Figure 5). The month-averaged K_c value based on the WB method was 0.68±0.25, 1.04±0.35, 1.29±0.39, 1.25±0.34, 0.98±0.30 and 0.72±0.26 from May to October in the three experimental years. The corresponding value obtained by the SF method was 0.68±0.27, 0.99±0.36, 1.18±0.35, 1.18±0.29, 0.98±0.30 and 0.84±0.25, and that calculated by the DCC method was 0.79±0.16, 1.01±0.17, 1.17±0.11, 1.11±0.13, 1.0±0.14, and 0.87±0.17, respectively. The averaged K_c value over the whole growth period of cherry tree was 1.0±0.31, 0.98±0.29, and 1.0±0.16 for the WB, SF, and DCC methods respectively. The data indicate that K_c values obtained by the three methods were mostly similar to each other. However, the K_c value calculated by the DCC method was slightly larger at the beginning and the late growth stages but smaller at the vigorous growth stage of cherry tree than that obtained by the WB and SF methods, which is similar to the results reported by Liu and Luo[36] and by Ayars et al[37] for peach trees.

The crop coefficient is the ratio of actual crop evapotranspiration to reference crop evapotranspiration, and it is a necessary parameter when the DCC method is applied to estimate actual crop evapotranspiration. Apart from the influences of crop characteristics themselves, some other factors such as canopy architecture, irrigation method and management, orchard ground management, and weather condition also affect the variability in K_c value[20,38,39]. The K_c values obtained by the WB and SF methods had a larger fluctuation extent at the middle growth stages of cherry trees than those in other growth stages. This was possibly because there were more rainfall events during this stage, making the influence of soil moisture change and meteorological factors more complex[37]. In addition, the wider spread of cherry tree canopy and its greater distance from the ground compared with that

recommended in the DCC method may also be a reason for relative large difference between the calculated and measured K_c values[1,16].
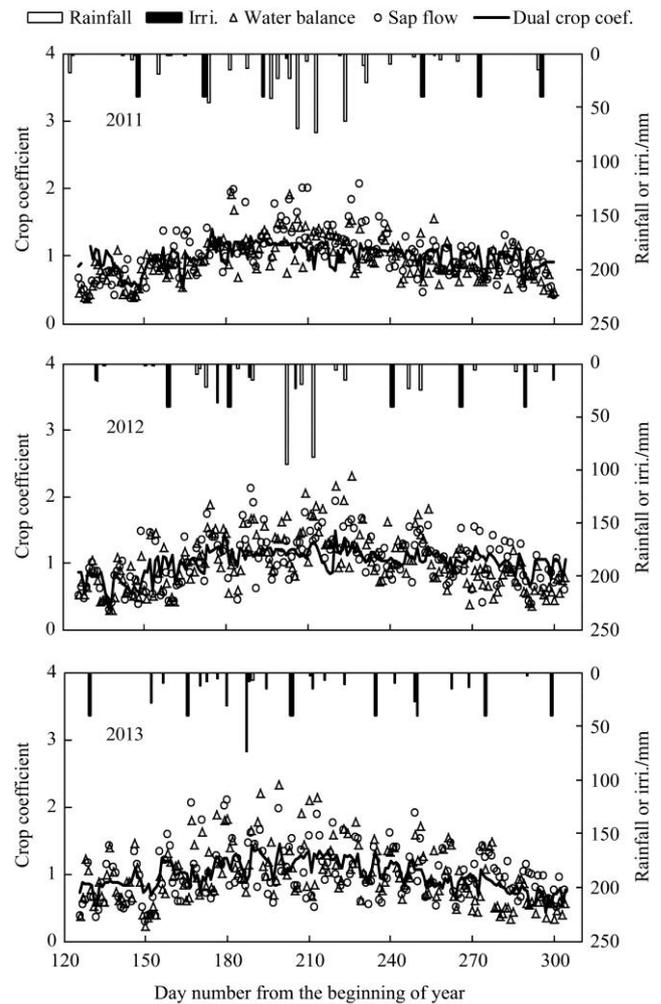
Figure 5   Crop coefficient obtained by water balance, sap flow, and dual crop coefficient methods during the growth seasons of cherry tree in 2011-2013

4   Conclusions

1) Daily evapotranspiration rates obtained by the WB, SF, and DCC methods showed a similar variation trend during the whole growth period of cherry trees. The evapotranspiration rate increased to a maximum in July or August and then declined. The value calculated by the DCC method was greater than the values measured by the WB and SF methods with a difference of 5.6%-50.0%, and the average daily evapotranspiration rate over the whole growth period was 2.9-3.1 mm/d, 3.0-3.2 mm/d, and 3.2-3.2 mm/d, respectively, for the WB, SF, and DCC methods. The total evapotranspiration during the whole growth period measured by the WB method was 560.0-569.3 mm during the 3 experimental years, the

corresponding values obtained by the SF and DCC methods were 544.7-569.8 mm and 564.1-574.6 mm respectively, and the differences between the three methods was within 4.3%.

2) For total evapotranspiration during the whole growth period, the consistency evaluation between the DCC method and WB method was above "Satisfactory", and that between the DCC method and SF method was "Very good". However, the consistency between monthly evapotranspiration calculated by the DCC method and measured by the WB method was mostly classified as "Unsatisfactory", and that between the values calculated by the DCC method and measured by the SF method was mostly "Satisfactory". The performance of the DCC method was worse for monthly evapotranspiration than on total evapotranspiration in whole growth period.

3) The variation patterns of crop coefficients, obtained by the three methods, generally showed a similar trend during the whole growth period of cherry trees, an increase and then a decrease, with growth time at a maximum value in July or August. The average crop coefficient over the whole growth period was 1.0, 0.98, and 1.0 for the WB, SF, and DCC methods, respectively, and they were similar to each other. However, the crop coefficient calculated by the DCC method was larger at the beginning and the late growth stages but smaller at the vigorous growth stage of cherry trees than that obtained by WB and SF methods.

4) It can be concluded that the DCC method can be used as an effective tool to estimate total evapotranspiration in the whole growth period of cherry tree in arid or semi-arid regions, but its performance on monthly evapotranspiration was not very high. An improvement in the crop coefficient calculation procedure for the DCC method is needed when the DCC method is used to estimate monthly evapotranspiration or daily evapotranspiration rate of cherry trees.

Acknowledgements

[References]

[1] Allen R G, Pereira L S, Raes D, Smith M. Crop evapotranspiration: Guidelines for computing crop water requirements. FAO Irrigation Drainage Paper No. 56, 1998; FAO, Rome, Italy.

[2] Angela A, Jaime A T S, Gabor S. Evapotranspiration and crop coefficient of common reed at the surroundings of Lake Balaton. Hungary. Aquatic Botany, 2014; 116: 53–59.

[3] Wilson K B, Hanson P J, Mulholland P J, Baldocchi D D, Wullschleger S D. A comparison of methods for determining forest evapotranspiration and its components: sap-flow, soil water budget, eddy covariance and catchment water balance. Agricultural and Forest Meteorology, 2001; 106(2): 153–168.

[4] Greacen E L, Higentt C T. Water balance under wheat modeled with limited soil data. Agricultural Water Management, 1984; 8(1-3): 291–304.

[5] Lovelli S, Pizza S, Caponio T, Rivelli A R, Perniola M. Lysimetric determination of muskmelon crop coefficients cultivated under plastic mulches. Agricultural Water Management, 2005; 72(2): 147–159.

[6] Abrisqueta I, Abrisqueta J M, Tapia L M, Munguí a J P, Conejero W, Vera J, et al. Basal crop coefficients for early-season peach trees. Agricultural Water Management, 2013; 121: 158–163.

[7] Choudhury B U, Singh A K, Pradhan S. Estimation of crop coefficients of dry-seeded irrigated rice-wheat rotation on raised beds by field water balance method in the Indo-Gangetic plains, India. Agricultural Water Management, 2013; 123: 20–31.

[8] Dunin F X. Extrapolation of 'point' measurements of evaporation: some issues of scale. Vegetatio, 1991; 91(1-2): 39–47.

[9] Lu P, Laurent U, Zhao P. Granier's thermal dissipation probe (TDP) method for measuring sap flow in trees: theory and practice. Acta Botanica Sinica, 2004; 46(6): 631–646.

[10] Rousseauxa M C, Figuerola P I, Guillermo C, Searles P S. Seasonal variations in sap flow and soil evaporation in an olive (*Olea europaea* L.) grove under two irrigation regimes in an arid region of Argentina. Agricultural Water Management, 2009; 96(6): 1037–1044.

[11] Cammalleri C, Rallo G, Agnese C, Ciraolo G, Minacapillib M, Provenzano G. Combined use of eddy covariance and sap flow techniques for partition of ET fluxes and water stress assessment in an irrigated olive orchard. Agricultural Water Management, 2013; 120: 89–97.

[12] Zhang H, Simmonds L P, Morison J I L, Payne D. Estimation of transpiration by single trees: comparison of sap flow measurements with a combination equation. Agricultural and Forest Meteorology, 1997; 87(2-3): 155–169.

[13] Clearwater M J, Meinzer F C, Andrade J L, Goldstein G, Holbrook N M. Potential errors in measurement of nonuniform sap flow using heat dissipation probes. Tree

Physiology, 1999; 19(10): 681–687.

[14] Trambouze W, Bertuzzi P, Voltz M. Comparison of methods for estimating actual evapotranspiration in a row-cropped vineyard. Agricultural and Forest Meteorology, 1998; 91(3-4): 193–208.

[15] Li X Y, Yang P L, Ren S M, Li Y K, Liu H L, Du J, et al. Modeling cherry orchard evapotranspiration based on an improved dual-source model. Agricultural Water Management, 2010; 98(1): 12–18.

[16] Allen R G, Clemments A J, Burt C M. Prediction accuracy for project wide evapotranspiration using crop coefficients and reference evapotranspiration. Journal of Irrigation and Drainage Engineering, 2005; 131(1): 24–36.

[17] Allen R G, Pereira L S, Smith M, Raes D, Wright J L. FAO-56 dual crop coefficient method for estimating evaporation from soil and application extensions. Journal of Irrigation and Drainage Engineering, 2005; 131(1): 2–13.

[18] Suleiman A A, Soler C M T, Hoogenboom G. Evaluation of FAO-56 crop coefficient procedures for deficit irrigation management of cotton in a humid climate. Agricultural Water Management, 2007; 91(1-3): 33–42.

[19] Alberto M C R, Quilty J R, Buresh R J, Wassmann R, Haidar S, Correa J, et al. Actual evapotranspiration and dual crop coefficients for dry-seeded rice and hybrid maize grown with overhead sprinkler irrigation. Agricultural Water Management, 2014; 136: 1–12.

[20] Lopez-Urrea R, Olalla F M S, Montoro A, Lopez-Fuster P. Single and dual crop coefficients and water requirements for onion (*Allium cepa* L.) under semiarid conditions. Agricultural Water Management, 2009; 96(6): 1031–1036.

[21] Odhiambo L O, Irmak S. Evaluation of the impact of surface residue cover on single and dual crop coefficient for estimating soybean actual evapotranspiration. Agricultural Water Management, 2012; 104: 221–234.

[22] Er-Raki S, Chehbouni A, Boulet G, Williams D G. Using the dual approach of FAO-56 for partitioning ET into soil and plant components for olive orchards in a semi-arid region. Agricultural Water Management, 2010; 97(11): 1769–1778.

[23] Fandino M, Cancela J J, Rey B J, Martíneza E M, Rosa R G, Pereira L S. Using the dual-K_c approach to model evapotranspiration of Albarino vineyards (*Vitis vinifera* L. cv. Albarino) with consideration of active ground cover. Agricultural Water Management, 2012; 12: 75–87.

[24] Kang S Z, Gu B J, Du T S, Zhang J H. Crop coefficient and ratio of transpiration to evapotranspiration of winter wheat and maize in a semi-humid region. Agricultural Water Management, 2003; 59: 239–254.

[25] Fan Y Q, Cai H J. Comparison of crop water requirements computed by single crop coefficient approach and dual crop coefficient approach. Journal of Hydraulic Engineering, 2002; (3): 50–54. (in Chinese with English abstract)

[26] Su M, Li J, Rao M. Estimation of crop coefficients for sprinkler-irrigated winter wheat and sweet corn using a weighing lysimeter. Transactions of the CSAE, 2005; 21(8): 25–29. (in Chinese with English abstract)

[27] Ministry of Water Resources of the People's Republic of China (MWR). Irrigation experiment standard (SL13-2004). Beijing: China Water Power Press, 2004. (in Chinese)

[28] Granier A. Transpiration of natural rain forest and its dependence on climatic factors. Agricultural and Forest Meteorology, 1996; 78: 19–29.

[29] Singh J, Knapp H V, Arnold J G, Demissie M. Hydrologic modeling of the Iroquois River watershed using HSPF and SWAT. Journal of the American Water Resources Association, 2005; 41(2): 343–360.

[30] Nash J E, Sutcliffe J V. River flow forecasting through conceptual models: Part I – A discussion of principles. Journal of Hydrology, 1970; 10(3): 282–290.

[31] Moriasi D N, Arnold J G, Van Liew M W, Bingner R L, Harmel R D, Veith T L. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. American Society of Agricultural and Biological Engineers, 2007; 50(3): 885–900.

[32] Zhao N N, Liu Y, Cai J B, Paredes P, Rosa R D, Pereira L S. Dual crop coefficient modelling applied to the winter wheat–summer maize crop sequence in North China Plain: Basal crop coefficients and soil evaporation component. Agricultural Water Management, 2013; 117: 93–105.

[33] Paredes P, Wei Z, Liu Y, Xu D, Xin Y, Zhang B, et al. Performance assessment of the FAO AquaCrop model for soil water, soil evaporation, biomass and yield of soybeans in North China Plain. Agricultural Water Management, 2015; 152: 57–71.

[34] Fernandez G P, Chescheir G M, Skaggs R W, Amatya D M. Development and testing of watershed-scale models for poorly drained soils. Transactions of the ASAE, 2005; 48(2): 639−652.

[35] Van Liew M W, Veith T L, Bosch D D, Arnold J G. Suitability of SWAT for the conservation effects assessment project: comparison on USDA agricultural research service watersheds. Journal of Hydrologic Engineering, 2007; 12(2): 173−189.

[36] Liu Y, Luo Y. A consolidated evaluation of the FAO-56 dual crop coefficient approach using the lysimeter data in the North China Plain. Agricultural Water Management, 2010; 97(1): 31–40.

[37] Ayars J E, Johnson R S, Phene C J, Trout T J, Clark D A, Mead R M. Water use by drip-irrigated late-season peaches. Irrigation Science, 2003; 22(3-4): 187–194.

[38] Girona J, Campo J, Mata M, Lopez G, Marsal J. A comparative study of apple and pear tree water consumption measured with two weighing lysimeters. Irrigation Science, 2011; 29(1): 55–63.

[39] Juhász A, Sepsi P, Nagy Z, Tokei L, Hrotkó K. Water consumption of sweet cherry trees estimated by sap flow measurement. Scientia Horticulturae, 2013; 164: 41–49.