Agricultural and Forest Meteorology 161 (2012) 116–122

Contents lists available at SciVerse ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet

Modeling sprinkler efficiency with consideration of microclimate modification effects

Weixia Zhao[a,b], Jiusheng Li[a,b,*], Yanfeng Li[a,b]

[a] State Key Laboratory of Simulation and Regulation of Water Cycle in River Basin, China Institute of Water Resources and Hydropower Research, Beijing 100038, China
[b] National Center of Efficient Irrigation Engineering and Technology Research-Beijing, Beijing 100048, China

ARTICLE INFO

Article history:
Received 8 August 2011
Received in revised form 12 March 2012
Accepted 20 March 2012

Keywords:
Sprinkler
Efficiency
Model
Sensitivity analysis

ABSTRACT

Irrigation efficiency is an important consideration for selecting a suitable irrigation method in arid and semiarid regions. Crop canopy interception and wind drift may reduce sprinkler efficiency. However, the evapotranspiration suppression resulting from temperature reduction and humidity increase in sprinkler-irrigated fields versus non-irrigated fields, defined as microclimate modification in this article, imposed a positive effect on sprinkler efficiency. In this study, a sprinkler efficiency model based on the Cupid program was proposed for considering the effects of microclimate modification. The air temperature, relative humidity, plant transpiration, soil evaporation and sprinkler efficiency during the irrigation season of corn in the North China Plain were simulated using the model. The results indicated that the microclimate within the sprinkler-irrigated field could be modified during irrigation, and the effects continued for 10–20 h after the application finished. When evapotranspiration suppression was considered, sprinkler efficiency could be improved by 5 percentiles versus non-irrigated fields. A sensitivity analysis of sprinkler efficiency was conducted by classifying the input variables of the model into three categories: constant, hourly and daily variables. It was found that the sprinkler efficiency was only generally sensitive to the leaf thermal emissivity for all constant and daily variables investigated. The sensitivity to hourly variables was greatly dependent upon the specific soil, plant and weather conditions during an irrigation event.

1. Introduction

Irrigation is one of the practices used to increase and stabilize crop yield. The application efficiency plays an important role in selecting a suitable irrigation method in arid and semiarid regions. Sprinkler irrigation supplies water to crops in a manner similar to natural rainfall. Sprinkler water losses are mainly caused by crop canopy interception, wind drift and evaporation. However, these losses can reduce temperature and increase humidity in the fields and consequently suppress plant transpiration and soil evaporation by microclimate modification (Wang et al., 2006; Cavero et al., 2009). McNaughtom (1981) believed that any “savings”, or decline, in crop transpiration from the wetted area compared with a non-irrigated field can be subtracted from gross interception losses for a reduced, or net, interception loss. Thompson et al. (1993b) reported that both soil evaporation and crop transpiration reduction led to effective water losses for sprinkler application.

The influence of sprinkler irrigation on evapotranspiration mainly depends on the amount of water intercepted by the crop canopy and the recovery time for the microclimate modification. Different researchers determined the recovery time for different temporal scales. Tolk et al. (1995) determined the transpiration suppression of corn during and after an irrigation event. Thompson et al. (1993b) calculated the effective loss of sprinkler water in a field during the process of irrigation, relative to a non-irrigated field. Liu and Kang (2006) reported that field microclimate modification continued throughout two consecutive sprinkler irrigations intervals. Through measurements of plant transpiration rate and microclimate in fields of winter wheat and corn, Wang et al. (2007) found that temperature and humidity had an approximately similar recovery time. They estimated the net interception loss by crop canopy from the beginning of sprinkler application to the point when the plant transpiration rate increased to the rate in the reference fields receiving surface irrigation. Playán et al. (2005) and Cavero et al. (2009) reported that daytime sprinkler irrigation strongly modified field microclimate during the irrigation and for a short period after the irrigation finished, while this modification was minimal for a nighttime irrigation.

The Cupid package is a comprehensive soil–plant–atmosphere model in which many of the essential physical and physiological

* Corresponding author at: Department of Irrigation and Drainage, China Institute of Water Resources and Hydropower Research, 20 Chegongzhuang West Road, Beijing 100048, China. Tel.: +86 10 68786545; fax: +86 10 68451169.
E-mail address: lijs@iwhr.com (J. Li).

0168-1923/$ – see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.agrformet.2012.03.019

processes that describe plant–environment interactions had been incorporated. To accomplish the structure of Cupid, the canopy, soil and atmosphere are divided into layers and leaves within each layer are divided into leaf-angle classes. This enables the boundary conditions for the soil and atmosphere to be defined so that profiles of air and soil temperature, relative humidity, leaf temperature, soil water content, intercepted rainfall or irrigation, dew formation and thus leaf wetness duration can be generated from the input information. The input data requirements for the model Cupid include five classes: initial conditions, ambient environment, soil characteristics, plant characteristics and site factors. The measurement of these data can be found in Norman and Campbell (1983). This detailed knowledge of crop energy and water balance produced by Cupid has permitted its applications to micrometeorology (Inclán and Forkel, 1995; Kustas et al., 2007), remote sensing (Huang et al., 2007) and integrated pest management (Norman, 1982). Since combining equations governing water droplet evaporation and droplet ballistics with the Cupid program (Thompson et al., 1993a), Cupid has become a useful tool to estimate the microclimate modification and evapotranspiration suppression from sprinkler irrigation (Thompson et al., 1993b, 1997).

The objectives of this study were to develop a sprinkler efficiency model based on the Cupid program that considers the effects of microclimate modification, to verify the model using the accessible field data of temperature and humidity for sprinkler-irrigated corn and to find parameters that have a relatively important influence on sprinkler efficiency from among a huge number of input variables.

2. Material and methods

2.1. Definition of sprinkler efficiency

Irrigation efficiency ($E1$, %) is defined as the ratio of total water stored in the root zone for plant use (W_s, mm) to the total amount of water applied (I, mm) (Hansen, 1960):

$$E1 = \frac{W_s}{I} \times 100\%. \tag{1}$$

The total water stored in the root zone in the Cupid program included two components. One is the stem flow (S, mm), and the other is the drip-off water (D, mm). The sum of stem flow (S) and the drip-off water (D) is an output parameter for the Cupid program. The stem flow (S) in the Cupid program is determined by

$$S = \sum_{j=2}^{n} f_s(P_j - e_j - p_{\max} \times 2.0 \times df), \tag{2}$$

where n is the total number of sublayers, f_s is the fraction of intercepted application that runs down the stem, P_j (mm) is the intercepted application by sublayer j, e_j (mm) is the evaporated water in sublayer j, $p_{\max}$ (mm) is the maximum effective thickness of water on one side of a leaf and df is the leaf area index for sublayer j.

The drip-off water (D) in the Cupid program is described as

$$D = P_1 + \sum_{j=2}^{n} d_j \times \exp\{-0.5 \times [(j-2) \times df]\}, \tag{3}$$

where d_j (mm) is the drip-off water from sublayer j and P_1 (mm) is the intercepted application by layer between the soil surface and canopy, namely, the part of the application water passing the canopy directly.

The contribution of microclimate modification to sprinkler efficiency was based on the comparison of evapotranspiration between a sprinkler-irrigated field and a non-irrigated field. The Cupid model was able to simulate the evapotranspiration under these two scenarios. Both plant transpiration (T_p, mm) and soil evaporation (E_s, mm) were two of the model outputs. Note that the plant transpiration and soil evaporation in the sprinkler-irrigated field were T_{p1} and E_{s1}, while they were T_{p2} and E_{s2} in the non-irrigated field. The sprinkler efficiency model was defined as

$$E2 = \frac{W_s + (T_{p2} - T_{p1}) + (E_{s2} - E_{s1})}{I} \times 100\% = \frac{W_s + \Delta T_p + \Delta E_s}{I} \times 100\%, \tag{4}$$

where ΔT_p (mm) and ΔE_s (mm) are the plant transpiration suppression and soil evaporation suppression relative to a non-irrigated field, respectively.

Because the air vapor deficit, which is a function of air temperature and humidity, is the main force for plant transpiration and soil evaporation, the calculation duration of the sprinkler efficiency model (t) was selected to span from the beginning of application to the point at which both air temperature and humidity recovered to the contrast level after the irrigation finished (Eq. (5)). To minimize the influence of the time step of the model simulation on the stability of ΔT_p and ΔE_s, the convergence criterion for the calculation duration t(h) was defined as

$$t = \max\{t(\Delta T \geq -0.01), t(\Delta RH \leq 0.01)\}, \tag{5}$$

where ΔT (°C) is the decrease in the air temperature in a sprinkler-irrigated field versus a non-irrigated field, ΔRH (%) is the increasing amount of relative humidity in a sprinkler-irrigated field versus a non-irrigated field, $t(\Delta T \geq -0.01)$ (h) is the time when ΔT is equal to or larger than −0.01 and $t(\Delta RH \leq 0.01)$ (h) is the time when ΔRH is equal to or smaller than 0.01.

2.2. Field experiments

The field experiment was conducted at the Experimental Station of the Agrometeorology Institute, Chinese Academy of Agricultural Science in Beijing, North China Plains (39°48′N, 116°28′E, 31.3 m above sea level) to provide the data related to the input variables and to verify the Cupid model. The experimental area, located in the temperate monsoon climate zone, is in a dry, subhumid region with an annual mean precipitation of 550 mm. The soil was sandy clay loam with a bulk density of 1.3 g/cm^3 and a field capacity of 0.30 cm^3/cm^3. An automated weather station was installed 80 m from the experimental field to measure the hourly ambient environment.

Impact sprinklers (80B2, LEGO Israel) with a nozzle diameter of 4 mm were used for irrigation. The flow rate for an individual sprinkler was 0.8 m^3/h at 0.3 MPa. The nozzle height of the solid-set system was 2.4 m above the soil surface. The entire irrigated plot was 15 × 45 m. Sprinklers were spaced in a square grid of 15 × 15 m. Twenty-seven TDR access tubes were uniformly distributed in the irrigated plot with an equal grid of 5 × 5 m. Normally, the soil–water contents at each access tube from depths of 10–100 cm were measured by time domain reflectometry (TDR) (TRIME-T3, IMKO Germany) with an interval of 10 cm. The initial soil–water contents for each irrigation event were also measured prior to the irrigation event. Irrigation was applied when the average soil–water content within the top 50 cm layers was depleted to approximately 75% of the field capacity. The soil–water content was measured before the sprinkler application and at the same time after the application finished for seven consecutive days.

Summer corn cultivar Zhongnuo No. 1 (*Zea mays* L.) was sown on 24 June with rows 0.6 m apart, with 0.4 m of spacing between plants and harvested on 15 September 2005. A 4 m high mast with three layers of sensors (U23-002, HOBO America) was installed in the center of the experimental area to measure the air temperature and relative humidity every 30 min. The height for each sensor layer was adjusted according to plant height during the growing season. The upper layer sensors were 0.3 m above the top of the canopy, and the second layer sensors were installed at the top of the crop canopy. To measure the temperature and humidity within the canopy, the third layer sensors were installed at 3/4 of the plant height. None of the sensors were shielded.

Three sprinkler irrigation events were applied on 29 July, 25 August and 5 September with an approximate application rate of 5.8 mm/h during the growing season. For the application event on 25 August, the irrigation was initiated at 09:24 and completed at 12:49 local time, and a total amount of 20 mm was applied. The plant height measured on this date was 2.0 m, and the leaf area index (LAI) was 2.6. The ratio of stem flow to total water applied was 0.4 (Wang et al., 2006).

The field measurements described above provided most of the data for input variables of the Cupid model, including the initial water content profile, atmospheric variables and soil water content, soil properties, plant characteristics, site factors and irrigation schedules of the sprinkler-irrigated field. Other input data was approximated from published information (Norman and Campbell, 1983; Huang et al., 2007). For the non-irrigated field, the input variables similar to the sprinkler-irrigated field were used but the flag variable to specify type of water application (IRRCHK) was set to zero (IRRCHK = 0 for no irrigation and IRRCHK = 1 for overhead sprinkler irrigation). Two of the model outputs, temperature and humidity above the canopy, were compared with the field observations to verify the model. Then the plant transpiration and evaporation from the soil surface either irrigated or non-irrigated fields simulated under different scenarios by the model (that were not measured in the field experiments) were used to evaluate microclimate modification and evapotranspiration suppression from sprinkler irrigation.

2.3. Sensitivity analysis

According to the temporal variation characteristics of the input variables of the Cupid model, the variables were classified into three categories: constant variables, daily variables and hourly variables. Considering the complexity and nonlinearity of the Cupid model, the local method was used in the sensitivity analysis. The sensitivity index (Huang and Zhang, 2010) was used to quantify the sensitivity of the sprinkler efficiency to each constant and daily variable:

$$SI_k = \frac{\Delta O}{\Delta F_k}\frac{F_k}{O} = \frac{f(F_1, F_2, \dots, F_k + \Delta F_k, \dots, F_m) - f(F_1, F_2, \dots, F_m)}{\Delta F_k} \frac{F_k}{f(F_1, F_2, \dots, F_m)}, \tag{6}$$

where SI_k is the sensitivity index of the kth input variable, O is the output of model simulation, either $E1$ or $E2$, and F_k are the input variables of constant and daily input variables. The larger the absolute value of SI, the higher the sensitivity of the variable F_k.

The relative deviation R (%) was used for sensitivity analysis of hourly variables because a constant value was unavailable for an hourly variable:

$$R = \frac{\Delta O}{O} \times 100\% = \frac{f(F_1, F_2, \dots, F_k + \Delta F_k, \dots, F_m) - f(F_1, F_2, \dots, F_m)}{f(F_1, F_2, \dots, F_m)} \times 100\%. \tag{7}$$

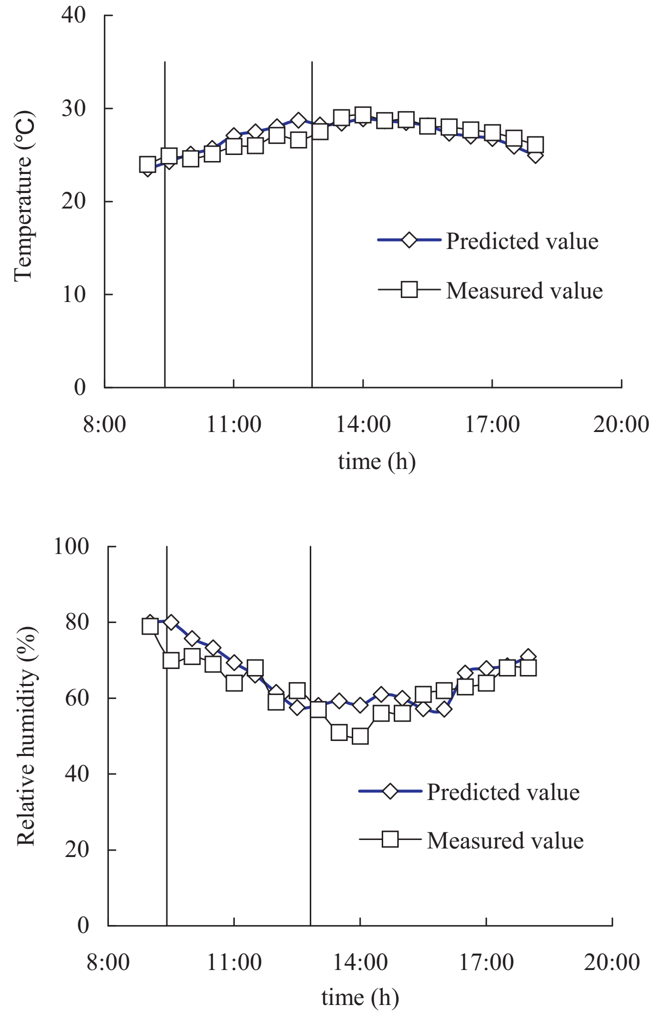

Fig. 1. Comparison of the air temperature and relative humidity predicted by the Cupid model with measured values from above the corn canopy during and after sprinkler irrigation events. Vertical lines represent the beginning and end of the irrigation.

3. Results and discussion

3.1. Model verification

The temperature and relative humidity values simulated by the Cupid model and the data collected at the height of 2.3 m from the ground (above the canopy) are compared in Fig. 1 for the selected event of sprinkler application on 25 August. A time step of 15 min was used in the simulation.

It can be seen in Fig. 1 that the model predictions were 0.5–2 °C larger than the temperature measured during the process of irrigation (from 924 h to 1249 h) and within 0.5 h after the irrigation finished. The sensors might be shielded by spray drops during water application. The evaporation of the drops could cool the sensors and resulted in an observed temperature lower than the actual value. However, a predicted temperature slightly (0–2 °C) lower than the value measured was observed after that time with a relative error (|measured value − simulated value|/measured value) ranging from 0 to 8%.

The measured relative humidity showed a random pattern of fluctuations during the irrigation. There were two facts that can account for these fluctuations. One was the evaporation of the spray drops on the surface of the sensors, and the other was the fluctuations in wind speed and direction that enhanced or suppressed the vertical exchange of vapor pressure. This randomness could become more significant because wind speed was integrated over the specific time interval selected (Thompson et al., 1993b). The values of relative humidity predicted by the Cupid model captured the general trend of the measured values, with a mean relative error of 14% during the process of irrigation and an error of 19% within 6 h after the irrigation finished.

3.2. Microclimate modification and recovery time

The air temperature simulated by the Cupid model from the beginning of application to the time when the temperature in the sprinkler-irrigated field recovered to the level of a non-irrigated field, for the selected event of sprinkler application on 25 August, is illustrated in Fig. 2. An approximately similar variation pattern of temperature with time was observed for the three simulation heights of 2.3 m from the soil surface (above the canopy), 2.0 m from the soil surface (at the height of canopy) and 1.5 m from the soil surface (below the canopy). During the process of water application, the air temperature in the sprinkler-irrigated field was almost similar to the value in the non-irrigated field. The temperature in the sprinkler-irrigated field was lower than that in the non-irrigated field within 6.4 h after the irrigation finished. The maximum temperature reduction in the sprinkler-irrigated field was 0.8, 1.1 and 1.2 °C for the three heights of above the canopy, at the height of the canopy and below the canopy, respectively. Cavero et al. (2009) also reported that the decrease of temperature due to sprinkler irrigation was higher as the measurement height was closer to the soil surface.

From 0.5 h after the beginning of irrigation to 10.75 h after the irrigation finished, the relative humidity in the sprinkler-irrigated field was higher than that in the non-irrigated field. The maximum increment was 21.2%, 30.8% and 27.8% for the three heights of above the canopy, at the height of the canopy and below the canopy, respectively (Fig. 3).

An increasing trend of temperature and a decreasing trend of humidity in the sprinkler-irrigated field can be examined during the process of water application (Figs. 1–3). The quickly increasing solar radiation during the application (from 924 h to 1249 h), which had a positive effect on the air temperature increase, can mainly account for this phenomenon.

For the sprinkler irrigation event on 29 July (from 900 h to 1155 h, a total amount of 17 mm was applied), the simulated recovery time versus the non-irrigated field was 9.75 h for temperature and 11.25 h for humidity. For the sprinkler irrigation event on 5 September (from 09:55 to 14:54, a total amount of 30 mm was applied), the recovery time was 6.25 h and 19.50 h for temperature and humidity, respectively. This indicated that the recovery time for temperature and humidity might be different for a given irrigation event, greatly depending on the specific weather conditions during the process of water application and several hours after water application ceased.

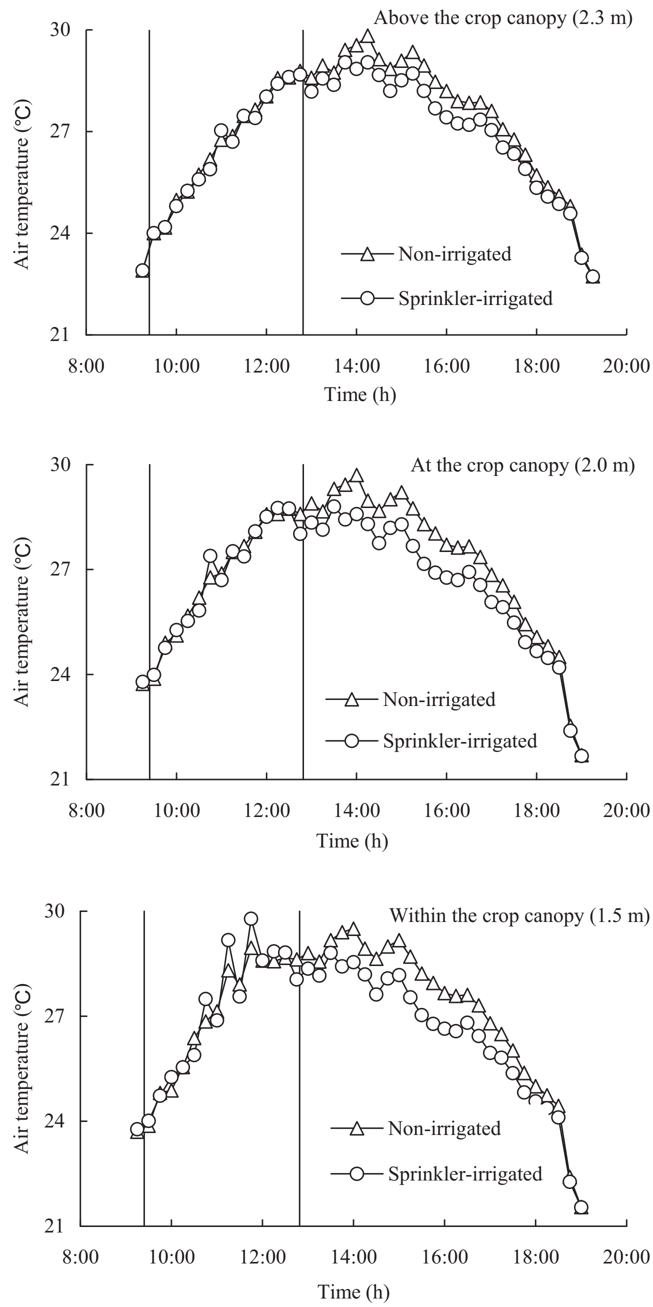

Fig. 2. Air temperature simulated by the Cupid model in the non-irrigated field and sprinkler-irrigated field above the crop canopy, at the crop canopy and within the crop canopy from application to the point at which the air temperature recovered to non-irrigated field level. Vertical lines represent the beginning and end of the irrigation.

3.3. Evapotranspiration suppression

The simulated corn transpiration and soil evaporation in the sprinkler-irrigated and non-irrigated fields for the selected sprinkler event on 25 August are compared in Fig. 4. The transpiration and evaporation rate in the sprinkler-irrigated field was substantially lower than that in the non-irrigated field during the process of water application and continued for several hours after water application finished. From the beginning of irrigation to the recovery time of microclimate modification, the average transpiration and the average evaporation in the sprinkler-irrigated field was 46.9% and 45.2% lower than that in the non-irrigated field, with a transpiration suppression of 1.01 mm and evaporation suppression of 0.25 mm.

3.4. Sprinkler efficiency

As defined in equation 5, the calculation duration of $E2$ for the three application events of 29 July, 25 August and 5 September was from the beginning of application to 9.75 h, 10.75 h and 19.50 h after the application finished, respectively. The simulated $E1$ and $E2$ are summarized in Table 1. Compared with $E1$, $E2$ increased 3 to 6 percentiles for the three irrigation events when considering transpiration and soil evaporation suppression versus a non-irrigated field. These results were similar to the finding of Tolk et al. (1995).

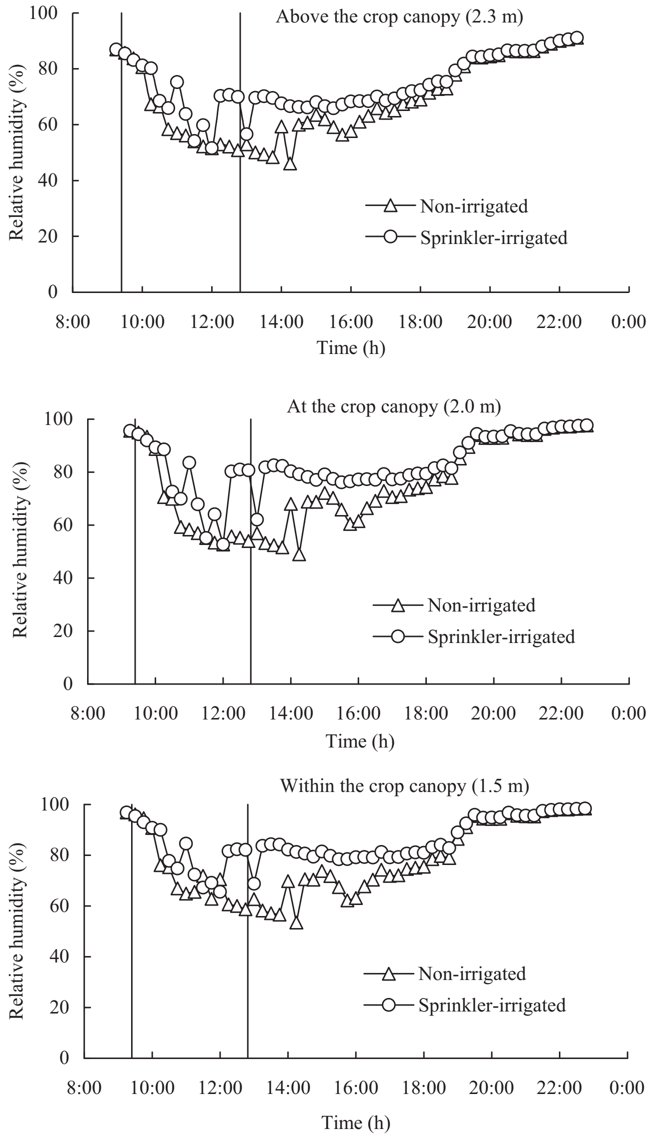

Fig. 3. Relative humidity simulated by the Cupid model in the non-irrigated field and sprinkler-irrigated field above the crop canopy, at the crop canopy and within the crop canopy from application to the point at which the relative humidity recovered to the non-irrigated field level. Vertical lines represent the beginning and end of the irrigation.

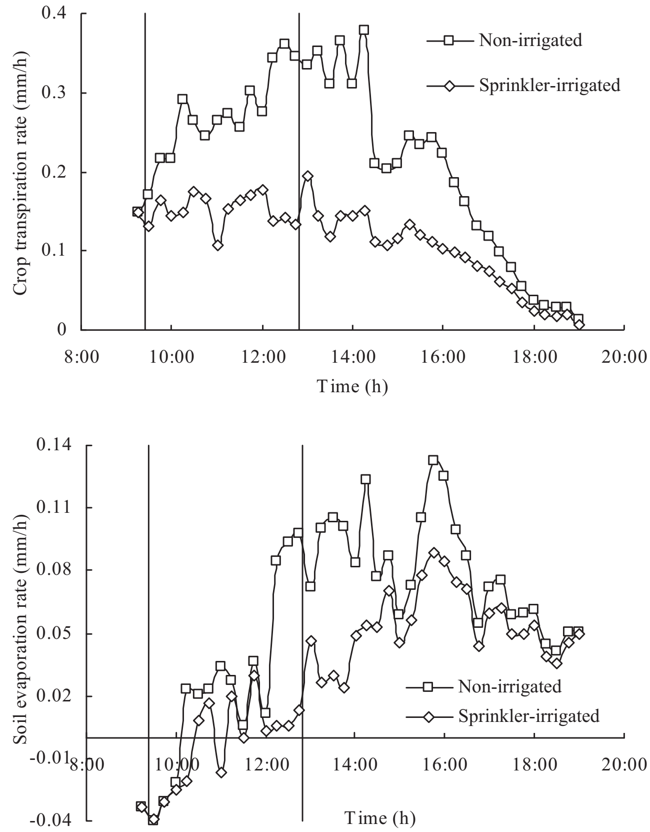

Fig. 4. Transpiration and evaporation rates simulated by the Cupid model during and after sprinkler irrigation events. Vertical lines represent the beginning and end of the irrigation.

They demonstrated that for an average daytime sprinkler application of 21 mm, the estimated average gross interception loss was 10.7% ($E1$ = 89.3%), but the resulting suppression of measured transpiration by 50% or more during the irrigation reduced the gross interception loss by 3.9% ($E2$ = 93.2% when only crop transpiration suppression was considered).

3.5. Sensitivity analysis for constant and daily variables

In the sensitivity analysis to constant and daily variables, the variation range of the input variable (ΔF_k) was between ±2% and ±50%. The absolute values of the sensitivity index for $E1$ and $E2$ are shown in Table 2. $E1$ was sensitive to 24 of the input variables, while $E2$ was sensitive to 19. The sensitive variables were not always identical for the three irrigation events because of the conditionality of the variables (Tan and Jin, 1998), which would change with the special soil–plant–atmosphere continuum. The average sensitivity indexes of the constant and daily variables were less than 0.05, except for the leaf thermal emissivity. According to the classification standard (Huang and Zhang, 2010), the leaf thermal emissivity is a generally sensitive variable, while all other input variables are the insensitive variables. To obtain an accurate determination of $E1$ and $E2$, the variation range of the leaf thermal emissivity should be controlled within 0.02% and 1.5%, respectively.

3.6. Sensitivity analysis for hourly variables

When the sensitivity analysis for hourly variables was conducted, a variation range of the input variables (ΔF_k) of ±10% was used. The relative deviation (R) for $E1$ and $E2$ is shown in Table 3. Compared with the reference values of $E1$ and $E2$, both $E1$ and E2 decreased with increasing wind speed, solar radiation and temperature. A decreasing air vapor pressure produced an increasing $E1$ and $E2$. The relative importance of the hourly variables to $E1$ was as follows: temperature > wind speed > air vapor pressure > solar

Table 1
Simulated results of irrigation efficiency ($E1$) and sprinkler efficiency ($E2$) for the three events of sprinkler irrigation.

Application time	I (mm)	ΔT (mm)	ΔE_s (mm)	W_s (mm)	$E1$ (%)	$E2$ (%)
29 July	17	0.68	0.28	16.11	94.76	100.44
25 August	20	1.01	0.25	18.71	93.55	99.85
5 September	30	1.03	0.23	28.47	94.90	98.34

Table 2
Sensitivity index (*SI*) of irrigation efficiency (*E*1) and sprinkler efficiency (*E*2) to the constant and daily variables for the three events of sprinkler irrigation.

Number	Sensitive parameters	Sensitivity index |SI| for E1			Sensitivity index |SI| for E2		
		2005.7.29	2005.8.25	2005.9.5	2005.7.29	2005.8.25	2005.9.5
1	Bulk density of soil	0.00	0.01	0.01	0.02	0.01	0.01
2	Value to match soil water flow equations with canopy vapor flow equations	0.00	0.00	0.03	0.00	0.00	0.01
3	Height of sprinkler nozzle	0.00	0.00	0.00	0.00	0.01	0.00
4	Number of layers above the sprinkler where droplet evaporation is occurring	0.00	0.00	0.00	0.00	0.01	0.00
5	Thinnest leaf layer in terms of LAI units	0.01	0.01	0.00	0.00	0.00	0.00
6	Clumping factor for canopy structure	0.01	0.01	0.00	0.00	0.00	0.00
7	Thermal emissivity of leaf	0.07	0.20	0.10	0.09	0.08	0.04
8	Thermal emissivity of the soil	0.00	0.00	0.01	0.00	0.03	0.01
9	Soil reflectance to visible	0.00	0.02	0.00	0.01	0.01	0.00
10	Soil reflectance to near infrared	0.00	0.00	0.00	0.00	0.01	0.00
11	Green leaf reflectance to visible	0.00	0.00	0.00	0.01	0.01	0.00
12	Green leaf reflectance to near infrared	0.01	0.02	0.02	0.02	0.01	0.00
13	Green leaf reflectance to thermal	0.00	0.01	0.02	0.01	0.01	0.01
14	Green leaf transmittance to visible	0.00	0.00	0.00	0.01	0.01	0.00
15	Green leaf transmittance to near infrared	0.01	0.02	0.02	0.02	0.01	0.00
16	Maximum size of leaf	0.01	0.01	0.01	0.00	0.01	0.01
17	Reference height for wind	0.01	0.01	0.01	0.02	0.01	0.01
18	Number of layers above the canopy	0.00	0.01	0.00	0.00	0.01	0.01
19	Height of upper boundary layer	0.01	0.01	0.02	0.02	0.04	0.02
20	Ambient atmospheric CO_2 concentration	0.01	0.01	0.01	0.00	0.01	0.01
21	Maximum fraction of leaf area wetted by precipitation	0.02	0.02	0.02	0.00	0.02	0.01
22	Maximum layer of water (mm) that can be held on a wet leaf in a uniform film	0.02	0.04	0.05	0.01	0.03	0.02
23	Leaf area index	0.04	0.05	0.04	0.01	0.03	0.03
24	Height of canopy	0.01	0.02	0.02	0.02	0.04	0.02
25	Relative height of the lowest green leaf	0.00	0.00	0.00	0.01	0.00	0.00
26	Water content of soil layers	0.00	0.00	0.00	0.02	0.01	0.00

Table 3
Relative deviation (*R*) of irrigation efficiency (*E*1) and sprinkler efficiency (*E*2) for the hourly variables for the three events of sprinkler irrigation.

Parameters	Relative deviation R for E1 (%)			Relative deviation R for E2 (%)		
	2005.7.29	2005.8.25	2005.9.5	2005.7.29	2005.8.25	2005.9.5
Wind speed (+10%)	−0.14	−0.11	−0.18	−0.17	−0.10	−0.02
Wind speed (−10%)	0.17	0.16	0.07	0.08	0.01	−0.05
Solar radiation (+10%)	−0.03	−0.05	−0.18	0.43	0.39	−0.05
Solar radiation (−10%)	0.00	0.27	0.11	−0.49	−0.27	−0.10
Air temperature (+10%)	−0.35	−0.27	−0.46	−0.17	0.27	−0.19
Air temperature (−10%)	0.35	0.43	0.18	0.85	−0.68	−0.21
Air vapor pressure (+10%)	0.56	0.16	0.04	0.00	−0.03	−0.05
Air vapor pressure (−10%)	−0.03	−0.21	−0.07	−0.16	−0.31	0.00
Reference value (%)	94.76	93.55	94.90	100.44	99.85	98.34

radiation, while the sensitivity of the sprinkler efficiency to the hourly variables was highly related to the specific weather conditions during the process of irrigation and several hours after water application ceased. For example, a 10% decrease in wind speed resulted in an increased *E*2 for the sprinkler irrigation event on 29 July, while a similar decrease in wind speed produced a reduced *E*2 for the sprinkler irrigation event on 5 September.

4. Conclusions

The evaporation of spray drops and the canopy-interception losses decreased sprinkler efficiency, while the evapotranspiration suppression resulting from microclimate modification of sprinkler irrigation contributed to an improvement in sprinkler efficiency. When modeling the sprinkler efficiency while considering the microclimate modification effects using the Cupid model, the following conclusions can be made:

- Because the evaporation process of canopy-intercepted water was an integrated result of the soil–plant–atmosphere continuum, the microclimate modification from sprinkler irrigation was highly related to the specific weather conditions during and after an irrigation event. Both irrigation efficiency and sprinkler efficiency showed flexible characteristics during an irrigation season.
- The microclimate modification occurred not only during the application but also continued for 10–20 h after the application finished. This modification resulted in an improvement of sprinkler efficiency by 5 percentiles.
- The leaf thermal emissivity was the only generally sensitive variable for both irrigation efficiency and sprinkler efficiency of the constant and daily variables. The relative importance of the hourly variables on irrigation efficiency was as follows: temperature > wind speed > air vapor pressure > solar radiation, while the sensitivity of the sprinkler efficiency to the hourly variables was greatly dependent upon the weather and plant conditions during and after an irrigation event.

Acknowledgements

This work was financially supported by the National High Technology Research and Development Program of China (Grant no. 2011AA100506), the China Postdoctoral Science Foundation (Grant no. 0135022010) and the Special project funded by the China

Institute of Water Resources and Hydropower Research (Grant no. 1102).

References

Cavero, J., Medina, E.T., Puig, M., Martínez-Cob, A., 2009. Sprinkler irrigation changes maize canopy microclimate and crop water status, transpiration, and temperature. Agron. J. 4, 854–864.

Hansen, V.E., 1960. New concepts in irrigation efficiency. Trans. ASAE 3, 55–61.

Huang, H.G., Xin, X.Z., Liu, Q.H., Chen, L.F., Li, X.W., 2007. Using CUPID to simulate wheat canopy component temperatures distribution: sensitivity analysis and evaluation. J. Remote Sens. 11, 94–102.

Huang, Q.H., Zhang, W.C., 2010. Application and parameters sensitivity analysis of SWAT model. Arid Land Geogr. 33, 8–15.

Inclán, M.G., Forkel, R., 1995. Comparison of energy fluxes calculated with the Penman–Monteith equaton and the vegetation models SiB and Cupid. J. Hydrol. 166, 193–211.

Kustas, W.P., Anderson, M.C., Norman, J.M., Li, F.Q., 2007. Utility of radiometric–aerodynamic temperature relations for heat flux estimation. Boundary Layer Meteorol. 122, 167–187.

Liu, H.J., Kang, Y.H., 2006. Effect of sprinkler irrigation on microclimate in the winter wheat field in the North China Plain. Agric. Water Manage. 84, 3–19.

McNaughtom, K.G., 1981. Net interception losses during sprinkler irrigation. Agric. Meteorol. 24, 11–27.

Norman, J.M., 1982. Simulation of microclimates. In: Hatfield, J.L., Thomason, I.J. (Eds.), Biometeorology in Integrated Pest Management. Academic Press Inc., New York, pp. 65–99.

Norman, J.M., Campbell, G., 1983. Application of a plant–environment model to problems in irrigation. In: Hille, D. (Ed.), Advances in Irrigation. Academic Press Inc., New York, pp. 155–188.

Playán, E., Salvador, R., Faci, J.M., Zapata, N., Martínez-Cob, A., Sánchez, I., 2005. Day and night wind drift and evaporation losses in sprinkler solid-sets and moving laterals. Agric. Water Manage. 76, 139–159.

Tan, B.Q., Jin, G.Y., 1998. Hydrological model and parameter identify, first ed. China Science and Technology, Beijing.

Thompson, A.L., Gilley, J.R., Norman, J.M., 1993a. A sprinkler water droplet evaporation and plant canopy model: I. Model development. Trans. ASAE 36, 735–741.

Thompson, A.L., Gilley, J.R., Norman, J.M., 1993b. A sprinkler water droplet evaporation and plant canopy model: II. Model application. Trans. ASAE 36, 743–750.

Thompson, A.L., Martin, D.L., Norman, J.M., Tolk, J.A., Howell, T.A., Gilley, J.R., Schneider, A.D., 1997. Testing of a water loss distribution model for moving sprinkler systems. Trans. ASAE 40, 81–88.

Tolk, J.A., Howell, T.A., Steiner, J.L., Krieg, D.R., Schneider, A.D., 1995. Role of transpiration suppression by evaporation of intercepted water in improving irrigation efficiency. Irrig. Sci. 16, 89–95.

Wang, D., Li, J.S., Rao, M.J., 2006. Sprinkler water distributions as affected by corn canopy. Trans. Chin. Soc. Agric. Eng. 22, 43–47.

Wang, D., Li, J.S., Rao, M.J., 2007. Estimation of net interception loss by crop canopy under sprinkler irrigation based on energy balance. Trans. Chin. Soc. Agric. Eng. 23, 27–33.